INNERVATE AR: MOBILE AUGMENTED REALITY AND DYNAMIC 3D ANIMATION TO VISUALIZE THE RELATIONSHIP BETWEEN CANINE MOTOR NERVES AND ANATOMICAL MOVEMENT

A Thesis

by

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ABSTRACT

Augmented reality applications for anatomy education have seen a large growth in their literature presence as an educational technology. However, the majority of these new anatomy applications limit their educational scope to the labelling of anatomical structures and layers, and simple identification interactions. There is a strong need for expansion of augmented reality applications, in order to give the user more dynamic control of the anatomy material within the application. To meet this need, the mobile augmented reality application, InNervate AR, was created. This application allows the user to scan a marker for two distinct learning modules; one for labelling and identification of anatomy structures, the other one for interacting with the radial nerve of the canine forelimb. The first module matches other existing anatomy augmented reality interfaces. The second module is unique, because it allows the user to play an animation of the three-dimensional anatomy, to show what the normal range motion of the limb is, based on the motor innervation of radial nerve. Afterwards, the user can select where to make a cut along the length of the radial nerve, to cause a nerve deficit to one or more of the muscles of the limb. Based on this user input, the application can then play a new animation of the altered range of motion of the canine thoracic limb. A formal user study was run with this new application, which included the Crystal Slicing test for measuring visual spatial ability, the TOLT test to measure critical thinking ability, and both a pre- and post- anatomy knowledge assessment. Data analysis showed both a positive qualitative user experience overall, and that the majority of the participants demonstrated

an improvement in their anatomical knowledge after using InNervate AR. This implies that the application may prove to be educationally effective. In future, the scope of the application will be expanded, based on this study's analysis of user data and feedback, and educational modules for all of the motor nerves of the canine forelimb will be developed.

DEDICATION

I would like to dedicate this work to my parents. I set out on this graduate school adventure to expand my educational horizons, and learn more about what I could do with my talents for veterinary anatomy, the arts, and technology. You both supported me 100%, and have lifted me up throughout this journey with lots of love and encouragement. Thank you for believing in me, and praying for me, I couldn’t have achieved this without you both at my side.

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A special thanks goes to Dr. Michelle Pine, for seeing potential in me that I didn't recognize, and introducing me to the idea of obtaining my graduate degree.

Thanks also go to my friends and colleagues and the department faculty and staff for making my time at Texas A&M University an extraordinary experience.

Finally, thanks be to God that I was blessed with the honor of this education and degree.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a thesis committee consisting of Professor Jinsil Hwaryoung Seo and Timothy McLaughlin of the Department of Visualization, and Professor Michelle Pine of the Department of Veterinary Integrative Biosciences. While all of the asset creation was done by the author of this work, the integration of all created assets into Unity and then to ARCore on a mobile device was completed by Austin Payne of the Department of Visualization. The pre- and post-activity questionnaires were created under the guidance of Dr. Michelle Pine. The rigging process for this work was based in part on a tutorial that included a Maya Script, and which rights to use were purchased from Andy Van Straten of CG Circuit. All other work conducted for the thesis was completed by the student independently.

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NOMENCLATURE

2D	Two-Dimensional
3D	Three-Dimensional
AR	Augmented Reality
BIMS	Biomedical Sciences
HMD	Head-Mounted-Display
IK	Inverse Kinematics
IRB	Institutional Review Board
mAR	Mobile AR
TAMU	Texas A&M University
TOLT	Test of Logical Thinking
UI	User Interface
VIBS	Veterinary Integrative Biosciences
VR	Virtual Reality
VTPP	Veterinary Physiology & Pharmacology

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1. INTRODUCTION

Due to the increased accessibility of educational technologies, the higher education anatomy curriculum has seen rapid reformation (Biassuto et al., 2006). Traditionally, anatomy courses are primarily taught with the methods of didactic lectures and cadaver dissection. The anatomy classroom teaching materials are characterized by static, two- dimensional images. Laboratory involves dissection guides, animal cadavers, and aids such as plastinated anatomical models (Peterson, 2016). However, decreased laboratory funding and laboratory time, and increased technology development, have led to limiting animal use to only teaching procedures which are considered essential (King, 2004; Murgitroyd et al., 2015; Pujol et al., 2016). With the evolvement of learning theories in the classroom, as well as the growth of 3D technology, there is a need for those who work in the anatomy higher education field to re-examine the learning tools that are used in anatomy courses (Azer & Azer, 2016).

One of several new trends to emerge in anatomy education technology is mobile augmented reality applications for anatomy education. Augmented reality is defined as a technology that superimposes a computer-generated image on a user's view of the real world, thus providing a composite view. This technology is usually developed as an application, and can be used with mobile devices. However, the majority of these new anatomy applications focus primarily on labelling of anatomical structures and layers, or simple identification interactions (Jamali, 2015, Kamphuis, 2014, Ma, 2016).

It is important that anatomy content in augmented reality (AR) be expanded from simple identification questions, and labelled three-dimensional structures. As a step toward this expansion, the goal of this project was to build a mobile AR application for mobile devices, which explores the selected topic: deficits to canine muscle movement, in response to motor nerve damage. The title of the application that was developed is "InNervate AR". It is expected that this project will act as a next great push in the field of anatomy education and mobile AR. Rather than making another simple interaction and labelling interface, the user is able to take a more interactive roll in what information is being presented by the anatomy mobile AR application.

InNervate AR was created to have two learning modules, each with its own augmented reality scannable marker. The first module involved labelling and identification of the structures of the canine thoracic limb. This was purposefully done to make sure that InNervate AR offered the same baseline tools for user experience and learning as the existing anatomy applications that are available. To be more specific in the content of this application, the topic of motor innervation deficits was chosen for the second learning module. This is a concept that is often frustrating to undergraduate anatomy students. The concept of motor innervation deficits is difficult for these students, due to the requirement of mental visualization of the anatomical structures involved, and the need to employ critical thinking for exam questions involving clinical reasoning scenarios. Figure 1-1 shows the view of the participant during both learning modules.

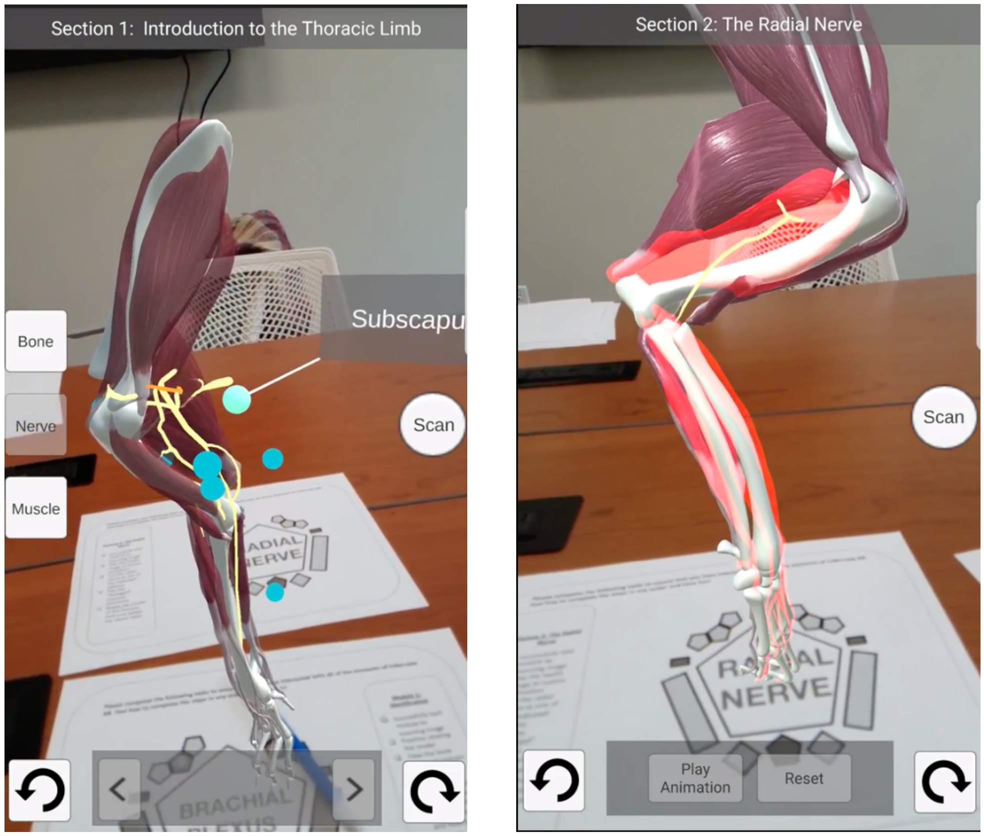

Figure 1-1 The view of InNervate AR participant during the labelling module (left) and the radial nerve animation module (Right).

Canine cadavers are used in many undergraduate school anatomy courses, as well as the course that participants in this study have used in their coursework. Therefore, the anatomy of the canine was used in this anatomy mobile AR application. The participant used the mobile AR device to interact with a photo-realistic canine thoracic limb, and play animations of a healthy canine limb's range of movement. They could then visualize "damage" to different areas of the nerves of the limb, and then be educated on what deficits existed. The "damage" was cuts to the nerve with the swipe of a finger on the device screen, and the resulting muscle action deficits were displayed with before and after animations of the muscles' ability (or inability) to move. Thus, the user could explore different combinations of affects upon the anatomy, and become more actively engaged in the educational process of the mobile AR application. This initial push for expansion of anatomy content in mobile AR will hopefully encourage other researchers to add additional interactive content to their educational tools, and strengthen the presence of this technology in higher education anatomy curricula.

Within an IRB Exemption for this user study, participants provided informed consent, took a pre-activities questionnaire, took a literature cited 3D mental rotation test, took a literature cited critical thinking test, interacted with the InNervate AR application on a mobile device, and then finished with a post-activities questionnaire.

By completing a user study to examine this mobile AR application, I hope to answer the following research question:

Can the InNervate AR platform serve as an educational tool for assisting student's with critical thinking and mental visuo-spatial abilities, as they relate to canine thoracic limb anatomy?

2. LITERATURE REVIEW

2.1. Traditional Anatomy Curriculum

In essence, the “traditional” method of teaching anatomy courses involves didactic lectures and cadaver dissection. The classroom teaching materials are characterized by static, two- dimensional images. Laboratory involves dissection guides, cadavers, and aids such as plastinated models (Peterson, 2016). However, decreased laboratory funding and laboratory time, and increased technology development, have led to limiting animal use to only procedures which are considered essential (King, 2004; Murgitroyd et al., 2015; Pujol et al., 2016). With the evolvement of 3D technology, as well as learning theories in the classroom, there is a need for those who work in the higher anatomy education field to re-examine the structure of these learning tools for anatomy courses (Azer et al., 2016).

