

INVESTIGATING THE ROLE OF AN INTERACTIVE SIMULATION MODEL ON
THE ABILITY TO VISUALIZE CONCEPTS RELATED TO GROSS ANATOMY

A Thesis

by

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ABSTRACT

Currently many different types of visual aids are available for teaching and studying gross anatomy: illustrations, cadavers, static physical models, plastinated models, and dissection videos are a few examples. These visual aids may be used to identify structures and, in some cases, to facilitate understanding of the spatial relationships amongst structures. However, knowing the identity and location of a structure is only a portion of the content that should be mastered in a gross anatomy course. A knowledge of the basic functions of structures is crucial to understanding anatomy and is often only explained verbally or in text. One major function that current teaching and learning tools leave to the imagination is that of skeletal muscle – the concept of movement. One possible solution to address this oversight is the creation of a kinetic, interactive model that demonstrates movement. In order to create the optimum teaching and learning tool, creation of this type of model should incorporate aspects of many different disciplines and should facilitate student learning by providing engaging and intuitive interaction. To demonstrate the effects on incorporating such a tool into anatomy education, a physical based interactive kinetic simulation model of the canine pelvic limb was constructed. Undergraduate students enrolled in the Biomedical Anatomy course at Texas A&M University were separated into two groups based on their lab section, one of which was allowed to use the model while the other was not. Positive student feedback as well as improved quiz scores show that the interactive simulation model had a positive effect on student comprehension in anatomy education.

DEDICATION

I dedicate this thesis to my family who, in so many ways, helped to make completion of this degree possible. I would especially like to thank my mom, Denise Hall Malone, whose support in every step of this journey has helped me through the bad times and the good times. I love you most Mom!

I would also like to dedicate this thesis to Dr. Michelle Pine and Dr. Jinsil Hwaryoung Seo. You are not only my trusted advisors, but also my mentors and my inspirations! You have facilitated and guided me through this program, which has allowed me to not only discover my biggest dreams, but to realize them. I am forever grateful that I was allowed to meet and work with both of you!

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NOMENCLATURE

CT	Computed Tomography
MRI	Magnetic Resonance Imaging
3D	Three-dimensional
2D	Two-dimensional
VR	Virtual Reality
SD	Standard Deviation

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1. INTRODUCTION

Obstacles in education in many traditional disciplines are rarely approached with solutions from new or different areas of study. This lack of outreach can be detrimental to growth and the innovative process. The challenge of effectively illustrating highly visual concepts related to movement in gross anatomy is one of these obstacles. Gross anatomy courses are most often taught using diagrams and cadavers as well as the occasional static model (Albanese, 2010). These illustrations, however useful for identification and rote memorization, are rarely able to accurately or clearly demonstrate movement (Cake, 2006; Smith and Brennan 2013). Incorporating aspects of visualization sciences such as design, kinetic sculpture, and physical computing to the task of demonstrating movement could provide more valuable tools for teaching and learning gross anatomy (Cake, 2006).

Tools currently available for teaching gross anatomy are either limited in their ability to demonstrate movement or are lacking a physical and tactile element. A long relied upon example that clearly illustrates these limitations is a diagram. Using diagrams, which are both two-dimensional and static, to illustrate functional anatomy, which is three-dimensional and in constant motion, may only allow for a limited amount of understanding. To address this, virtual tools and static models for improving identification and spatial reasoning skills have been implemented in classrooms in recent years with seemingly positive results (Chatterjee, 2011). Unfortunately, even with the

move toward three-dimensional interactive tools, the issue of visualizing movement remains to be addressed.

This project explores the implementation of tools for anatomy education which employ physical computing and tactile interaction by specifically addressing the following questions:

- How does the use of a physically based interactive kinetic simulation model affect the ability of a student to visualize and understand concepts related to movement in gross anatomy?
 - o How effective is the model on students' comprehension of the concept of fixator muscles?
 - o How effective is the model on students' comprehension of the action of muscle groups?
 - o How effective is the model on students' comprehension of muscle actions and function such as flexion, extension, contraction, and relaxation?

2. LITERATURE REVIEW

2.1 The Current State of Anatomy Education

As is reflected in the core curriculum required of both human and veterinary medical professionals, anatomy is a foundational course that is crucial to understanding and orienting clinically significant information (Collins, 2008; Mills, 2003; Paalman, 2000). In classrooms around the world, anatomy education has been approached with a variety of different methods and tools. The importance of spatial reasoning and visualization in anatomy is generally agreed upon (Chatterjee, 2011). However, the best approach to facilitate the development of these skills is not as clear.

2.1.1 Existing Methods and Tools in Anatomy Education

The most commonly used tool in learning gross anatomy is the cadaver (Collins, 2008). Whether it be veterinary anatomy or human anatomy, cadaver dissection is crucial to the development of recognition skills and the understanding of spatial relationships (Theoret, Carmel and Bernier, 2007). Other tools introduced into anatomy instruction are generally supplemental to cadaver dissection. With the time, cost and ethical issues that these cadavers pose combined with the decreasing time and curriculum dedicated to gross anatomy, alternatives such as dissection videos have been explored (Collins, 2008). In response to this movement in the field of anatomical instruction, a study evaluating the effectiveness of dissection videos in place of prosected cadavers with students of veterinary medicine at the University of Montreal was conducted.

Researchers found that students who were instructed with prosected cadavers performed

significantly better than students who were instructed with dissection videos (Theoret, Carmel and Bernier, 2007). Al-Khalili and Coppoc (2014) combined the use of videos and cadavers in comparing the efficiency of traditional 2D video, 3D video and a dissection guide in facilitating student learning of canine anatomy. 2D videos utilized images such as diagrams and illustrations, while 3D videos used renderings of 3D models. The study concluded that students perform significantly better when instruction incorporates the combination of video and cadaver than when a dissection guide and cadaver were used alone (Al-Khalili and Coppoc, 2014).

Recently the creation of highly detailed and accurate three-dimensional models using computed tomography (CT) scans and magnetic resonance imaging (MRI) has improved (Nicholson, Chalk, Funnell, and Daniel, 2006; Noller, Henninger, Gronemeyer, and Budras, 2005). Educators who noticed the increasing accessibility and accuracy of these models, have begun to rely upon virtual 3D models to illustrate structures and relay concepts that are difficult or impossible to show on a cadaver. Certainly 3D visualization is preferred over 2D visualization in studying anatomy as is demonstrated by Jurgaitis et al. (2008). This study compared the effect of two-dimensional CT liver scans versus three-dimensional visualizations on the ability of medical students to precisely determine the localization of tumors. The study concluded that 3D visualizations were significantly more effective (Jurgaitis et al., 2008). Similarly, a study at the University of Lyon 1 in France, utilized a 3D model of the human scapula. First-year kinesiology students were exposed to either a dynamic or static visualization of the model and then asked to

complete an assignment. Researchers found that there was no difference in dynamic versus static visualization of the model on the students' comprehension, but that independent learning of 3D structures and movements was possible for novice learners with a 3D visualization (Berney, Betrancourt, Molinari, and Hoyek, 2015).

Methods to increase the level of student interaction have been explored across multiple different platforms for more than two decades. In 1994 researchers in Athens, Greece published an article on a computer-based veterinary anatomy tutoring system. While the program was developed before the advent of accurate and easily accessible 3D models, the researchers concluded that the unique ability of an interactive computer program to focus and combine certain aspects of veterinary anatomy, provide immediate feedback and individualize the learning experience by allowing users to move at their own pace and choose what and when they wanted to study a particular topic, was undoubtedly beneficial (Theodoropoulos, Loumos and Antonopoulos, 1994). More recently, researchers at Linkoping University in Sweden were able to develop a web-based educational virtual reality (VR) tool to improve anatomy learning. Using virtual contrast injection, interactive segmentation and 3D VR software they were able to convert CT and MRI data into an interactive web-based virtual reality program exploring the major arteries within the human body. The program was well-received by medical students studying gross anatomy and generally preferred over study with a textbook and cadaver alone (Pettersson, Sinkvist, Want, and Smedby, 2009).

Once the ability to incorporate virtual 3D models into interactive programs and virtual environments was fully developed, the development of interactive computer-based programs began to increase. A collaboration between the Oregon Health and Science University and McGill University in Montreal used MRI data from a scan of a human cadaver to create a 3D model of the inner ear. Students who had access to a web-based tutorial which included the 3D model scored an average of 83% on a post-instructional quiz while students without access to the 3D model only scored an average of 65% (Nicholson, Chalk, Funnell, and Daniel, 2006). Currently, researchers at Oregon State University are exploring the use of a virtual 3D model of the canine skull and hyoid apparatus to allow interactive virtual articulation (Viehdorfer, Nemanic, Mills, and Bailey, 2014). At Texas A and M University Catherine Ruoff developed a computer program which demonstrated the anatomy of the equine paranasal sinuses. She concluded that, allowing the user to interact with 3D models by rotating them in space and choosing which aspects of the model to focus on, anatomical structures which are difficult to visualize can be sufficiently illustrated and understood (Ruoff, 2011).

Researchers in Munich, Germany have taken interaction a step further by allowing the user to become the 3D model (Blum, Kleeberger, Bichlmeier and Navab, 2012). This team of anatomists and computer scientists have created what they refer to as an “augmented reality magic mirror” (Blum, Kleeberger, Bichlmeier and Navab, 2012, p. 115) which they have named “Mirracle”. Users stand in front of a large display which is equipped with a depth-sensing and pose-tracking camera. Different views of a virtual 3D

model are displayed on the screen overlaying the image of the user based on the user's position and gestures. Although the 3D model was created using a set of CT scan data and is, therefore, consistent for all users, the system essentially provides a mirror that allows the user to interactively explore their own anatomy (Blum, Kleeberger, Bichlmeier and Navab, 2012).

With the increasing use of virtual methods for visualizing and experiencing anatomy, many educators felt that the inherently physical nature of anatomy might soon be overlooked (Preece, Williams, Lam, and Weller, 2013). In response to this, researchers Oh, Kim and Choe (2009) created anatomical models for learning anatomy that brought CT scan and MRI data back into the physical realm. As an initial exploration of the idea, students at the Sungkyunkwan University School of Medicine were asked to create clay models of a series of organs that are generally characterized as difficult to examine with cross-sectional information such as that from a CT scan or MRI. The clay models were created using different colored clay to represent major organ regions. The fully-formed models were then cut along transverse planes to represent scan data and images. The study revealed that students who had used the clay modeling technique scored significantly higher on CT examinations than did their peers who did not use clay models (Oh, Kim and Choe, 2009). With a focus on a constructivist approach to learning anatomy, Hermiz, O'Sullivan, Lujan, and DiCarlo (2011) asked students to develop a protocol for creating postmortem anatomical casts of the bronchial tree and coronary arteries of rats. These researchers concluded that the integration of concepts requiring

more dynamic skills such as logic, deduction and problem solving allowed students to create their own assumptions and approach anatomy dynamically rather than with simple memorization. This approach and the exploration of the physical casts which the process created resulted in a significantly easier and more effective means for students to learn, understand and remember concepts related to anatomy (Hermiz, O’Sullivan, Lujan, and DiCarlo, 2011). The distinct advantage of physical 3D models over virtual 3D models in understanding anatomy was explored at The Royal Veterinary College at the University of London. This study compared three different methods for studying equine hoof anatomy: the use of a physical model, a virtual 3D model and a textbook. Results from this study indicate that the advantage of using physical 3D models is far greater than either virtual 3D models or textbooks. In fact, researchers found that there was no significant difference in student comprehension amongst groups that used the virtual 3D model and groups that used only a textbook (Preece, Williams, Lam, and Weller, 2013).

Combining the benefits of the physical and virtual 3D models, researchers at Ohio University and in Sophia-Antipolis, France created haptic virtual simulation tools for learning and practicing anatomists. The Ohio University Virtual Haptic Back is a palpatory training tool for medical students. The system provides both visual and haptic feedback combining the use of a virtual 3D model with the latest haptic feedback technology. Students are able to palpate the simulated back, which is pre-loaded with various virtual patient simulations ranging from normal to severely abnormal, with or without the aid of viewing the underlying vertebrae. Initial evaluations of the system

yielded data in strong favor of its efficacy in training. After the initial sessions learning to use the software and getting used to the hardware, data showed that the accuracy of identification increased and required palpatory examination time decreased (Howell, Williams, Conatser, Burns, and Eland, 2005). A similar study conducted at a research facility in France explored the application of haptic feedback in combination with virtual 3D models for visual feedback in hepatic surgery simulation. The complex liver pathologies as well as the dynamic nature of any abdominal organ in vivo presents especially challenging obstacles to hepatic surgery simulation. Computer scientists and artists utilized geometric models created from CT scan images combined with carefully researched physical modeling algorithms specifically designed to replicate realistic deformation of liver tissue in real time. Haptic feedback was provided via visual display in response to surgical gestures communicated to the computer systems via robotics. This system continues to be altered and improved as the understanding physical behavior of human tissues advances and scientific and technological issues are overcome (Delingette and Avache, 2005).

Scientific advancements and discoveries result in the introduction of many new disciplines into undergraduate, human and veterinary medical curriculum alike. Although understanding of these new disciplines and advancements creates demand for an increasingly vital and significantly more comprehensive understanding of anatomy, introduction of new disciplines also results in the reduction in anatomy curriculum (Older, 2004; Smith and Mathias, 2010). Cadaver dissection continues to be the

preferred method of understanding and interpreting anatomical knowledge, but the incorporation of supplemental aids which utilize the latest technological advances is of increasing importance to accelerate as well as improve anatomy education (Wilhelmsson et al., 2010). While 2D images, videos and computer programs may aid student learning, they lack the elements which allow students to explore spatial reasoning (Chatterjee, 2011). Virtual 3D models address this issue in part, but are limited in that they can only be viewed on 2D screens. This creates an additional obstacle for students to overcome as they must have enough initial understanding of spatial reasoning to be able to explore a space in which they are not present. Physical 3D models alone have proven useful for anatomical study, but present little more benefit than cadavers. It is clear that the most effective methods for enhancing anatomy education incorporate both physical and virtual technological tools. This combination best facilitates the true objective of learning anatomy which, as Collins (2008) describes it, is “to integrate an understanding of normal function with recognition of normal structure,” (p. 666) so as to facilitate better recognition and diagnosis of clinically significant abnormalities and pathologies.

2.2 The Importance of Interaction

Educational psychologists are constantly searching for the best way to facilitate learning. Studies on the most effective methods for learning and teaching were being conducted as early as 1937. Generally, these studies have shown that the more engaged the student is in learning the material, the better they will understand and retain the knowledge (Benjes-Small and Archer, 2014). Further, these studies have been useful in classifying

such methods and helping us to understand the cognitive processes involved in certain activities (Krathwohl, 2002). Particularly, learning models developed by educational psychologists such as Edgar Dale, Charles Hoban, Samuel Zisman, and Benjamin S. Bloom bring light to the benefit students gain from interaction and engagement while learning anatomy.

2.2.1 The Learning Pyramid

Transference and retention of information is central to most forms of education and has been extensively explored. Edgar Dale proposed the Cone of Experience model in *Audio-Visual Methods in Teaching* in 1946, and before that Charles Hoban Jr. and Samuel Zisman explored the idea in *Visualizing the Curriculum* in 1937 (Benjes-Small and Archer, 2014). These two models were combined into the idea of “The Learning Pyramid,” an educational model which highlights methods of learning and classifies them as either active or passive.