2.1.1. Arguments Against Animals Used in Science Education

Currently, animals are used as anatomy cadavers on all levels of education, and a strong argument exists among teachers that there is no educational substitute for dissection. However, decreased laboratory funding and laboratory time, and increased technology development, have led to limiting animal use to only procedures which are considered essential (King, 2004; Murgitroyd et al., 2015; Pujol et al., 2016). Researchers and veterinary teaching faculty have responded to this change with a continuous trickle of new teaching methods and tools that attempt to replace animal use, while still effectively teaching the information to the veterinary students (Hart et al., 2005).

2.2. Visual Spatial Ability and Learning Anatomy

Visual-spatial ability has been defined as the mental manipulation of objects in three- dimensional space. When learning anatomy, spatial visualization is important, as students must learn spatial relationships and interactions between anatomical structures. This knowledge is crucial for surgical skills, because anatomy education gives the baseline skill set for accurate diagnosis in organs and body systems (Azer & Azer, 2016). Traditionally, this three-dimensional mental understanding has been taught with cadaver use. As aforementioned, the amount of cadaver contact has been reduced in higher education, and so new three-dimensional models are being created to compensate. 3D modeling tools allow the user to the add or remove structures and observe them from different angles in three-dimensional space, thus enhancing the teaching process of complicated anatomical areas (Pujol et al., 2016). Many studies have shown a positive relationship between the use of 3D technology and student performance, when related to visual spatial ability. However, the literature has shown mixed results, indicating that more research needs to be done to explore this relationship (Hackett et al., 2016, Berney et al., 2015).

2.3. Critical Thinking in Higher Education

One of the goals of InNervate AR is to deepen the learning that a student can gain from their interaction with this application. By taking the anatomical material beyond pure identification, and into more complex and dynamic interaction, an element of critical thinking can possibly be introduced. According to Abraham et Al, "critical thinking is the process of actively and skillfully applying, relating, creating, or evaluating information that one has gathered.” The ability to think critically is vital to science education, and is crucial for life-long learning (Abraham, 2004). Kumar and James support this argument by adding that critical thinking is a rational process, with personal reflection to reach a conclusion. This approach to learning has become a high focus in educational research (Kumar, 2015).

2.4. Three-Dimensional (3D) Technology to Supplement Traditional Curriculum

Even though the amount of class time devoted to anatomy has decreased, cadaver dissection and traditional teacher interaction have been shown to still be important for excellence in student learning (Corton et al., 2006; Tanasi et al., 2014). Therefore, the literature is full of studies comparing new 3D technology to cadaver dissection, to see how various ratios of cadaver and 3D technology exposure can impact learning.

2.4.1. Mobile Devices and Augmented Reality for Anatomy Education

Augmented reality (AR) has been granted a large literature presence in higher education. AR is a platform which combines the physical and virtual worlds, with user control over the interaction between the two. In order for this technology to be effectively implemented as an educational tool, specialists from both hard/software sectors and educational backgrounds must work together (Kesim et al, 2012). To start, it must be noted that there are AR applications with complex simulation user interfaces, however those systems tend to be used in medical programs, for exploratory surgical practice, such as the Sakellariou Inguinal AR program (Sakellariou, 2009). The focus of this review is on AR technology for learning general anatomy through the use of mobile devices, not for practice in surgical techniques. For the purposes of this study, we are defining mobile devices as tablets or smart mobile phones.

One example of mobile AR study (mAR) was a multi-university study with a specific mobile application, HuMAR. The intent of implementing HuMAR was to teach general human anatomy to students. Overall, they hoped to measure the user experience of the application, in three different anatomy courses, across three different universities. They performed a pilot test, and after analyzing their pre- and post-surveys, they determined that this mAR application could be effective in motivating and improving student learning (Jamali, 2015). Another research project tested to see if mobile augmented reality (mAR) could be implemented in a Turkish medical school anatomy class, as an educationally impactful tool. The researchers concluded that mAR decreases cognitive load, increases academic achievement, and can make the learning environment more flexible and satisfying (Küçük et al., 2016).

2.4.2. Existing User Interfaces in AR

In terms of the user interface of AR, most projects seem similar in nature. The Miracle system is described as providing an identification of structures interaction and "a meaningful context compared with textbook description (Kamphuis, 2014)". The work done by Chien et al includes a system that has "pop-up labeling" and an interactive 3D skull model, that the users can rotate to view different angles of the model. They also found results showing that the 3D display of AR helped students improve their spatial memory of the location of anatomical structures, as compared to a traditional 2D display (Chien, 2010).The MagicMiror project of Ma et al. is mapped to the users own body, but it is still a simple point and click interface. The user is quizzed based on definitions and asked to identify structures (Ma, 2016). There is a lack of understanding of how AR can support more complex learning in anatomy, and how to ensure that the AR system has strong usability in a classroom environment (Kamphuis, 2014, Cuendet et al, 2013). But as seen in the review by Lee et al, this technology has a large potential to serve in education, as it can make the educational environment more engaging, productive, and enjoyable. Furthermore, it can provide a pathway for students to take control of their own learning and discovery process (Lee et al., 2012).

2.4.3. Mobile Augmented Reality vs. Virtual Reality

While both augmented reality (AR) and virtual reality (VR) technologies have their own advantages and disadvantages, it is unknown whether or not VR or AR is the better platform, particularly for 3D object manipulation. (Krichenbauer et al, 2018). For the purposes of this work, VR will refer to the traditional head-mounted-display (HMD) systems, and mobile VR will refer to systems that use smartphones with a handheld display, i.e. GoogleCardboard. The mobility of smart phones helps to eliminate constraints on time-of-use, size-of-location, or other demanding technical requirements (Fetaji et al, 2008). In terms of mobile AR and mobile VR use, there are again no definitive answers as to which is more educationally impactful. Huang et al performed a comparative AR/VR study on science knowledge retention. This study showed that mobile VR is more immersive and engaging because of the spatial presence of the VR environment, while mobile AR is more effective for conveying auditory information, because its less-immersive experience requires less cognitive effort (Huang et al, 2019).

VR and mobile VR have the advantage over AR of not having to wait for camera images, or perform rectification and correction of images (Krichenbauer et al, 2018). However, AR also does not elicit the same loss of depth perception that VR does, and it allows the user the advantage of being able to see their own body in their environment (Krichenbauer et al, 2018).

2.4.4. Augmented Reality and Cognitive Load

When designing a technology for education, its effect on the students' cognitive load must be carefully considered. Cognitive load is defined as a multidimensional mental representation, or "load", constructed in the student's mind while they are carrying out a specific task. The total cognitive load of a task must not exceed the working memory that is being used by the student, or the instructional effectiveness of the technology may be reduced. Cognitive load can be made up of intrinsic load, extraneous load, or germane load. Intrinsic load deals with how much prior experience the student has with the material. Extraneous load involves exposure to excessive information. Germaine load is the amount of working memory that the student must employ to handle the demands of intrinsic load. The correct balance of these three categories must be built into the design of an educational technology. Ideally, more working memory should be spent processing intrinsic load than is spent processing extraneous load. (Lai et al, 2019)

Previous research has been done to show that an augmented reality technology can either lower or overload cognitive load of the student. A Turkish research project tested to see if mobile augmented reality (mAR) could be implemented in a Turkish medical school anatomy class, in order to decrease cognitive load and increase academic achievement. The researchers concluded that the mAR did decrease cognitive load, increase academic achievement, and made the learning environment more flexible and satisfying (Küçük et al., 2016). However, a review of the literature by Akçayır and Akçayır showed that there have been insufficient research findings to decisively settle the question of AR technology's effect on student cognitive load (Akçayır & Akçayır, 2017). A study by Turan et al addressed this call for clarity by performing an AR study with geology students, specifically to test AR's effects on cognitive load. Their results showed a statistically significant decrease in cognitive load, as well as improved educational achievement, for the experimental group that was using AR (Turan et al, 2018).

2.5. Animation and Rigging for Anatomy Education

To animate the anatomy of a character, traditionally the artist uses a workflow that is both efficient and aesthetically pleasing. Many work-flows in anatomy animation have emerged to accomplish this, but usually the focus of these work-flows is not anatomical accuracy. Muscle models of a body are usually developed so that the deformations of the skin sitting superficial to the muscles looks accurate and aesthetically pleasing (Pratscher et al, 2005, Pan et al, 2009). Previous researchers have explored different approaches to their work-flow by trying to leverage 3D body scan data, physics-based volumetric modeling, and the combination of the two. Kadlecek et al. in particular used several 3D scans of an actor and reconstructed a fully volumetric physics-based character which would react correctly to gravity and collisions (Kadlecek et al, 2016). While all of these techniques correctly convey the movement of the anatomical structures in a believable manner, they still do not fundamentally rely on anatomical accuracy to produce their animations. The muscle models are not what drive the animation. Instead, the actual skeleton drives the body's movement, or the appearance of the deformations under the skin determine how the body moves, based on pre-determined poses. To be anatomically accurate, the muscles would have to contract, producing movement of the joints based on their attachments to them, and thereby producing movement of the entire body. For the purposes of the animation industry, this attention to anatomical detail is not a necessity, because the message of the movement is successfully conveyed without it. However, for an anatomical education setting, the animation must be correct to ensure the educational integrity of the material.

2.6. Technology User Interface Usability

Designing a technology's user interface involves many elements, and one of the most important ones for a successful learning environment is its usability. Usability is defined as the ability for a system to be exercised to achieve the intended goal and to complete a specific task effectively. Usability can be used as a qualitative measure of the ease-of-use of a technology. To help achieve good usability, three categories must be considered: learnability and memorability, effectivity vs errors, and efficiency. A usable learning technology is important in a mobile learning application because it heavily contributes to the user's ability to learn from the application, and influence the user's overall satisfaction (Fetaji et al, 2008).

3. MATERIALS AND METHODS

The content range for this application was provided by the curriculum included in the undergraduate VIBS 305 Biomedical Anatomy course at Texas A&M University. This is an upper-level course, but no pre-requisite anatomical knowledge is expected or required. The course is restricted to enrollment of Biomedical Sciences majors only. All three- dimensional (3D) models of the anatomical structures for the application were based in the information from this course. The focus of this application was the canine thoracic limb bones, intrinsic muscles, and motor nerves.