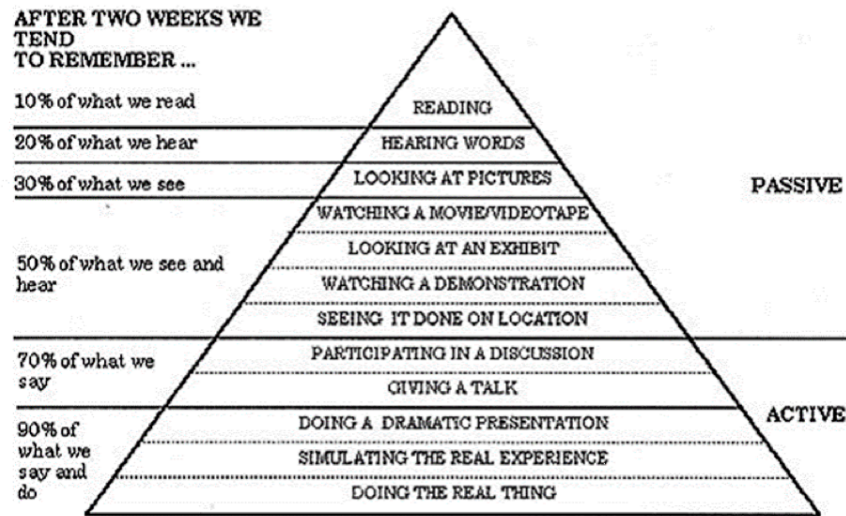


Figure 1. “The Learning Pyramid” Adapted from: Edgar Dale *Audio-Visual Methods of Teaching*, Holt, Rinehard and Winston

Examples of each learning method are ranked in the pyramid with the method resulting in the lowest percent of retention at the top. The pyramid ranks passive learning methods such as “reading”, “hearing”, and “looking” at the top of the pyramid and ranks active learning methods such as “participating”, “talking”, “simulation”, and “doing”, at the bottom. “Doing” and “simulating” are active methods at the bottom of the pyramid corresponding to a 90% retention rate. Applying this educational model to learning gross anatomy highlights the gaps in existing teaching materials as well as the importance of the kinetic, interactive model. Currently students are expected to practice passive learning methods such as listening to a lecture or reading a textbook. The Learning Pyramid ranks these methods at the top of the pyramid corresponding to only a 10% retention rating. As interacting with a kinetic model would incorporate both active

methods of “doing” as well as “simulating”, it is expected that the retention of information can be improved by as much as 80% (Brueckner and Macpherson, 2004).

2.2.2 Bloom’s Taxonomy

Benjamin S. Bloom’s 1956 “Taxonomy of Educational Objectives”, has become the basis for building curriculum in schools around the world (Krathwohl, 2002). The original taxonomy defined six categories within the cognitive domain; knowledge, comprehension, application, analysis, synthesis, and evaluation. Each of these categories, with the exception of the category of application, was then broken down into subcategories. As the title of “Taxonomy” suggests, the organization of these categories was such that, in order to master the more complex categories, (the most complex of which is evaluation), one must first master the simpler categories, thus creating a cumulative hierarchy (Krathwohl, 2002).

Bloom’s original taxonomy has been most frequently employed to classify learning objectives and assessments, the classification of the objective or assessment representing its breadth. An overwhelming and unfortunate number of analyses on educational objectives in classrooms around the world revealed a definite emphasis on objectives in the least complex of all six categories – knowledge. Objectives which fall into the categories of comprehension and synthesis are those which call upon the basic level of knowledge to build a level of understanding and skill with application of the knowledge. Interestingly enough, it is these objectives, not those which fall under the category of

knowledge, which are most often considered the principal goals of education (Krathwohl, 2002).

A learning objective is generally intended to communicate what a student is required to learn and an instructor is required to teach. Customarily, objectives consist of two parts – the subject content and what should be done with that content (Anderson and Krathwohl, 2001). For example, an objective for anatomy would be the following: Understand the difference in the actions of the caudal muscles of the thigh on the stifle joint when the limb is fixed or not fixed. For this objective the subject content is “the difference in the actions of the caudal muscles of the thigh on the stifle joint when the limb is fixed or not fixed,” and the verb describing what should be done with the content is “understand”.

“A Taxonomy for Learning, Teaching, and Assessing; A Revision of Bloom’s Taxonomy of Educational Objectives” reorganizes and modifies Bloom’s original taxonomy so that it takes into account recent findings in cognitive psychology and reflects more commonly used terms. The categories of knowledge, comprehension, application, analysis, synthesis, and evaluation were renamed to correspond to verbs used in educational objectives. Revised categories in order of increasing complexity are as follows: remember, understand, apply, analyze, create, and evaluate (Krathwohl, 2002). These categories and their subcategories are outlined in the following table.

Cognitive Process Dimension	Cognitive Processes Emphasized
1. Remember – retrieving relevant knowledge from long-term memory.	1.1 Recognizing 1.2 Recalling
2. Understand – Determining the meaning of instructional messages, including oral, written, and graphic communication.	2.1 Interpreting 2.2 Exemplifying 2.3 Classifying 2.4 Summarizing 2.5 Inferring 2.6 Comparing 2.7 Explaining
3. Apply – Carrying out or using a procedure in a given situation.	3.1 Executing 3.2 Implementing
4. Analyze – Breaking material into its constituent parts and detecting how the parts relate to one another and to an overall structure or purpose.	4.1 Differentiating 4.2 Organizing 4.3 Attributing
5. Evaluate – Making judgments based on criteria and standards.	5.1 Checking 5.2 Critiquing
6. Create – Putting elements together to form a novel, coherent whole or make an original product.	6.1 Generating 6.2 Planning 6.3 Producing

Table 1. “Structure of the Cognitive Process Dimension of the Revised Taxonomy”

Adapted from: D.R. Krathwohl *A Revision of Bloom’s Taxonomy: An Overview*

A further revision of the original taxonomy is the classification of knowledge into four different dimensions: factual knowledge, conceptual knowledge, procedural knowledge, and metacognitive knowledge. These dimensions are described in Table 2.

The development of these four dimensions of knowledge adds a second dimension to the categorization and analysis of objectives and assessments. Using the knowledge dimensions in combination with the taxonomy of verbs, (known as the Taxonomy Table), creates a tool for indicating, not only the cognitive processes involved in achieving the objective, but the scope of complex cognitive knowledge that is required (Krathwohl, 2002).

Knowledge Dimension	Subtypes of Dimensions	Examples
A. Factual Knowledge - Basic elements students are required to know in order to be acquainted with a discipline.	Aa. Knowledge of terminology Ab. Knowledge of specific details and elements	<i>Aa. Technical vocabulary, music symbols</i> <i>Ab. Major natural resources, reliable sources of information</i>
B. Conceptual Knowledge - Interrelationships between basic elements within a larger structure which allow them to work together.	Ba. Knowledge of classifications and categories Bb. Knowledge of principles and generalizations Bc. Knowledge of theories, models and structures	<i>Ba. Periods of geological time, forms of business ownership</i> <i>Bb. Pythagorean theorem, law of supply and demand</i> <i>Bc. Theory of evolution, structure of Congress</i>
C. Procedural Knowledge – How to do something, methods of inquiry, and criteria for using skills, algorithms, techniques, and methods.	Ca. Knowledge of subject-specific skills and algorithms Cb. Knowledge of subject-specific techniques and methods Cc. Knowledge of criteria for determining when to use appropriate procedures	<i>Ca. Skills used in painting with water colors, whole-number division algorithm</i> <i>Cb. Interviewing techniques, scientific method</i> <i>Cc. Criteria used to determine when to apply a procedure involving Newton’s second law</i>
D. Metacognitive Knowledge – Knowledge of cognition in general as well as awareness and knowledge of one’s own cognition	Da. Strategic knowledge Db. Knowledge about cognitive tasks, including appropriate contextual and conditional knowledge Dc. Self-knowledge	<i>Da. Knowledge of outlining as a means of capturing the structure of a unit of subject matter in a text book</i> <i>Db. Knowledge of types of tests particular teachers administer</i> <i>Dc. Knowledge that critiquing essays is a personal strength, whereas essays is a a person weakness</i>

Table 2. “Structure of the Knowledge Dimension of the Revised Taxonomy”

Adapted from: L. W. Anderson and D. R. Krathwohl *A Taxonomy for Learning, Teaching, and Assessing: A Revision of Bloom’s Taxonomy of Educational Objectives*

This information can then be used to design instructional techniques which both meet and exceed the cognitive and knowledge level of the objective as well as assessment techniques which evaluate student learning at the appropriate levels as defined by the objective (Anderson and Krathwohl, 2001).

In anatomy education, asking students to *recognize* a structure on a diagram or cadaver are appropriate instructional and assessment techniques for objectives which fall under the knowledge dimension of “Factual Knowledge” and under the cognitive process of “Remember”. However, objectives such as the previous example objective “Understand the difference in the actions of the caudal muscles of the thigh on the stifle joint when the limb is fixed or not fixed” fall under the knowledge dimension of “Conceptual Knowledge” and under the cognitive process of “Understand.” It follows, then, that simply asking a student to *recognize* the caudal muscles of the thigh on a diagram or cadaver, or *recall* the action of the muscles, (both processes under the cognitive process dimension of “Remember”), will not be sufficient to either teach or assess the objective. According to Bloom’s revised taxonomy, instruction of this objective should be approached within the factual, conceptual and procedural dimensions and by asking students to carry out tasks involving multiple dimensions of cognitive processes such as *interpreting, exemplifying, executing, differentiating, checking, generating, and producing* (Anderson and Krathwohl, 2001). In order to provide instruction that properly aligns to objectives outside of the “Factual Knowledge” and “Remember” dimensions, more sufficient and versatile instructional tools must be created and implemented in the anatomy classroom.

3. METHODOLOGY INFLUENCING MODEL DESIGN

In order to create a learning tool that would fill the gap in anatomy education which current tools are not addressing, and to encourage active learning that promotes a higher level of overall comprehension, we considered a few key factors in the conceptual design of this model. Conceptually, this model would:

- improve upon the use of 2D images by incorporating elements which allow for development of spatial reasoning skills,
- move past the virtual 3D model's limitation of a 2D screen by providing a physical, tactile, element,
- improve upon the use of static physical models and specimens by demonstrating movement,
- encourage active methods of learning by simulating functional anatomy, and
- promote higher levels of comprehension by requiring the use of more complex cognitive processes.

4. INFLUENCE ON MODEL DESIGN AND CONSTRUCTION

Model construction was completed with four basic components in mind:

a. Structural Support:

The stand for this model required sufficient stability as well as space for demonstration of movement. As the fully-articulated, standing, pelvic limb was approximately two feet tall, the stand had to be taller than two feet in height.

Considering that the model would be used in the gross anatomy lab alongside many different chemicals, it was important that the stand was not able to absorb and withhold the smell of these chemicals. The stand also had to be easy to clean.

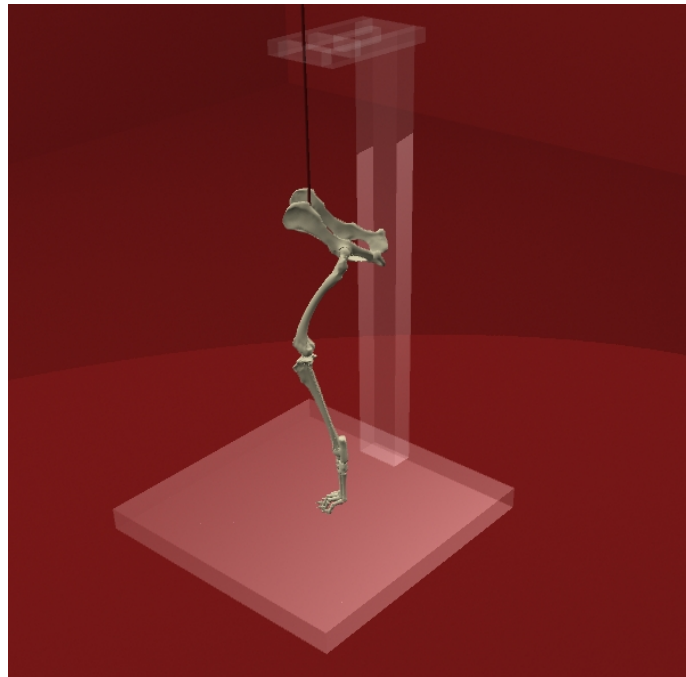


Figure 2. Example of Model Design with Plexiglas Stand Created with 3D Animation Software

b. Muscle function simulation:

A single muscle is composed of many muscle fibers (cells) arranged in parallel striations. Skeletal muscles attach to two or more bones and cross at least one joint (Sherwood, 2007). When they contract, or become shorter, they bring the bones closer together. When the muscle relaxes, it must become longer and allows the bones to return to their previous orientation. Simulation of skeletal muscle function for this model was accomplished using physical computing techniques and tools including a programmable micro controller.

c. Simulated muscle structure:

While representing each of the individual muscles in the canine pelvic limb may be useful for identification purposes, it was not necessary for this project.

Information on the effect on student learning could be sufficiently gathered by representing only the major groups of muscles and their actions. A basic visual representation of these groups on the canine pelvic limb could allow students to differentiate amongst muscles and supporting structural features. Therefore, such a representation was addressed in the construction of this model.

d. Simulated skeletal structure:

The skeleton is the structural basis of the body. Bones must be stable enough to withstand the pressure of body weight but also light enough to allow for movement. While simulated bones for this model had to be light enough to allow for movement, they did not require sufficient stability to withstand any body weight as the model was suspended from and supported by the stand. The

simulated bones did, however, require sufficient stability to withstand the pull of simulated muscles as well as the attachment of these muscles, which, on occasion, necessitated drilling holes into the bones. Simulated bones in this model also had to be able to support the weight of servo motors, which, on occasion, attached directly to the bone.

Materials and designs were tested for their ability to sufficiently and accurately simulate anatomical structures and functions such as described above. Once optimal materials were discovered, they were used to build the full-scale model. Testing throughout the duration of the construction as well as preliminary testing with the fully constructed model provided assurance that the model met the following basic criteria:

- Durable and physically stable
- Demonstrated proper movement
- Accurately represented the canine pelvic limb
- Provided sufficient interaction capability

5. MATERIALS AND METHODS

The pelvic limb model is based on the skeletal structure of a canine pelvic limb. Material choice was informed by construction of a previous thoracic limb kinetic model as well as experimentation (Malone and Pine, 2014).

In previous models casts of actual canine bones made using Alumilite's "Slow Set 7" casting resin provided sufficient stability for attachment of muscles as well as the force generated by pulling attached strings (Malone and Pine, 2014). Students' force in pulling on strings to simulate muscle function was observably greater than the force applied by the servo motor system. For this reason, Alumilite's "Slow Set 7" casting resin was also used to create the bones for this model. Latex tubing was cut and fixed to the bones to both visually and functionally represent ligaments and tendons. Pads of silicone rubber were sculpted into menisci and fixed to the tibia with small screws mimicking the function of the tibial-meniscal ligaments. A stand constructed of Plexiglas addressed both the issues of stability and space for movement. Further, Plexiglas can be used alongside cadavers in a gross anatomy lab without absorbing and retaining any of the chemicals used to embalm cadavers. This type of stand can also be painted or treated to improve aesthetics (Malone and Pine, 2014). The Plexiglas stand was constructed with a base that was two feet wide by two feet long and half an inch thick. The vertical arm on the stand was three feet tall and two inches in depth. A specialized armature at the top of the model was designed and constructed so that the sacrum and pelvis could be properly supported and suspended.