3.1. InNervate AR Application Development

As seen in the background section of this proposal, mobile devices are growing as a tool for anatomy education. With the deployment of more robust devices, smart phones can be more easily used as platforms for augmented reality. For this project, an augmented reality application, InNervate AR, was built on the platfo rm of a smart phone. The purpose of creating InNervate AR was to explore a more interactive user experience while learning about motor nerve deficits as they relate to the canine thoracic limb.

3.1.1. Model Asset Creation

The focus of this application was the bones, intrinsic muscles, and motor nerves of the canine thoracic limb. All of these concepts are included in the undergraduate VIBS 305 Biomedical Anatomy course curriculum at Texas A&M University. All of the three-dimensional muscle models in the InNervate application were first created in Sculptris Alpha 6 by Pixologic, and then imported to Autodesk Maya 2017 for retopolization. The models of the bones were taken from existing models and corrected to be anatomically accurate in their articulation and shape. This accuracy was determined by reference to the content in the TAMU VIBS 305 anatomy course. The models of the motor nerves were created in Autodesk Maya 2017. The skinned paint weights were adjusted to make sure that as the limb moved, the models wouldn't inappropriately collide at their articulation points.

3.1.2. Asset Rigging and Animation

To rig all of the models together for animation, several steps were taken. First, a single inverse kinematics (IK) joint chain was built along the bones of the canine limb. Next, a Maya script was run to generate a 5- joint hierarchy for each muscle individually, along the path set between two locators. These two locators were placed at the origin and insertion points of the muscle. All muscles were given the same length 5-joint hierarchy. The joint chains for each muscle were only different in how far the distance was between the two locators was, which would either shrink or expand the space between each joint. The newly generated joint hierarchy was then bound to its muscle with the Maya Smooth Bind command. The top and bottom locators of the muscle's joint hierarchy were then bound to the main inverse kinematics (IK) rig with a Parent constraint command at the closest intersection with a canine skeletal joint. This parent constraint relationship between the main IK rig and the locator allowed for the bound muscle model to inherit the transformations of the IK rig with a global orientation. In other words, the model would remain attached to the IK rig along the canine skeleton as the entire limb was animated to move. This process was repeated until all of the modelled muscles had been connected to the main IK rig. Please see Figure 3-1 for a visualization of this process. The nerves were rigged in a similar workflow.

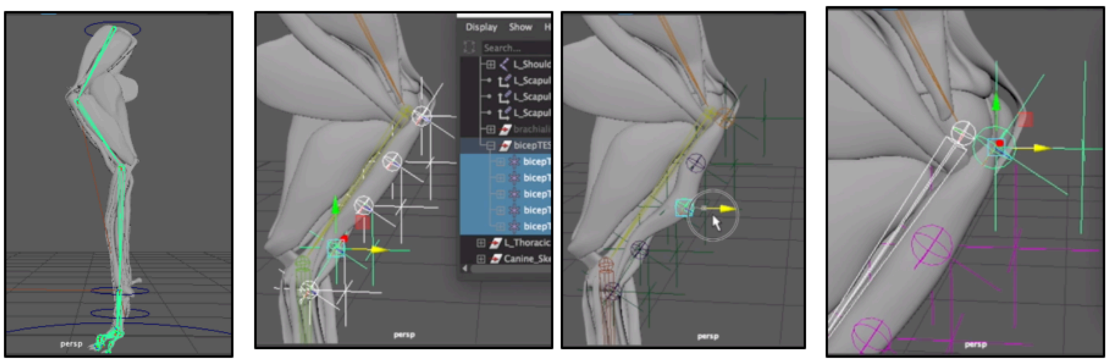

Figure 3-1 The rigging process of InNervate AR

After all of the assets were rigged, they were animated for anatomically accurate movement. All actions of the canine limb were driven by the contraction and relaxation of the muscles, forcing movement of the skeleton. For example, the elbow joint would flex because the biceps brachii muscle contracted, bringing its origin on the humerus bone closer to its insertion on the radius and ulna bones. The “bulging” of a muscle to visualize contraction was managed by adjusting the scale of the appropriate joints in the muscle model’s Smooth bound joint chain. In other words, if the muscle was meant to contract and bulge in the middle, then the third joint down in the hierarchy, the one in the middle, would be scaled up in size.

A total of five animation sequences were created. The first animation sequence was the entire healthy range of motion of the canine thoracic. The other four scenarios involved changes in movement capabilities of the limb, based on the motor innervation provided by the radial nerve. These four radial nerve scenarios represented different possibilities of damage that could have occurred to the radial nerve. All of the keyed animation in these scenarios was baked down onto the rig, and then the files were exported as .fbx files to Unity. These animation scenarios were reviewed for accuracy of motion. This review was based on reference from the TAMU VIBS 305 Anatomy course materials, the other anatomy graduate courses I have taken, and my personal experiences working with canines.

Due to the infinite number of possible damage scenarios to an organic animal's nerves, the number of nerve damage scenarios was narrowed down to a more finite set of 4 ranges. These 4 ranges would produce the most visually distinctive results between each of the scenarios. This was done so that the scenario possibilities would not overwhelm the user.

3.1.3. Asset Texturing

The muscle models were textured in Substance Painter 2018. A low-polygon mesh of each model was imported, and then the high-polygon mesh of the same model was baked down onto the low-polygon model. After the layers of the muscle had been painted on, the normal, height, roughness, and color maps of the texture were then exported to Unity.

3.1.4. Asset Assembly in Unity and ARCore Software

After all of the assets were created, they were assembled in Unity. First the import settings of Unity were adjusted to successfully accept the fbx animation files. The fbx format was chosen because we found that Unity was most successful at accepting the baked animation keys of the Maya files in this format. Next, appropriate scripts were written to accommodate for either the labelling content learning module interactions, or the radial nerve animation content learning module interactions. A pre-fabrication, also known as a Unity prefab, instance was created in Unity for each asset, along with a UI screen. Once all of the assets were assembled in Unity, the script for ARCore's Image AR Controller was modified with a pre-fabrication instance and UI screen to accommodate the Unity assets.

InNervate AR was designed as a marker-based system with Google ARCore software, utilizing image recognition developments from Viro Media. This means that the camera of the mobile device detects a shape on a piece of paper, known as the marker, and then the application loads the programmed learning module that corresponds to that marker (see Figure 3-2).

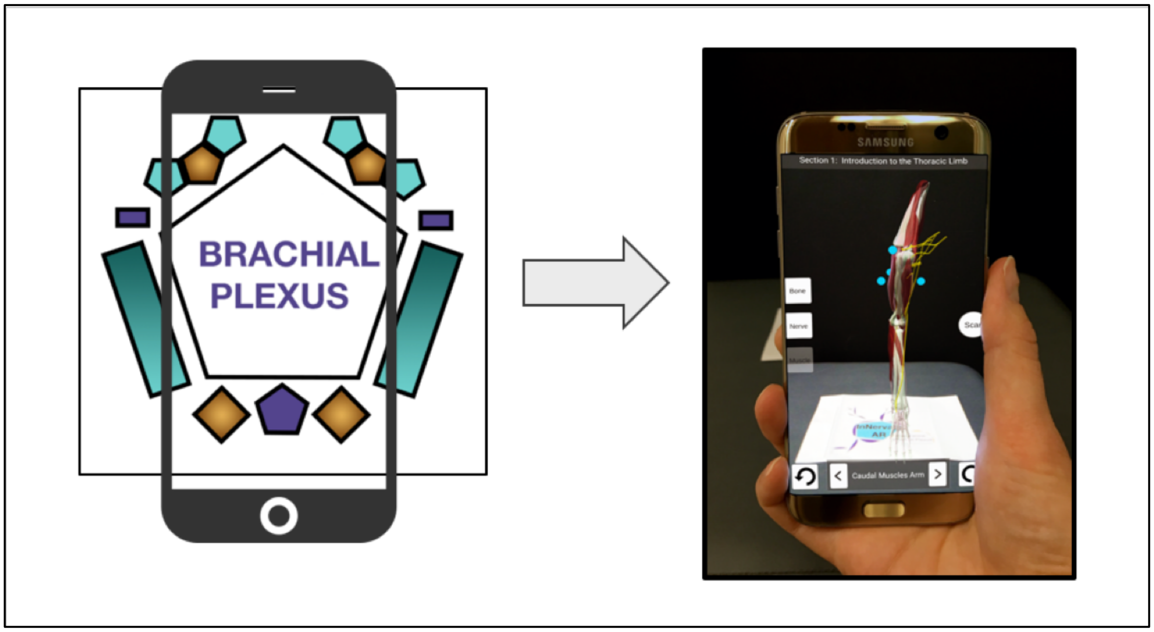

Figure 3-2 The process of image recognition with a mobile device to load the InNervate AR application

To accomplish this marker recognition, a learning module specific AR marker was added to the ARCore image database script. The markers were created in Adobe Photoshop, and tested for scannable quality with ARCore's image (arcoreimg) tool. In order to be a strong candidate for marker recognition, the image had to score greater than 75 on a scale of 0 to 100. Multiple iterations of the markers were created in order to ensure that the highest possible image quality score was achieved.

After the markers had successfully scored for quality, the ARCore and Unity script was tested and debugged. The final script build was uploaded to a Samsung Galaxy smart phone for use in the InNervate AR user study.

3.2. Learning Objectives of Augmented Reality Application

Anatomy students struggle with combining several layers of their knowledge together to make logical conclusions about motor nerves and their relationship to the muscles which they innervate. An example of this difficulty is when the students are asked to answer an exam question about which muscle movement deficits would exist based on the information provided about an injury to a specific section of the thoracic limb. When answering that question, the student has to complete several mental steps. First, they must correctly mentally visualize the muscles and nerves of the thoracic limb. Next, they must recall which motor nerves are located in the injured section of the thoracic limb. Afterwards, they must recall which muscles are specifically innervated by the motor nerves in that area of the thoracic limb. By processing that information, they can recall what the actions of those muscles are, and then describe which muscle movements will be impaired. The final consideration that they must make is if the nerves which were damaged continued further down the limb, because if so, then further deficits might exist distally due to the linear relationship between nerve signals and the muscles that they communicate with.

InNervate AR was designed to give students a learning platform for seeing a 3D representation of these clinical reasoning scenarios. The AR technology allows the students to view all of the anatomical structures together, and then actually see how they work together when healthy, or become impaired with damage. With this in mind, the InNervate AR user learning objectives are listed in Table 1.

Table 1 Learning objectives implemented in design of InNervate AR.