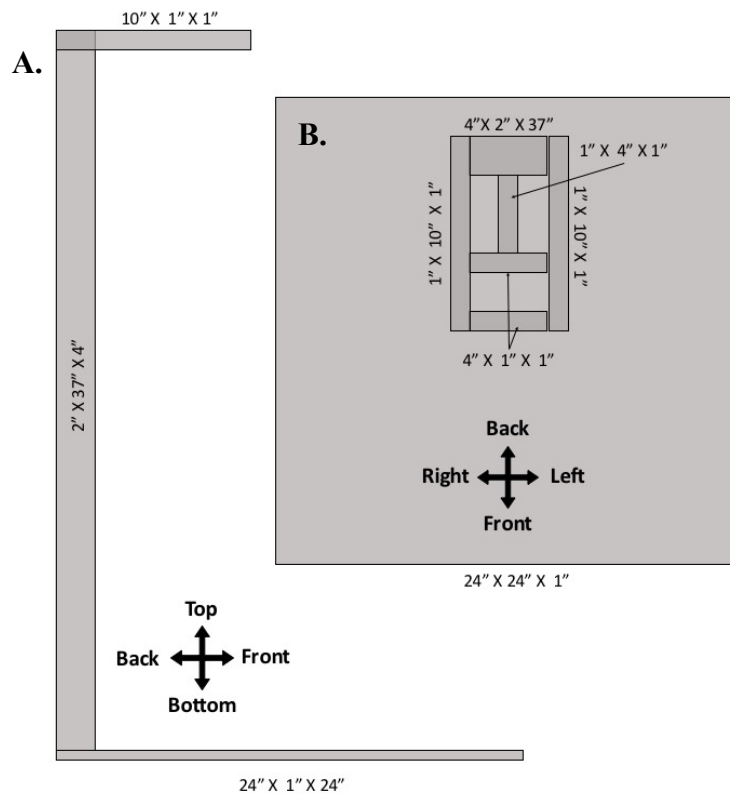


Figure 3. A. Right Side View and B. Top View of Plexiglas Stand with Dimensions

A visual representation of muscles making up each muscle group were created from maroon felt cut into the shape of the muscle body. Tendons and aponeuroses were created for the appropriate muscles from cut sheets of an off-white felt. Large sheets of fascia which serve as insertion points for major muscles were created from white sheets of felt. Tendons and muscle bodies were attached using fabric glue. Small, white, pieces of Velcro were cut to size for each origin and insertion point of the major muscles being represented in felt. One side of the Velcro was fixed to the felt muscle, and the other to the appropriate point on the skeletal model.

5.1 Servo-Motor Muscle Simulation System

Servo motors, sometimes referred to simply as servos, are electronic devices that utilize different angles and rotation patterns combined with an array of motor arm options to create movement. Common uses for these self-contained electronic devices include toys such as remote-controlled cars and airplanes (Eglowstein, n.d.). Servos come in a variety of sizes and strengths as well as two types of rotational capabilities: 360° rotation and 180° rotation. The variety of servo motors available, as well as their versatile nature made the motors the best option for this study.

Four standard size generic high torque servo motors (FS5106B from SparkFun Electronics Inc.) were mounted onto the model. Two of these motors were mounted directly to the femur of the model using Lynxmotion aluminum multi-purpose servo brackets (from RobotShop.com), while the remaining two were mounted on the top of the Plexiglas stand using the same mounts. Each of the four servo motors included a large vertical motor arm which extended approximately an inch and a half on either side of the center of rotation of each motor. An assortment of small, medium and large zinc-plated screw eyes was put on the model and the stand at major origin and insertion points as well as along the cranial and caudal aspects of the long bones. White nylon string was attached at one end to the furthest point from the center of rotation on the servo motor arm. The other end of the string was fixed onto a screw eye representing a point of insertion or origin common to a muscle group. When an action could not be

created by direct connection of the motor arm and attachment site on the bone, the string used to create the action of one muscle would first run through the screw eye representing an origin or insertion of a different muscle, and then run back to its appropriate location on the model, creating a pulley system. Strings also ran through screw eyes in the middle of long bones when crossing multiple joints to guide it and prevent unwanted rotation, abduction or adduction of the limb.

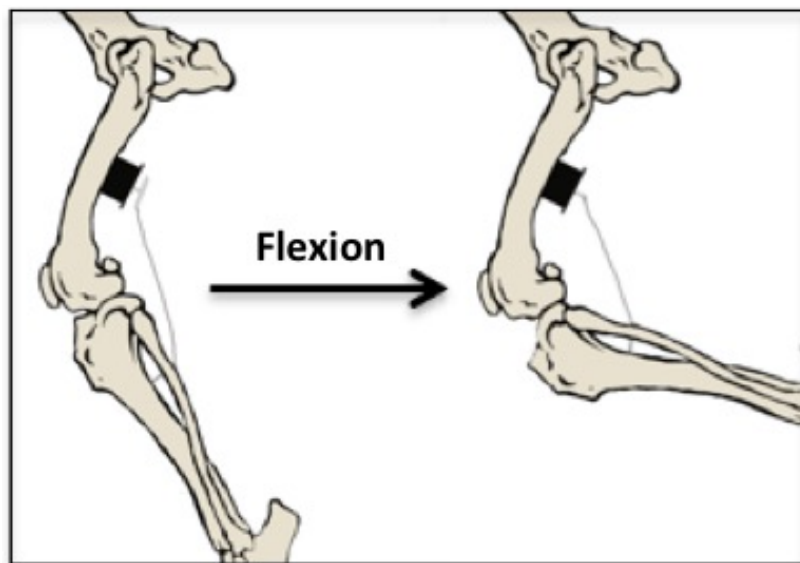


Figure 4. Example of Implementation of Servo Motor System to Simulate Muscle Function

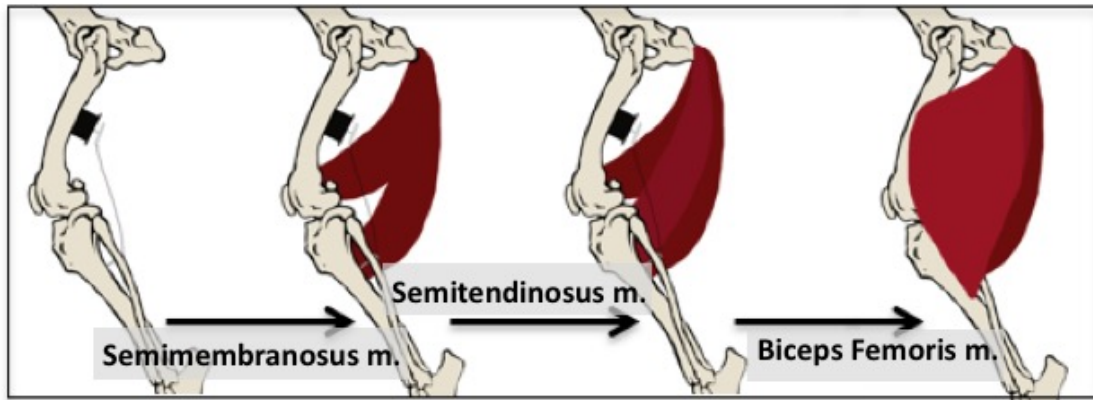


Figure 5. Example of Aesthetic Modifications to Simulation Model to Accommodate Servo Motor System and Represent Muscle Groups

A single two-foot long threaded rod was run through the middle of the specialized armature at the top of the model stand and through the midline of the sacrum. Washers and nuts were used to adjust the height of the limb on the rod as well as for support. In addition to hardware, epoxy and epoxy putty fixed the rod to the sacrum and accounted for uneven surfaces allowing for proper alignment of the pelvic girdle. An Arduino MEGA 2560 microcontroller and one full-sized bread board were placed at the top, back of the armature at the top of the model stand, opposite the threaded rod. Various lengths and colors of extension wires allowed the Arduino microcontroller to connect to the servo motors which were mounted on the femur. A Macintosh laptop, equipped with Arduino software and a USB port, was attached to the Arduino microcontroller with a USB cord.

5.2 Creating Interaction

A computer was connected to the Arduino microcontroller via a USB port and a serial monitor, or text-input window was displayed on the computer screen. The user would type the name of a muscle into the serial monitor and hit the return button on the computer. Motors that represent that muscle's action would then be activated, turning the motor arm 90 to 180 degrees, thus creating the action of the muscle that was typed.

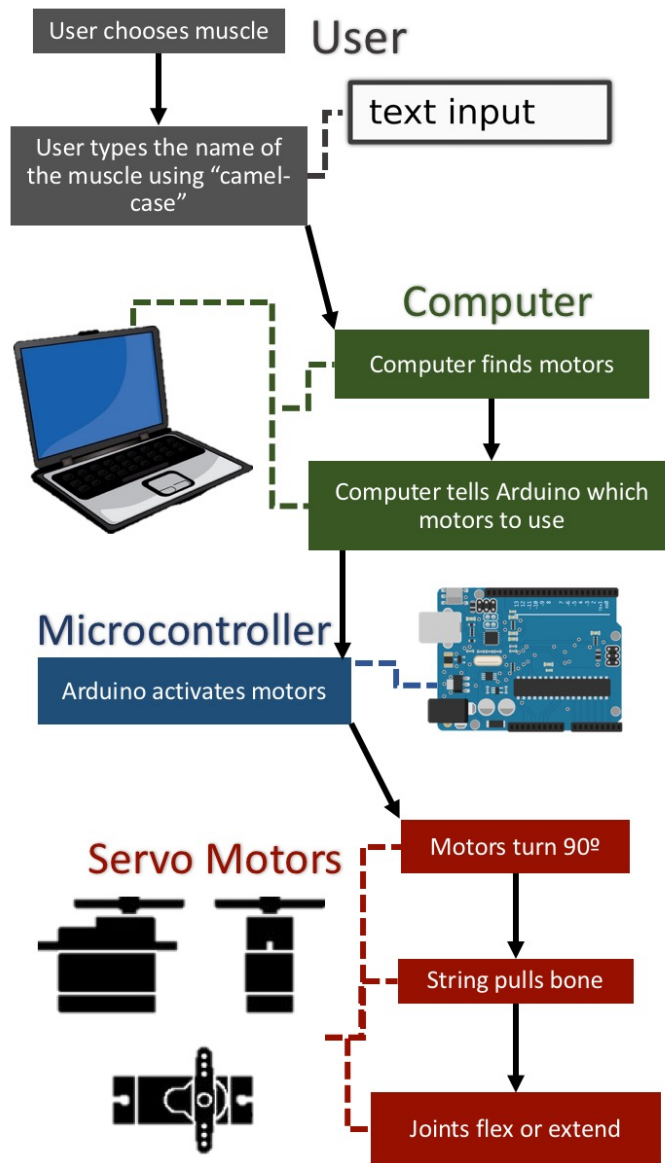


Figure 6. Connection and Communication Diagram Illustrating Information Flow within the Serial Input System

For muscles which have different actions based on whether or not the limb is bearing weight users had the option of typing only the name of the muscle, which would

demonstrate the action of the muscle on a limb that was not bearing weight, or add the word “Weight” to the end of the muscle name to see the action of the muscle while the limb was bearing weight. In order to accommodate the software used, a “camel-case” text input method was employed. The camel-case input method allows the user to exclude any spaces between words. Instead the first letter of each word, (excluding the first word), is capitalized. For instance, in order to see the action of the semitendinosus muscle while the limb is fixed and bearing weight the user would type “semitendinosusWeight” instead of typing “Semitendinosus bearing weight”.

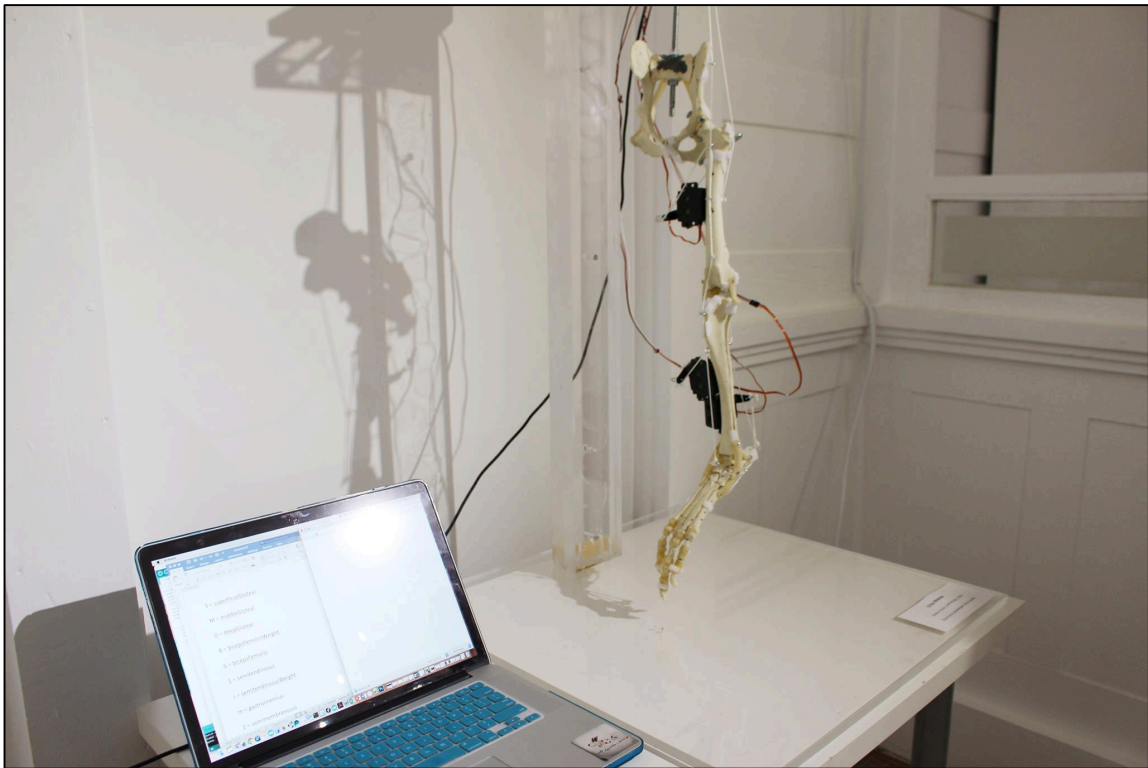


Figure 7. Thesis Model on Display at “The Creative Anatomy Art Showcase” in Bryan, Texas, April 1st, 2016. Photo by Glen Vigus.

6. USER STUDIES

6.1 User Study Participants

User studies included a class of approximately 130 undergraduate students enrolled in Biomedical Anatomy (VIBS 305) at Texas A and M University's College of Veterinary Medicine. This is a required course for all students majoring in Biomedical Sciences. Generally, students enrolled in this course are preparing for a professional career in a medical field such as veterinary medicine, human medicine, physical therapy, or dentistry – all professions in which an understanding of anatomy is crucial.

Students enrolled in the course were separated into two different sections based on their lab period – section 500 (N=58) and section 501 (N=50). The unit covering the pelvic limb included a series of 50 minute lectures and a dissection of the pelvic limb on canine cadavers. Lectures were given to both sections together and covered osteology, arthrology and myology specific to the pelvic limb. Students were introduced to major biomechanical concepts such as flexion, extension and fixation at the beginning of the semester with examples using the thoracic limb and were expected to apply the knowledge to the pelvic limb. Dissection was completed in separate sections following a student guide adapted from Miller's Anatomy of the Dog and was overseen by faculty and student instructors.

6.2 User Study Design and Procedure

One section of students, section 501 (control group), was allowed only the materials that would normally have been provided to them during the course. The other section, section 500 (experimental group), also had access to these materials, but were allowed access to the interactive model for individual and group study as well. Students from both groups spent same amount of time (two hours) during the studies. Both at the introduction and at the conclusion of the relevant section of the course all students were given a pop-quiz (See Appendix B). The quiz covered objectives specific to the pelvic limb unit and focused on evaluating the students' understanding of the concepts which the simulation model was capable of demonstrating. Students in section 500 were then asked to complete a questionnaire which evaluated their personal opinion on the effect of the model on their ability to understand related concepts using a 5-point Likert Scale Survey (See Appendix A) as well as open-ended questions. Both the students' qualitative and quantitative perspectives and opinions given in the questionnaire, as well as the students' quantitative scores on the quizzes, were analyzed.