	Learning Objectives for InNervate AR
1	Student is able to identify the bones of the canine thoracic limb that are included in the InNervate AR application
2	Student is able to identify the intrinsic muscles of the canine thoracic limb that are included in the InNervate AR application
3	Student is able to identify the motor nerves of the canine thoracic limb that are included in the InNervate AR application. Some motor nerves were excluded, due to the fact that they are not dissected in the TAMU VIBS 305 course. The sensory nerves do not fall within the scope of this application.
4	Student can form mental visual spatial relationships between the anatomical structures of the canine thoracic limb included in the InNervate AR application
5	Student understands the relationship between the thoracic limb motor nerves and their locations relative to the muscles that they innervate.
6	Student can mentally visualize the healthy range of movement that is created by muscles with normal innervation.
7	Student can use critical thinking skills to rationalize which movements of the canine thoracic limb can no longer occur, based on motor nerve deficits caused by trauma to the limb.

3.3. Artistic Decisions in Content Creation

The anatomy of any living being is so beautifully complex, that artistic decisions have to be made when trying to recreate it in 3D. All of the assets were created to be as anatomically accurate as possible, with references from the TAMU VIBS 305 Anatomy course, as well as my other graduate anatomy coursework.

3.3.1. 3D Model Creation Decisions

The first decision involved selecting which canine muscle models should be created, and which should be left out of the application. Because I was not planning to have the canine thoracic limb attached to the body of the dog, but instead free-standing, I decided to leave out the extrinsic muscles of the canine thoracic limb. This included the trapezius, rhomboideus, omotransversarius, brachiocephalicus, serratus ventralis, latissimus dorsi, superficial pectoral muscle, and deep pectoral muscles. I chose to leave the limb free-standing so that the medial side of the limb, where all of the brachial plexus nerves begin to branch, could be clearly visualized. I also did not include any superficial muscles which would impair the user's ability to visualize the triceps. This included the deltoideus muscle and the tensor fascia antebrachia muscles. I decided to do this to simplify the level of interaction that the user had with the application, so that they wouldn't have to worry about removing a muscle layer.

Since the major animation learning module of this application involved the radial nerve, which innervates the triceps, I wanted the user to have a clear view of the relationship between the radial nerve and these muscles. I did not create the axillary nerve, which innervates muscles that were already not included in the application. Any nerves or muscles which are not dissected in the TAMU VIBS 305 Biomedical anatomy course were left out of the application. Examples of these structures include the pectoral nerves, the sensory nerve branches of the thoracic limb, and the teres minor muscle.

Finally, I chose not to create detailed connective tissue, i.e. fascia layers. I made this decision because I knew that that creating these sheet-like models would be incredibly time consuming to create accurately, attach to the limb, and rig/animate smoothly in a way that would not be a distraction to the user. They might have also impaired the user's view of the nerves. All of these decisions were made with the goal of achieving a simple learning experience about the relationship between muscle movement and motor nerves.

3.3.2. Texturing Decisions

The cadavers that the students interact with in a laboratory setting are very different colors from the 3D anatomical muscles that one usually sees in anatomy education tools. These artistic liberties are taken to make the structures a more life-like and aesthetically pleasing color than cadavers tend to be. Following this thread of thought, I chose a red-burgundy color. I didn't want the structures to be a bright blood-red, because that can seem alarming to users sometimes, particularly if they do not come from an anatomy background. The muscle striations were painted intentionally, to be anatomically accurate, and a normal map was applied to make the muscle feel more authentic and less like a perfectly modelled 3D object. The muscle striation references came from the TAMU VIBS 305 Anatomy dissection guide images, as well as from experience working with canine cadavers in-person to study the muscle shapes and appearances.

3.3.3. Animation Decisions

The ultimate guiding principle for this application was that the muscles needed to appear to be driving the bones' movements. In many other anatomy applications, the muscles contract and relax, but those actions do not move the skeleton. Rather, the bones are moving on their own, while the muscles ride along and contract and relax to appear as though they are working with the bones. I chose to follow a tutorial for creating n-cloth muscle models which had controls on the rig for contracting and relaxing the muscles. I had to change my base rig extensively from that tutorial's because theirs was a human arm, and mine was a canine's thoracic limb. But overall, I was able to animate the limb in such a way that let the actions of the muscles drive how the bones of the limb were moving. In terms of the range of motion of the limb, I tried to remain within normal anatomical range, while giving a lot of visual cues to the user of the application to make the movements of the limb very understandable. These anatomical ranges were created to be as anatomically accurate as possible, with references from the TAMU VIBS 305 Anatomy course, as well as my other graduate anatomy coursework, and my personal experiences working with canines.

3.4. Development of Content to Measure Application Effectiveness

For this user study's design, two peer-reviewed testing instruments were selected to test the participant's visual spatial ability and logical thinking ability. A pre- and post-questionnaire were also created.

3.4.1. Crystal Slicing Test

In order to assess mental visuo-spatial ability in this study, I elected to use the Crystal Slicing test. The participant was asked to choose which shape is produced as the result of an intersection between a plane and a crystal solid. This test was originally developed to provide practice of spatial thinking to undergraduate geosciences students (Ormand et al., 2014). It has since been used to study the development of student's spatial thinking skills over time (Ormand et al, 2017). In addition, the Crystal Slicing Test has been positively reviewed as an instrument for quantifying the spatial ability of the test taker, as it relates to visualizing 3D objects (Gagnier et al., 2016). This tool is how we measured each participant's visual-spatial thinking in this study.

3.4.2. Tobin and Capie 1981 TOLT (Test of Logical Thinking) test

In order to assess formal reasoning and critical thinking abilities, I selected the Test of Logical Thinking (TOLT) test for this study. This test measures different categories of reasoning, including probabilistic, correlational, and combinatorial reasoning. The statistical power of the results of the test is strengthened by the fact that the test taker must justify why they chose their answer (Trifone, 1987). This instrument is how we measured each participant's critical thinking ability in this study.

3.4.3. Pre and Post Activity Questionnaires to Test Learning

Within the quasi-experimental design of this study, the non-equivalent groups design is being followed. This means that no randomized control group exists, but a pre- and post- test is given to groups of people that are as similar as possible, in order to determine if the study intervention is effective or not. The pre- test was written to include anatomy knowledge questions, a free response question, demographics questions, and Likert-Scale based questions about their anatomy education experience. The post- test was written with five knowledge-based questions, three of which mirrored the anatomy knowledge questions of the pre-test, with the same concept being asked in a different way. The post-test also included Likert-Scale based questions about their experience with the InNervate AR system, as well as place to write additional feedback. The objective of these questionnaires was to obtain quantitative data based on the anatomy knowledge questions, and qualitative data based on the Likert and free-response questions. Please see these two tests in Appendix A and Appendix B of this document.

3.4.4. Handout to Accompany InNervate AR Use

In order to ensure that all of the participants had a similar experience while using the InNervate AR application, a handout including the scannable markers was provided. This two-page handout had tasks for the users to check off for each learning module, to make sure that they interacted with all elements offered by InNervate AR. Please see Appendix C to view this handout.

3.5. User Study

To test this educational intervention, a formal user study was performed.

3.5.1. Institutional Review Board Exemption

The appropriate Institutional Review Board (IRB) approval was applied for. An Exemption status has been applied to the study, which is allowed to run for up to five years. The IRB Study number is: IRB2018-0867. All participants were asked for informed consent before their participation in this user study.

3.5.2. Sample Selection

Participants were eligible to participate in the user study as long as they had completed the Texas A&M VIBS 305 Anatomy course within the timeframe of the previous 2 academic years. Our hope was to recruit students that had already taken the course, but since this study was voluntary, and not for course credit, we did not expect a high participation rate. Participants that had not taken TAMU VIBS 305 were excluded from participation, due to lack of required background knowledge needed to complete the study effectively.

3.5.3. Recruitment of Participants

A scripted announcement was read before the TAMU VTPP 423 Physiology course. This course is the class that VIBS 305 students are required to take in their degree plan after completion of VIBS 305. The announcement highlighted that participating in this user study would have no effect upon their physiology course grade. A web-address to an online form was provided, allowing those who accessed it to sign up for a time slot to participate in the user study. They were asked to provide a contact email address.

A posted-notice containing the same information as the scripted announcement was posted in noticeable locations around the Texas A&M College of Veterinary Medicine Education Complex. The students of the TAMU VTPP 423 Physiology course were also sent an email reminder about signing up for participation in the study if they were willing to do so. The day before their participation in the study, the volunteered participants were sent an email reminder about their time to participate in the user study the following day. At the day and time of their user study participation time slot, the user was asked to provide informed consent before beginning their participation in the user study.

3.5.4. User Study Sequence of Events

All participants were given 90 minutes maximum to complete the activities of the user study. The participant entered the assigned meeting space and was provided with the informed consent form. The study facilitator explained the form's content, and allowed the user to read the form, and ask questions, before the facilitator signed and dated the form. After the consent form was signed, the user was assigned a unique identification number to place on all of their activities for the remainder of the study. This number provided confidentiality for the participant's identity and data produced during the course of the user study. Next, the participant was asked to complete a pre-activity questionnaire, which contained three anatomical knowledge questions, a set of Likert scale questions, and one free-response question.

The participant was then asked to complete the timed Crystal Slicing Test. They had 3 minutes to complete the test. The participant was next asked to complete the Tobin and Capie 1981 TOLT (Test of Logical Thinking) test. The participant had 38 minutes to complete this test.

After completion of the TOLT test, the participant was provided with a mobile device (SAMSUNG Galaxy) and a corresponding paper handout for how they were to proceed with interacting with InNervate AR. This handout asked them to perform specific tasks, in a defined sequence, in order to ensure that the user had interacted with all parts of the application. The handout had a place for them to check-off when they had completed a task within the application. This handout also had image markers that Innervate AR could scan, to bring up the different learning modules that are built into the application (see Figure 3-3).

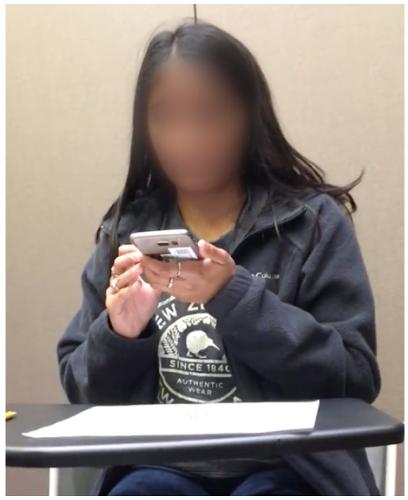

Figure 3-3 Shows a participant scanning a marker to interact with InNervate AR.

The participant's duration of use of the application was recorded. The participant was free to ask the user study facilitator questions about navigation of the application.

While the participant was using the application, another mobile application on the same device was recording the screen of the device. The participant's interaction with the mobile AR application was also recorded on video with a camera. After completing their interaction with InNervate AR, the participant was asked to complete a post-activity questionnaire. All participants were given a $10 Target gift-card in appreciation for their time.

4. RESULTS & DISCUSSION

4.1. Participant Demographics

There was a total of 22 participants in the user study for the Innervate AR application. All of the participants were Biomedical Sciences majors at Texas A&M University, and had taken the TAMU VIBS 305 Biomedical Anatomy course within the two previous academic years. Five of the participants were male, and 17 were female. When asked, 18% of these participants answered "Strongly Agree" and 59% of them answered "Agree" to the statement "I consider myself to have a high level of critical thinking ability." 11 of the participants obtained an "A" in the TAMU VIBS 305 Anatomy course, 9 of the participants obtained a "B" and 2 participants obtained a "C" in the course.

4.2. Participant Crystal Slicing Test Results

The highest possible score that a participant could make on this 3-minute test was 15 points. Only 9.09% of participants scored a 10 or better on this test. The majority of the user study pool (54.55%) made a score in the point range of 7-9. The next most common point range (22.73%) was a score of 5 or 6. The remainder of the participants (13.64%) scored less than 5 points. Figure 4-1 shows a distribution of these scores in graphical form.

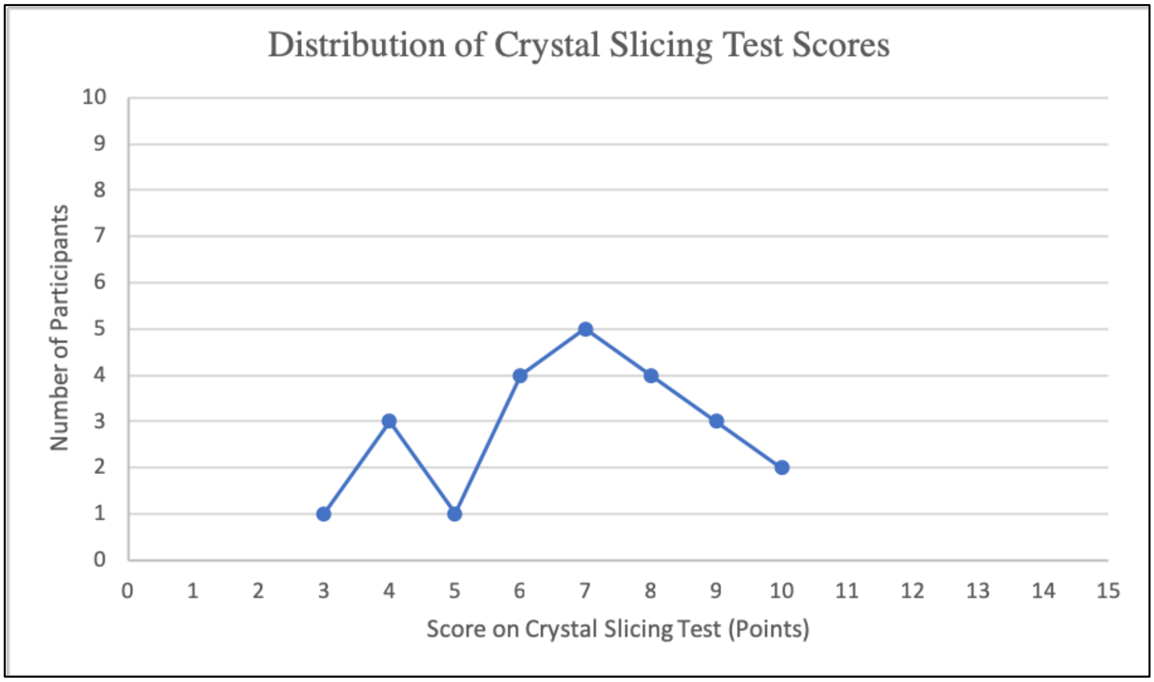

Figure 4-1 Graph of distribution of Crystal Slicing Test Scores for the 22 participants

This data demonstrates that the participants in this user study had average or low visual spatial ability in general.

4.3. Participant Test of Logical Thinking Results

With an allotted time of 38 minutes, the highest score that a participant could make on the TOLT was 10 points. A perfect score of 10 was made by 40.91% of the participants. A score of 9 was achieved by 31.82% of the participants. A score of 8 was made by 9.09% of the participants. Only one participant (9.09% scored a 7 on the test. The remaining participants (13.64%) scored a 6 or lower on the TOLT. Figure 4-2 shows a distribution of these scores in graphical form.

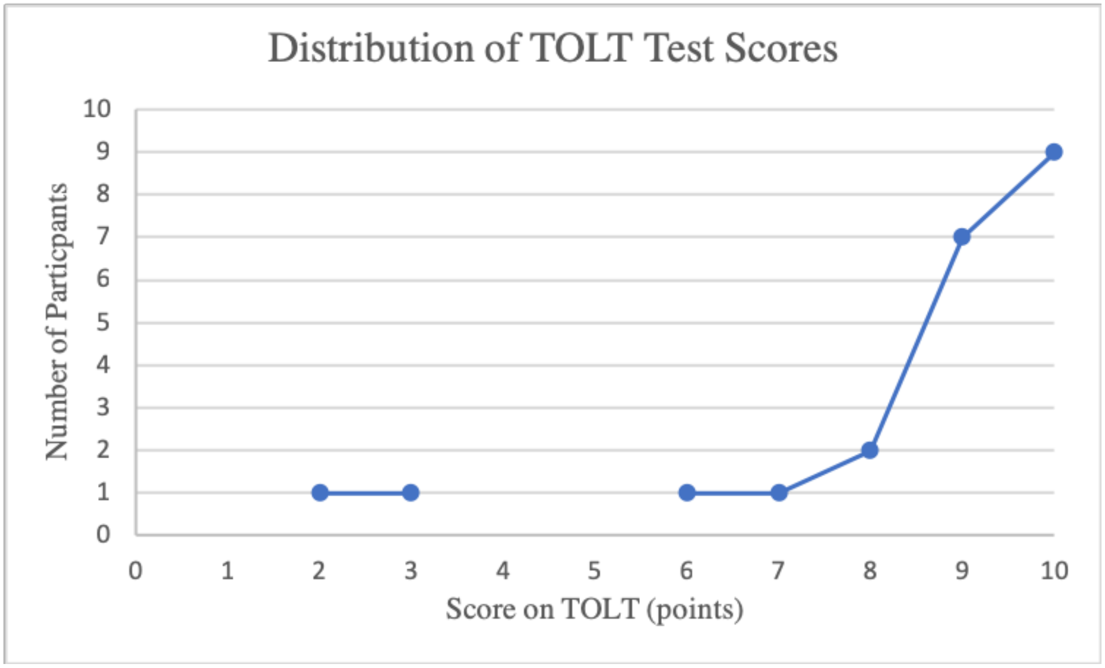

Figure 4-2 Graph of distribution of TOLT Test Scores for the 22 participants

This data showed that the participants trended toward having high critical thinking skills.

4.4. Participant Anatomical Knowledge Scores Results

In the pre-questionnaire, the participants had 3 anatomical knowledge test questions. In the post-questionnaire, the participant had 5 anatomical knowledge test questions, 3 of which were matched to the pre-questionnaire test questions. In other words, the same content was tested on in those 3 questions, but asked in a different way. The scores of the participants were analyzed, and 77.27% of the participants' scores improved on the 3 matched questions, after using the InNervate AR application. 18.18% of the participants made the exact same score on the matched anatomy questions, and

4.55% of the participants had a lower score in the post-questionnaire on the 3 matched questions. This data is visualized in Figure 4-3.

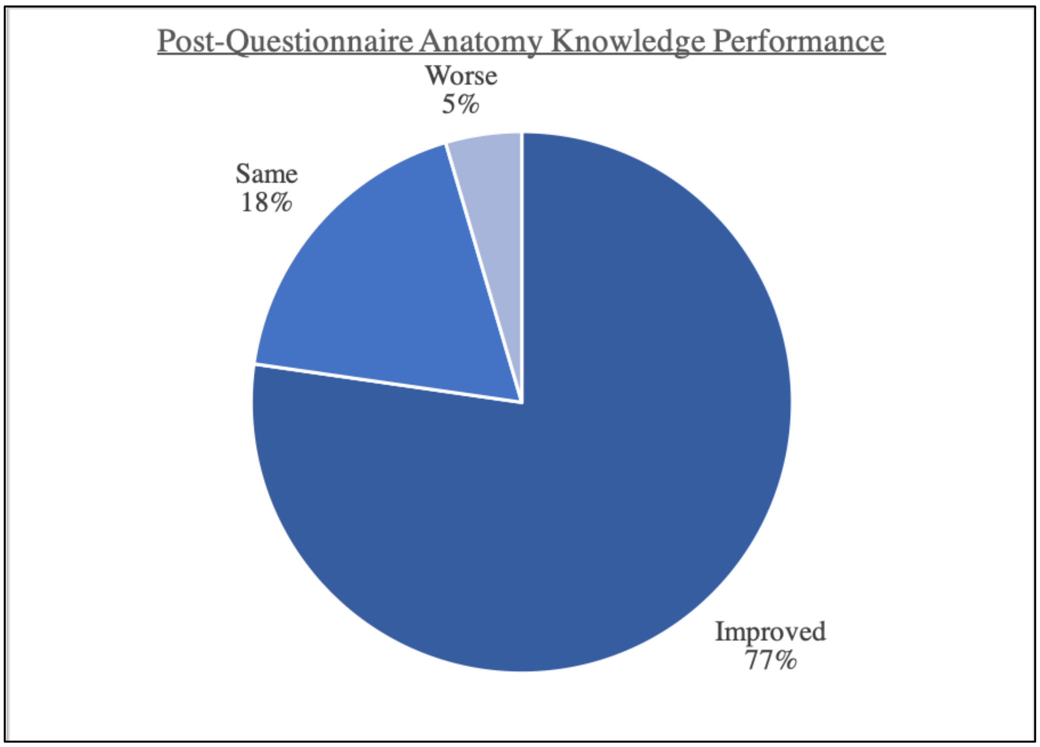

Figure 4-3 Graphical distribution of matched anatomy knowledge question performance in the post-questionnaire.

This data shows that the majority of the user study participants showed an improvement in their performance on the matched anatomy knowledge questions in the post-questionnaire.