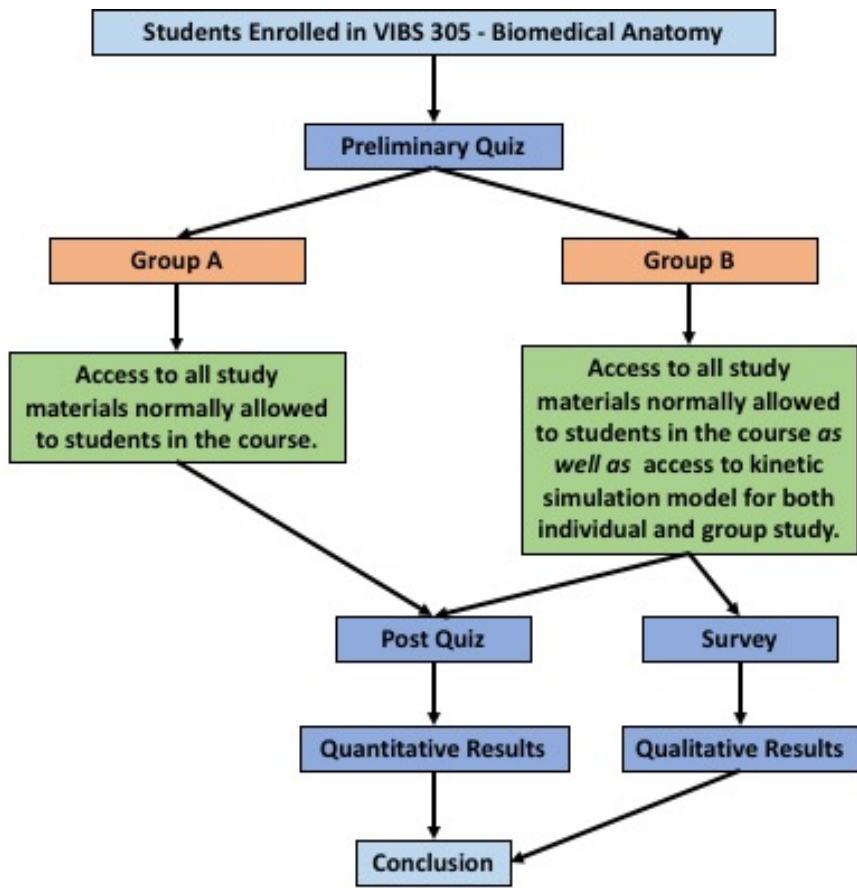


Figure 8. Graphic Representation of User Study Design and Procedure

7. RESULTS

7.1 Quiz Scores

User studies revealed that the students using the interactive simulation model performed better than their peers who did not use the model. The average quiz score for students who used the model (N = 58) improved significantly ($p < 0.05$) from mean: 49.83% (SD: 21.50%) to mean: 65.26 % (SD: 18.76%), while the average quiz score of the students who did not use the model (N = 50) only improved from mean: 49.50% (SD: 18.77%) to mean: 58.60% (SD = 18.87%) – not a significant difference.

Scores on the pre-quiz between the two groups were not significantly different ($p = 0.47$). However, scores on the post-quiz revealed that the students who used the model performed significantly better ($p = 0.03$) than students who did not use the model.

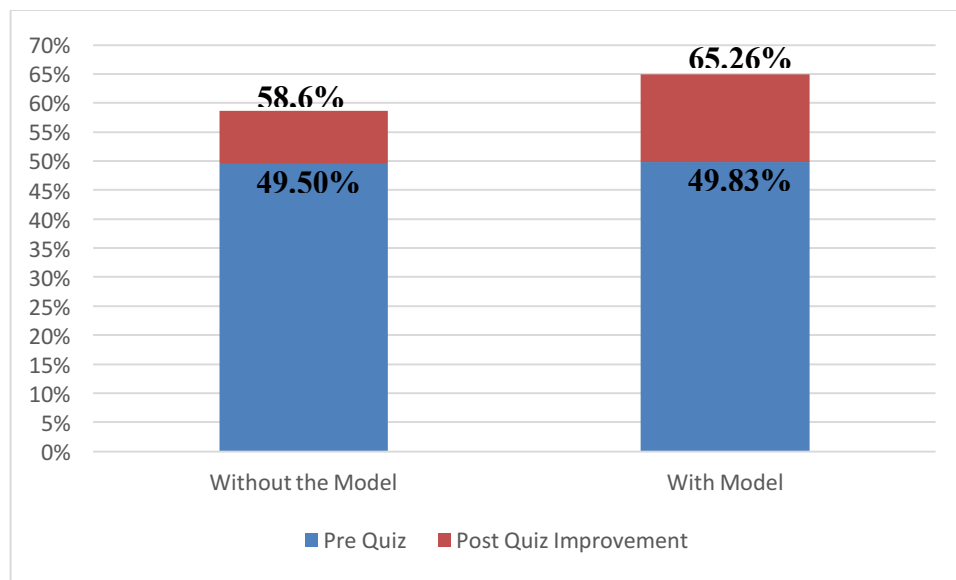


Figure 9. Bar Graph Comparing Average Quiz Scores

7.2 Students' Feedback on the Interactive Simulation Model

Evaluation of student feedback on surveys showed that the model helped 68.4% of students with at least one concept related to movement.

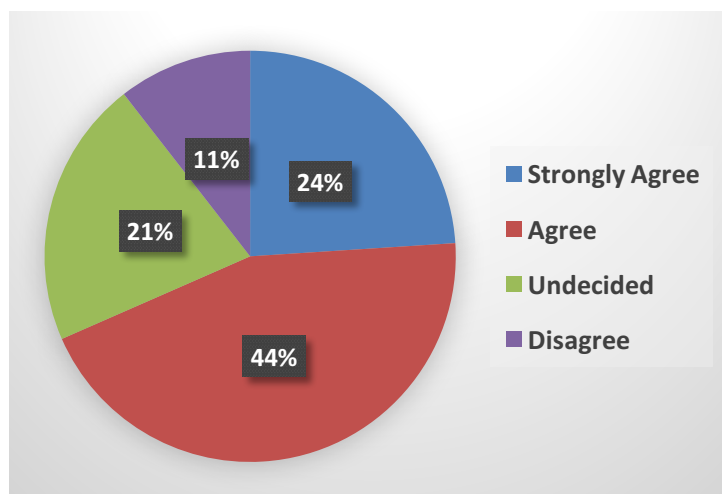


Figure 10. Pie Chart of Students Who Said the Model Helped with at Least One Concept

60.41% of students agreed that the model was specifically helpful in understanding the concept of fixator muscles. Of these students 37.3% identified fixation as the concept the model helped them with the most while 35.6% of all students who used the model said that the model was not at all helpful in regard to the concept of fixation. 67.31% of students who used the model agreed that it was helpful in understanding contraction and relaxation of muscles and 57.12% agreed that the model helped them to understand the action of muscle groups. Understanding of these concepts can be attributed to multiple aspects of the model. Students were asked to identify the most beneficial from a

selection of these aspects. 6.8% of students identified the ability to manipulate bones, 25.4% identified being able to see joints move, 39% identified the ability to watch flexion and extension, and 23.7% identified the overall simulation of muscle movement. Only 8.5% of students said that the model did not help them to understand the concept of flexion and only 3.4% said that it did not help with the concept of extension. When asked whether the model improved their understanding of a concept which they struggled with before interacting with the model, a majority of students, (51.64%), agreed that it had. Participant ID 039 commented that the model “demonstrated a lot of good [and] important concepts.”

Results from student surveys on questions regarding the model construction revealed that 75.55% of the students found it easy to use. Only 37.32% of students agreed that they were concerned about breaking the model.

None of the students had any experience with physical 3D models previous to the course and 58.5% of students agreed that they would recommend using this model. Many students expressed the desire for more of the same models and similar models representing other parts of the body.