Of the 17 participants whose anatomy knowledge scores improved, 14 increased their correct answers by 1 question. The remaining 3 participants improved their score by 2 questions. The participant whose anatomy knowledge score was worse after using InNervate AR decreased their score by 1 question.

4.5. Comparison of Visual Spatial Ability and Anatomical Knowledge Performance

The literature shows gaps when it comes to analyzing the direct relationship between a student's visual spatial ability and their anatomy knowledge performance after using 3D anatomy tools. I was interested in looking at if those with lower visual spatial ability were able to improve their anatomy knowledge score after using InNervate AR. The crystal slicing test results showed that 13 out of the 22 participants scored a 7 or lower on this test, with the highest possible score being 15. This means that these 13 participants scored with a lower visual spatial ability. I compared those participants' crystal slicing test scores to performance scores on the matched anatomical knowledge questions of the post-questionnaire. I wanted to see if their score improved, remained the same, or became worse. The results are shown in Figure 4-4.

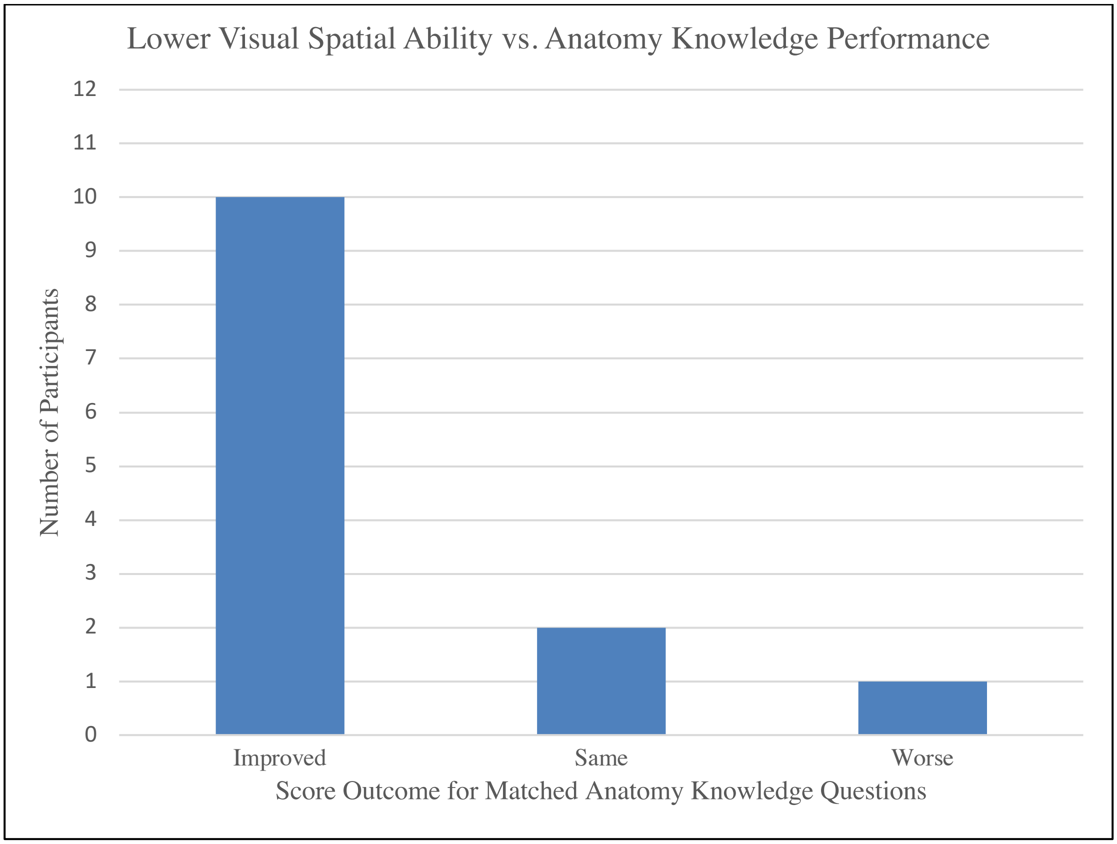

Figure 4-4 Performance on matched anatomy knowledge questions, in relationship to scoring 7 or less points on the Crystal Slicing test

These results showed that the majority of the students with a lower visual spatial ability improved on their matched anatomy knowledge questions in the post-questionnaire.

Next, I decided to compare a higher visual spatial ability to anatomy knowledge question performance. To clarify, the remaining 9 participants scored higher, with a score between 8 and 10 out of 15 points. The results are shown in Figure 4-5.

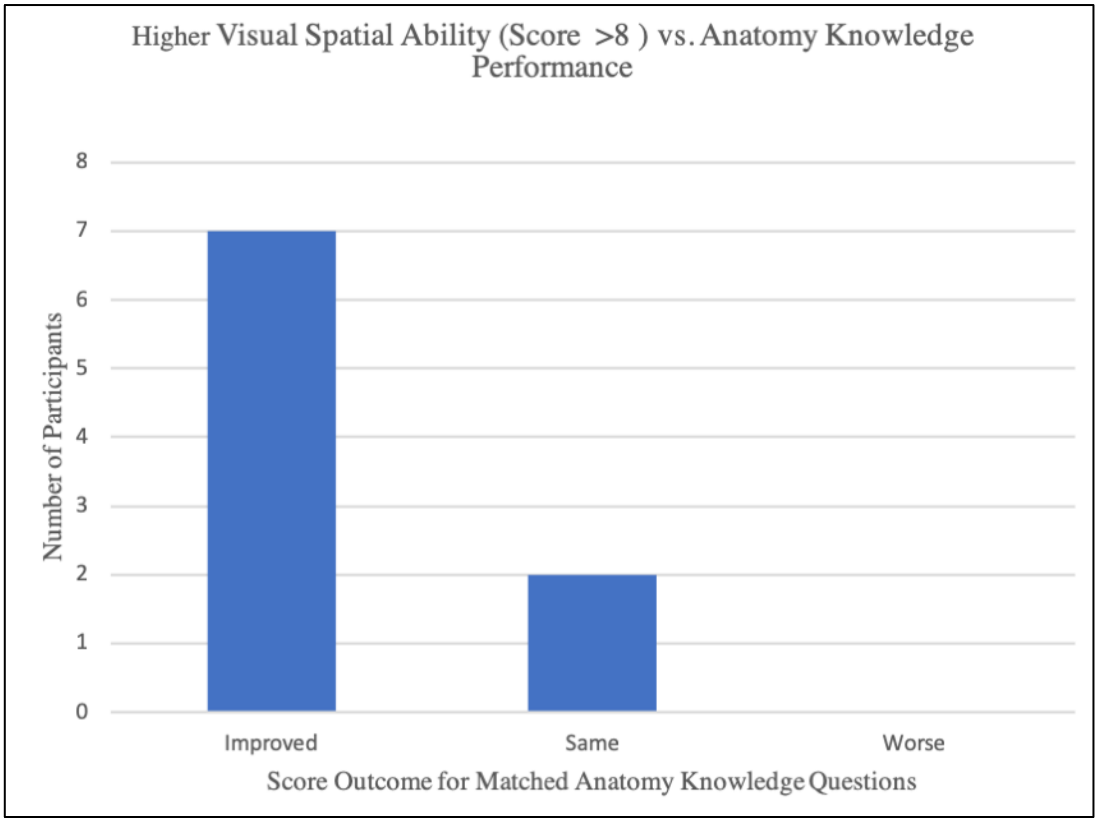

Figure 4-5 Performance on matched anatomy knowledge questions, in relationship to scoring between 8 and 10 points on the Crystal Slicing test

The interesting difference here is that none of these participants did worse on their anatomy knowledge score. Still, there is not a large difference in performance between the two groups of students. More analysis with a larger sample size would be required to find the statistical logic between the visual spatial ability of the participant and their anatomy knowledge performance.

4.6. User Interface Analysis

The participants in this study were video recorded while they used the InNervate AR application mobile device. In addition, the screen of the mobile device was recorded during their InNervate AR use. This data allowed for the user interface (UI) of the application to be analyzed for in the following usability categories: learnability and memorability, effectivity vs errors, and efficiency. These categories of analysis are important in a mobile learning application because they contribute to the user's ability to learn from the application, and influence the user's overall satisfaction (Fetaji et al, 2008).

4.6.1. Learnability and Memorability

These combined categories refer to: how easily the user could master the use of the user interface (UI) without outside help, and how easily they could navigate the application if they made a mistake while using it (Fetaji et al, 2008). While reviewing the screen and video footage from the study, it was notated when a participant asked a point of clarification, or had to be assisted with navigating the application. 32% of the participant needed assistance with how to rotate the canine limb model in the application. 23% of the participants verbally clarified that to switch between the learning modules they would have to scan the next AR marker, or asked how to scan the AR marker properly. 14% of the participants asked about navigation or selection in the labelling learning module. Finally, 32% of the participants asked a clarification question about how to move through the functions of the radial nerve animation module. While these clarifications did occur, all of the participants selected "Strongly Agree" or

“Agree” to the statement “The flow and user interface of the application is intuitive and easy to follow.”

Some issues with the learnability of the UI were encountered, but for the most part the participants grasped how to use the InNervate AR application quickly. There are several possible reasons that the problems mentioned could have occurred. The user may have been in a hurry, and not read the provided AR marker handout directions. The user also might have been new to mobile AR, and so that novice experience could have interrupted how quickly they picked up on how to navigate through the application. One UI issue was immediately apparent, and will be addressed in the future for further study. Once the participant has “cut” the nerve in the radial nerve animation scenario, they can only view the damaged animations. In order to return to the healthy animation to compare and contrast, the user has to re-scan the marker and start the module over again. Furthermore, the rotation buttons for the UI might not have been intuitive enough. When a problem was experienced, the rotation function would either be asked about directly, or the study facilitator would inform the user that they could use the rotation buttons because they were leaning their entire body around the model with the phone in their hand. The UI button choice for rotation will be investigated for more intuitive options in the future.

4.6.2. Effectivity vs. Errors

With the help of the screen and video footage, analysis was done to see how successfully the tasks that the users were supposed to carry out were performed, and how many errors may have occurred. It is important to detect how many errors are made while the UI is being used, and analyze the importance of those errors (Fetaji et al, 2008). All of the users were able to successfully use both of the mobile AR anatomy modules. The most significant user error was that 36% of the users did not properly use the UI to switch between the layers of muscle groups available for learning in the labelling module of the application. This means that they missed information because they did not explore all of the possible muscle label settings. There were also marker scanning issues which occurred for 27% of the participants. None of these scanning issues ultimately impeded their use of both learning modules. The last issue involved the user accidently hitting the "Scan" function button of the UI in mid-use of the application, which occurred for 27% of the participants. This meant that the user would have to unintentionally restart their use of that learning module.

In regards to the scanning issues that were encountered during the study, we discovered that there was a camera-focus issue within the ARCore software itself. Unfortunately, we were unable to update the ARCore software to correct this issue for the study, at the risk that the change would make the Unity platform of the application too unstable. It was decided that the working version of the application, with occasional scanning issues, would be less of a risk to use in the study. The problems with the UI for viewing the muscle group layers will need to be addressed.

The handout that the participant received did not explicitly say to “use the arrows” to switch between the different muscle group layers. So that could mean that the UI for switching between the groups was not intuitive for the users that failed to view all of the muscle group layers. Another explanation is that the participant was in a hurry, and did not take the time to explore all of the UI buttons and their functions. Finally, the “Scan” button for the application may need to be moved to another location of the screen in future iterations of the application, in order to avoid the accidental touch of this UI while the user is holding the mobile device.

4.6.3. Efficiency

The efficiency of the user interface refers to how quickly tasks can be completed using the interface of the application (Fetaji et al, 2008). There was no set time limit for the user study participants while they used the InNervate AR application. They were only required to use both of the learning modules in the same initial order: the brachial plexus labelling module, then the radial nerve animation module. The participant could then return to any module if they wished to do so. The tasks that the user was asked to complete were all on the handout that accompanied their scannable markers for the learning modules. The total length of time that the participants spent using the InNervate AR application was recorded. The mean of all of the participants’ usage times was 10.5 minutes. The median was 9 minutes. The range of the usage times was 25 minutes, with the shortest usage being 5 minutes, and the longest usage being 30 minutes.

Overall, none of the video or screen recordings suggest that the users felt that completing tasks was inefficient or too slow. There seemed to be a correlation between increased InNervate AR usage time, and increased satisfaction or enjoyment while using the application. Shorter usage times might mean that the participant was in a hurry to complete the study, but none of the recorded responses suggest that any of the participants were dissatisfied with the efficiency of the InNervate AR application.

4.7. User Experience with InNervate AR

In the post-study questionnaire, a series of Likert-Scale questions were asked in regards to the participants' perception of InNervate AR. The responses were positive, and can be seen in Table 2 below:

Table 2 Participants' Likert Response in the Post-Study Questionnaire

Likert Scale Question	Percentage of Participants who Said "Strongly Agree"	Percentage of Participants who Said "Agree"	Percentage of Participants who Said "Neutral"	Percentage of Participants who Said "Disagree" or "Strongly Disagree:
InNervate AR is useful for learning about the relationship between the nerves and muscles of the canine thoracic limb.	77.3%	18.2%	4.5%	0%
The 3D anatomy models in InNervate AR are a good representation of the bones, muscles, and nerves of the canine	81.8%	18.2%	0%	0%
The flow and user interface of the application is intuitive and easy to follow.	63.6%	36.4%	0%	0%
InNervate AR is a useful tool for visualizing the spatial/location relationships between the anatomical structures of the canine thoracic limb	77.3%	22.7%	0%	0%
InNervate AR is a useful tool for practicing critical and clinical thinking situations	63.6%	31.8%	4.6%	0%
InNervate AR would be a useful teaching tool in TAMU VIBS 305	90.9%	9.1%	0%	0%

The participants were also given free response questions. The first question asked: “What did you like least about the InNervate AR application?” Common themes to how the participants answered this question included: no “zoom” feature, problems with how to cut the nerves, and problems with selecting the labelling spheres. The second question asked was “What did you like most about the InNervate AR application?” The most frequent responses to this question included: getting to visualize the actions of the muscles with the animations, the graphic aesthetic of the application, how easy the application was to use, and the accuracy of the anatomical content. The last free response question asked the participants if they had any further suggestions about the InNervate AR application. The responses included adding the ability to compare the healthy and damaged animation scenarios side-by-side, adding even more details about the muscles in the labelling module, and further customizing the visual UI of the tool.

Finally, some of the verbal comments of the participants during their use of the InNervate AR application were:

“Oh man I wish I had had this when I was in anatomy lab...because it really connects it all together, especially with all of the bones articulating and everything being there. I remember having to draw so many layers. (User ID: 1001).”

“This is super helpful, I just can't get over it, it’s one thing to see the words on paper, but to see a cut branch! (User ID: 1001)."

"Very interactive compared to other apps I've tried…You can't always go into the lab, and even then, you can't see through the muscles to see branching (User ID: 1008)."

"Nice way to look at the anatomy from different angles... Most apps don't have what would happen if something is wrong, they just have the structures (User ID:1009)."

"That's so cool, that's really fun, I wish we had had that when we were taking the class…I like that a lot. That's like the maps I drew, but in 3D basically, which is nice (User ID: 1011)."

"This would have been so nice. It's one thing to look at a 2D lab manual, but I just really like the animation part too, because that's what I always struggled with. Is it a flexion, is it an extension etc.…I love that you scan it, not just something you look at, it's so interactive (User ID 1019)."

4.8. Limitations to Study

As with any research project, there is a potential for problems to arise, and for threats to validity to be present. Careful planning was done to minimize or prevent as many of these potential issues as possible. For example: The largest threat to any quasi-experimental design like this one is a threat to internal validity, due to lack of a randomized control group. This control group wasn't possible because of ethical reasons, as it is an educational intervention, and educational resources must be made equally available to all students. To minimize this internal confounding bias, all of the who were selected to participate had as similar of a background knowledge as possible. The participants had to have taken TAMU VIBS 305 within the previous 2 academic years. In order to be eligible to take this course, all of the students had to be in the same Biomedical Sciences academic major. The reason that a wide margin for finishing the course was allowed, was to increase the pool of eligible participants for this voluntary study. If the study had been a course requirement, with a guaranteed large number of participants, then the margin of eligibility would have been reduced.

In order to account for the differences in time elapsed since taking the anatomy course, the participants were asked the Likert question: "I feel that in my time since taking VIBS 305, I have retained the information that I learned." 68.2% of participants gave a positive response of "Agree" or "Strongly Agree" to that question. The complete distribution of responses is shown in Table 3.

Table 3 Distribution of participants' responses to a Likert question about knowledge retained since taking the TAMU VIBS 305 course

Likert Scale Question	Participants who Said "Strongly Agree"	Participants who Said "Agree"	Participants who Said "Neutral"	Participants who Said "Disagree"	Participants who Said "Strongly Disagree"
"I feel that in my time since taking VIBS 305, I have retained the information that I learned."	9.1%	59.1%	13.6%	18.2%	0%

Of the 4 participants who indicated “Disagree” to this question about knowledge retained since taking TAMU VIBS 305, 3 of them answered “Disagree” and 1 answered “Strongly Agree” to the Likert question “Most of what I learned in 305 was based on memorization.” These participants took TAMU VIBS 305 in Fall 2017, Fall 2018, Spring 2018, and Spring 2018, respectively. Two of these participants made an “A” in the course, 1 made a “B” and 1 made a “C.” This is interesting data because it shows there isn’t a definitive reason for why those participants feel that they didn’t retain what they learned in TAMU VIBS 305.

There may be a problem with the data in terms of the vast differences in how long the users interacted with the InNervate AR application in the study. However, if their time had been limited, then factors such as different reading paces, fluencies in the technology, and the appropriate length of time to learn the material, would have to be accounted for in the data analysis. Therefore, the amount of time the user had with the InNervate AR application was not limited.

The results of this study do show that the majority (77%) of the participants showed an improvement of their anatomy knowledge score in the post-questionnaire. This data was determined using 3 anatomy knowledge questions which were matched between the pre- and post- questionnaires. The same content was tested in these 3 questions, just asked in 2 different ways between the questionnaires. The potential problem with this is that there weren’t enough matched knowledge questions to be positive that the data collected was accurate. The reason that only 3 matched questions were written was the desire to limit the amount of time that the participant would be asked to volunteer for. With the study design as is, the participant was already asked to give up 90 minutes of their time voluntarily. If longer knowledge-based portions of the study questionnaires had been written, then the extended length of time being requested from the participants might have deterred more participants from volunteering to be a part of the user study.

A potential threat to external validity may exist because of the sample size and the choice of sample participants. The user study participation deadline was extended twice, yet I was only able to collect data from 22 participants, due to the voluntary nature of this study. The average class size in an anatomy course is well above that number. There is also a gender bias to the data because 5 of the participants were male, while 17 of the participants were female. On a positive note, the participants had taken the TAMU VIBS 305 course in different years and semesters, with different professors, so this does diversify their data in some ways. In addition, according to the demographics listed by Texas A&M for the BIMS academic major, there is a similar gender distribution of 70.2% female enrollment, with only 29.8% male enrollment (Accountability, n.d.). Therefore, the sample might not be a poor representation of the higher education anatomy student population existing at Texas A&M.

Only having 22 participants also severely limited what statistics could be run with this data. The study population size wasn't large enough to make correlation assumptions or calculate significant differences about this data pool, as compared to all higher education anatomy students.

Finally, it is possible that these anatomy undergraduates are prepared differently than anatomy undergraduates at other universities. For example, some anatomy students at other universities to not have access to cadaver dissection like the students at Texas A&M do, and/or they might have been required to take a pre-requisite anatomy course. Their course class sizes might be a lot larger or smaller, and so this sample might not represent them. However, the Biomedical Sciences department is distinguished for its excellent preparation of its students, and is a competitive pre- professional undergraduate program (CVM, n.d.). It was assumed that other students in an anatomy course are very likely to also be pre-professional students, and so their study environments are very similar. TAMU VIBS 305 also an upper-level course, which tends to have smaller numbers due to all of the prior courses that are taken first in the part of the degree program. In addition, because of enrollment restrictions, this sample of students was guaranteed to completely come from the Biomedical Science department, which eliminates influences from multiple educational backgrounds.

5. CONCLUSIONS

The goal of this project was to create a mobile anatomy augmented reality application, InNervate AR, which was more dynamic than mobile AR applications that have been previously created. This mobile augmented reality technology is innovative because rather than having another simple interaction and labelling interface, the user was able to take a more interactive roll in what information was being presented by the application. The participant used a mobile device to interact with a photo-realistic canine thoracic limb, and play animations of a healthy canine thoracic limb's range of movement. They were then able to visualize "damage" to different areas of the nerves of the limb, and be educated on what deficits existed. The resulting muscle action deficits were displayed with animations of the muscles' ability (or inability) to produce movement. Thus, the user could explore different combinations of affects upon the anatomy, and become more actively engaged in the educational process of the anatomy AR application. By completing a user study to examine the InNervate AR application, I hoped to answer the following research question:

Can the InNervate AR platform serve as an educational tool for assisting student's with critical thinking and mental visuo-spatial abilities, as they relate to canine thoracic limb anatomy?