8. CONCLUSION AND FUTURE WORK

While kinetic, interactive models for learning gross anatomy are a vastly under researched area, evidence collected from studies on current tools being used in anatomy education reveal that an obvious gap in anatomy education exists that can be bridged with these types of tools.

Implementation of a physically based interactive kinetic simulation model in an undergraduate biomedical anatomy has revealed an improvement in student ability to visualize and understand concepts related to movement in gross anatomy. Specifically, comprehension of muscle actions and functions such as flexion, extension, contraction, and relaxation were most improved, followed by the comprehension of the concept of fixator muscles and then by the comprehension of the action of muscle groups.

The fact that none of the students who interacted with this model had ever experienced learning with a 3D kinetic model previous to the course and that the model helped a large majority of them to understand at least one concept related to movement is further evidence of the necessity and vast potential benefit of these types of teaching and learning tools in anatomy education.

Some students reported that the model might have benefited them more if the movements had not been as sudden. They described a few of the actions as “jerky” which caused the entire limb to sway slightly. This swaying confused some students

because they were unable to distinguish between purposeful movement of joints and movement that occurred unintentionally. This can be attributed to the limitations created by servo motors. The servo motors used rotate at a set speed and can only be programmed to change the angle to which they rotate and how long they hold that position.

Overcoming this limitation might involve the use of different types of motors, such as stepper motors, which are able to provide smoother and more precise movement.

Another complaint that students reported about the model was the range of motion at the tarsal joints. The limb's natural orientation in space was such that the tarsal joints were nearly completely extended. Therefore, when a muscle called for the extension of the tarsal joints, the model would only demonstrate a very slight extension at that joint. This can be attributed to the roughness on articular surfaces of simulated bones as well as the limitations of the servo motor arms. The range of motion can be improved by assuring a smooth surface for bones to articulate with one another on by means of sanding down the appropriate points on the casts of bones or by using a different material for the casts. The issue may also be addressed by employing motors that are able to pull string farther than a few inches at a time.

In addition to the improvements necessary to overcome these limitations, future work with this model includes the development of a companion application for students to use alongside the model. A mobile application will provide a more intuitive interaction

method for students as well as eliminate the need for wires, freeing the student from the necessity to view movement based on the position of the computer.

The application will utilize wireless Bluetooth communication with the model which will allow the student to choose from a variety of muscle functions or actions. A student will choose which muscle function or action they would like to see and the physical model will simulate that function for them. In example, suppose a student opens the application to a screen similar to the image shown in the figure below.

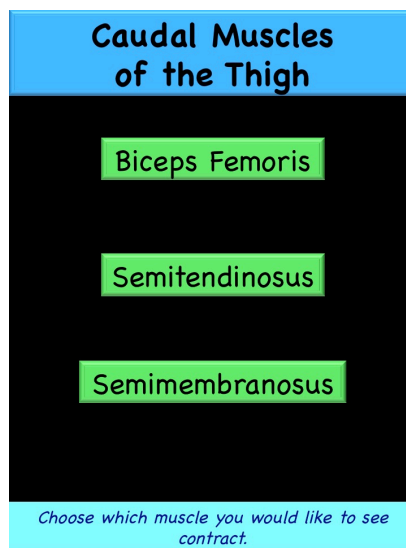


Figure 11. Possible User Interface for Companion Mobile Application, 1st Screen

The student taps the button that says, “Semitendinosus” and the application proceeds to the next screen:

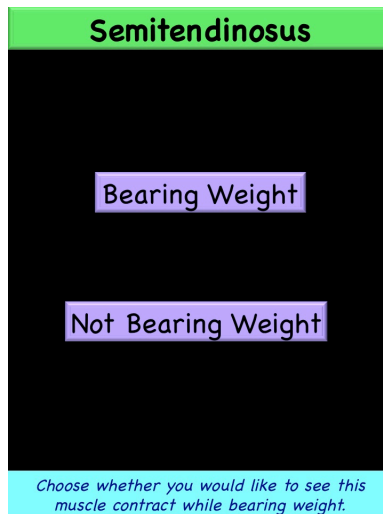


Figure 12. Possible User Interface for Companion Mobile Application, 2nd Screen

The student then chooses “Bearing Weight”, indicating that they would like to see the action of the semitendinosus muscle while the limb is fixed and bearing weight. The motors used to create the actions of the semitendinosus muscle while the limb is bearing weight, (extend the hip, stifle and tarsal joints), are then activated.

As an extension to this application a virtual 3D representation of the model for students to reference when the physical model is not available will be available within the application. Any action or function that the physical model is capable of will also be available with the virtual model.

Once normal muscle action and function is clearly and accurately illustrated with both the physical and virtual models in cooperation with the companion application, clinical cases and common pathology simulations will be added to the capabilities of the model.

This will include simulations of deficits seen when nerves are damaged or when a bone has been fractured.

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APPENDIX A

USER STUDY SURVEY

Teaching and Learning Anatomy with an Interactive Simulation Model

We are conducting a student survey on how interacting with the simulation model of the canine pelvic limb affects student comprehension. Your voluntary participation in this survey is requested so that we may use your suggestions to improve upon the model. This survey should take about 10 minutes to complete, and your responses will be kept confidential. You may choose not to answer any or all of the questions on the questionnaire even after you begin the survey. Please honestly answer the following questions based on your experience interacting with the model of the pelvic limb. Whether or not you choose to participate in this survey will not affect your course grade.

Pelvic Limb Simulation Model Questions

UIN: _____

1. Which aspect of the model did you benefit from the most? (rank numerically with #1 indicating the most beneficial)

- _____ Seeing the manipulation of bones
- _____ Seeing joints move
- _____ Watching flexion and extension of the joints
- _____ Simulating muscle movement
- _____ I did not find the model helpful

2. Which aspect of the model did you benefit from the least?

3. Which concepts and/or objectives did the model help you to understand, if any? (please rank numerically with #1 indicating the most beneficial)

- _____ fixation of joints
- _____ flexion of joints
- _____ extension of joints
- _____ I did not find the model helpful

4. Which concepts and/or objectives was the model not helpful with?
Circle all that apply.

- fixation of joints
- flexion of joints
- extension of joints

5. If you could add anything to this model, what would it be?

6. If you had to remove one thing from the model, what would it be?

7. What other concepts would you want this model to demonstrate?

8. If you could use any other material for the muscles, bones and ligaments, what would you use?

9. Have you had any experiences with other 3D models which demonstrate movement, if so please explain?

	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
This model helped me to understand fixator muscles.					
This model helped me to understand contraction and relaxation.					
This model helped me to learn the actions of muscle groups.					
This model made a concept(s) I previously found difficult to master easier to understand.					
The model was easy to use.					
I was concerned about breaking the model.					
I would encourage my friends learning gross anatomy to use this model.					

APPENDIX B
PRE AND POST QUIZ

PRE and POST QUIZ Questions 5 point exam

5 minutes (30 seconds/question)

1. Contracting the cranial tibial muscle and deep digital flexor (of the crus) muscle at the same time will result in _____ of the interphalangeal joints and _____ of the tarsal joints.
2. If the tuber calcanei is fractured, a dog would be severely limited in its ability to extend the _____ joint due to disruption of the muscles which insert there.
3. Contraction of the sartorius muscle _____ the flexor angle of the hip joint.
4. A muscle which could be a fixation muscle to the action of the long digital extensor m. on the tarsal joints is the _____.
5. A muscle that attaches to the ischiatic tuberosity proximally and the calcaneus distally will _____ the hip joint when it contracts.
6. The _____ muscle is an antagonist to the action of the long digital extensor m.
7. The _____ muscle GROUP crosses the caudal aspect of the hip and knee joints.
8. Muscles which cross the cranial aspect of the tarsal joints will _____ the joint when they contract.
9. A muscle which inserts on the tibial tuberosity will _____ the stifle joint when it contracts while the limb is bearing weight.
10. Contraction of the _____ muscle GROUP will result in flexion of the tarsal joints and extension of the interphalangeal joints.