The results of this user study showed a positive response from the participants, both in their qualitative feedback data, as well as their quantitative anatomical knowledge improvement. The majority of the participants tested for a high critical thinking ability, and an average or low visual spatial ability. In addition, the majority of the participants with both a higher and a lower visual spatial ability showed an improvement in their anatomical knowledge score on the matched anatomy knowledge questions.

The qualitative feedback from the participants demonstrated areas where the InNervate AR application could use improvement, such as problems with how to cut the nerves, and problems with selecting the labelling spheres. However, the responses from participants were overwhelmingly positive in many categories. They enjoyed getting to visualize the actions of the muscles with the animations, the graphic aesthetic of the application, how easy the application was to use, and the accuracy of the anatomical content.

In terms of the usability and user interface of InNervate AR, this study allowed for errors in design to be uncovered. Some of the participants requested that the application's features include the ability to compare the healthy and damaged animation scenarios side-by-side, the addition of even more details about the muscles in the labelling module, and further customization of the visual UI of the tool. The data allowed for the user interface (UI) of the application to be analyzed for in the following usability categories: learnability and memorability, effectivity vs errors, and efficiency. While some issues with the learnability of the UI were encountered, for the most part the participants grasped how to use the InNervate AR application quickly. One UI issue was immediately apparent, and will be addressed in the future for further study. Once the participant has "cut" the nerve in the radial nerve animation scenario, they can only view the damaged animations. In order to return to the healthy animation to compare and contrast, the user has to re-scan the marker and start the module over again.

All of the users were able to successfully use both of the AR anatomy modules. The most significant user error was that 36% of the users did not use the UI to switch between the layers of muscle groups available for learning in the labelling module of the application. This means that they missed learning information because they did not explore all of the possible muscle label scenarios. There were also marker scanning issues which occurred for 27% of the participants.

In regards to the scanning issues that were encountered during the study, we discovered that there was a camera-focus issue within the ARCore software itself. Unfortunately, we were unable to update the ARCore software to correct this issue for the study, at the risk that the change would make the Unity platform of the application too unstable.

Overall, none of the video or screen recordings suggest that the users felt that completing tasks was inefficient or too slow. There seemed to be a correlation between increased InNervate AR usage time, and increased satisfaction or enjoyment while using the application. Shorter usage times might mean that the participant was in a hurry to complete the study, but none of the recorded responses suggest that any of the participants were dissatisfied with the efficiency of the InNervate AR application.
This study was a wonderful learning opportunity because it showed the great potential that InNervate AR has for anatomy higher education, and brought to light what weaknesses in the technology and research study design should be worked on in the

future. It is my hope that this initial push for expansion of anatomy content in mobile AR will hopefully encourage other researchers to add additional interactive content to their educational tools, and strengthen the presence of this technology in higher education anatomy curricula.

5.1. Future Plans

It is planned to use the data and feedback from this study as a guideline while further expanding InNervate AR to include all of the motor nerves of the limb as learning modules. Any future user studies will be completed in a classroom setting, so that a larger participant population can be guaranteed, and statistically significant results can be achieved. Furthermore, the limitations such as a low number of matched anatomy knowledge questions, and gender bias will be addressed. Future user study and application design will also be more error tolerant, so that user errors with the technology, or differences in user background will not have huge consequences when analyzing results (Rouse, 1990).

It is already planned for this innovative approach to anatomy education technology to be deployed on a virtual reality (VR) platform as well. All of the applicable canine thoracic limb motor nerves will be included, with learning modules for healthy and damaged animation scenarios. This learning concept may also be applied to a VR version with the anatomy of the human upper limb. Hopefully, this project is only the beginning of a ripple effect towards the positive growth of educational technology in higher education anatomy.

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APPENDIX A

PRE-ACTIVITIES QUESTIONNAIRE

Pre-activities Questionnaire

1. What was your final course grade in TAMU VIBS 305?
    a. A
    b. B
    c. C
    d. D-F
    e. Prefer not to disclose

2. During what semester/year did you take TAMU VIBS 305?
    ____

3. What is your gender?
    a. Female
    b. Male
    c. Prefer not to disclose

4. Who was your professor for TAMU VIBS 305?
    a. Dr. Lynn Ruoff
    b. Dr. Michelle Pine
    c. Dr. Cheryl Herman
    d. A professor not listed here
    e. Prefer not to disclose

5. Which nerve provides innervation to the triceps brachii muscle?
    a. The Median Nerve
    b. The Radial Nerve
    c. The Axillary Nerve
    d. The Musculocutaneous Nerve

6. Which group of muscles does the radial nerve innervate, distal to the elbow joint?
    a. Medial muscles of the arm
    b. Craniolateral muscles of the forearm
    c. Lateral muscles of the arm
    d. Caudomedial muscles of the forearm

7. Consider the muscles that are innervated by the radial nerve in the canine. All of the following movements of the joints thoracic limb are assisted by innervation from the radial nerve **EXCEPT**?
    a. Flexion
    b. Extension
    c. Pronation
    d. Abduction
    e. None of the abov

8. Please rate the following concepts:

Questions					
1. I think that VIBS 305 was a valuable learning experience.	Strongly Disagree 1	Disagree 2	Neither 3	Agree 4	Strongly Agree 5
2. VIBS 305 prepared me with enough knowledge to apply what I learned in clinical settings	Strongly Disagree 1	Disagree 2	Neither 3	Agree 4	Strongly Agree 5
3. Most of what I learned in 305 was based on memorization	Strongly Disagree 1	Disagree 2	Neither 3	Agree 4	Strongly Agree 5
4. I was asked to used my critical thinking skills on exam questions in VIBS 305	Strongly Disagree 1	Disagree 2	Neither 3	Agree 4	Strongly Agree 5
5. I consider myself to have a high level of critical thinking ability	Strongly Disagree 1	Disagree 2	Neither 3	Agree 4	Strongly Agree 5
5. I feel that in my time since taking VIBS 305, I have retained the information that I learned	Strongly Disagree 1	Disagree 2	Neither 3	Agree 4	Strongly Agree 5
6. VIBS 305 gave me a good understanding of the nerves of the canine thoracic limb	Strongly Disagree 1	Disagree 2	Neither 3	Agree 4	Strongly Agree 5

5. Please briefly describe how you studied for lecture exams in VIBS 305?

APPENDIX B

POST-ACTIVITES QUESTIONNAIRE

Post-activities Questionnaire

The following questions pertain to ONLY the muscular innervation of the radial nerve. Please disregard sensory innervation.

1. Which of the following muscles is NOT innervated by the radial nerve in the canine?
   e. Extensor Carpi Radialis m.
   f. Triceps Brachii m.
   g. Bicep Brachii m.
   h. Common Digital Extensor m.

2. Consider the muscles that the radial nerve innervates in the canine. If radial nerve damage were to occur distal to elbow joint, which muscle group would be impacted the **most**?
   e. Medial muscles of the arm
   f. Lateral muscles of the arm
   g. Craniolateral muscles of the forearm
   h. Caudomedial muscles of the forearm

3. Consider the muscles that are innervated by the radial nerve in the canine. Which movement of the joints thoracic limb is **most** assisted by innervation from the radial nerve?
   f. Flexion
   g. Extension
   h. Abduction
   i. Pronation

4. Which two muscles does the radial nerve travel between, to move from the medial side of the thoracic limb to the lateral side of the thoracic limb?
   a. Medial and Lateral Heads of the Triceps Brachii m.
   b. Medial and Long Heads of the Triceps Brachii m.
   c. Medial and Accessory Heads of the Triceps Brachii m.

5. Which joint or group of joints is **not** affected by the muscles innervated by the radial nerve?
   a. The shoulder joint
   b. The elbow joint
   c. The antebrachiocarpal joint
   d. The carpo-metacarpal joint
   e. The interphalangeal joints
   f. None of the Above

6. Please rate the following concepts

Questions	
1. InNervate AR is useful for learning about the relationship between the nerves and muscles of the canine thoracic limb.	Strongly Disagree (1) · Disagree (2) · Neither (3) · Agree (4) · Strongly Agree (5)
2. The 3D anatomy models in InNervate AR are a good representation of the bones, muscles, and nerves of the canine	Strongly Disagree (1) · Disagree (2) · Neither (3) · Agree (4) · Strongly Agree (5)
3. The flow and user interface of the application is intuitive and easy to follow.	Strongly Disagree (1) · Disagree (2) · Neither (3) · Agree (4) · Strongly Agree (5)
4. InNervate AR is a useful tool for visualizing the spatial/location relationships between the anatomical structures of the canine thoracic limb	Strongly Disagree (1) · Disagree (2) · Neither (3) · Agree (4) · Strongly Agree (5)
5. InNervate AR is a useful tool for practicing critical and clinical thinking situations	Strongly Disagree (1) · Disagree (2) · Neither (3) · Agree (4) · Strongly Agree (5)
5. InNervate AR would be a useful teaching tool in TAMU VIBS 305	Strongly Disagree (1) · Disagree (2) · Neither (3) · Agree (4) · Strongly Agree (5)

7. If you have any further comments regarding the ratings you gave above, please briefly state them here. If not, simply state "N/A".

8. What other ranges of movement would you like this application to explore in the canine?

9. What did you like least about the InNervate AR application?

10. What did you like most about the InNervate AR application?

11. If you have any suggestions about the InNervate AR application, please describe.

APPENDIX C

HAND-OUT TO ACCOMPANY INNERVATE AR USE

Please complete the following tasks to ensure that you have interacted with all of the elements of InNervate AR. Feel free to complete the steps in any order, and have fun!

Module 1: Identification

- ☐ Successfully load module by scanning image
- ☐ Practice rotating the model
- ☐ View the bone layer and interact with its labelling spheres
- ☐ View the muscles layer and interact with different muscle groups and labelling spheres
- ☐ View the nerves layer and interact the labelling sphere

Please complete the following tasks to ensure that you have interacted with all of the elements of InNervate AR. Feel free to complete the steps in any order, and have fun!

Module 2: The Radial Nerve

- ❑ Successfully load module by scanning image
- ❑ Play the healthy range of motion animation
- ❑ Cut the radial nerve at one of the indicated spheres
- ❑ Play the "damaged" scenario animation
- ❑ Rotate the model of the thoracic limb and repeat the above steps