An Interactive 3D Virtual Anatomy Puzzle for Learning and Simulation — Initial Demonstration and Evaluation

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Abstract. To inspire young students (grades 6-12) to become medical practitioners and biomedical engineers, it is necessary to expose them to key concepts of the field in a way that is both exciting and informative. Recent advances in medical image acquisition, manipulation, processing, visualization, and display have revolutionized the approach in which the human body and internal anatomy can be seen and studied. It is now possible to collect 3D, 4D, and 5D medical images of patient specific data, and display that data to the end user using consumer level 3D stereoscopic display technology. Despite such advancements, traditional 2D modes of content presentation such as textbooks and slides are still the standard didactic equipment used to teach young students anatomy. More sophisticated methods of display can help to elucidate the complex 3D relationships between structures that are so often missed when viewing only 2D media, and can instill in students an appreciation for the interconnection between medicine and technology. Here we describe the design, implementation, and preliminary evaluation of a 3D virtual anatomy puzzle dedicated to helping users learn the anatomy of various organs and systems by manipulating 3D virtual data. The puzzle currently comprises several components of the human anatomy and can be easily extended to include additional organs and systems. The 3D virtual anatomy puzzle game was implemented and piloted using three display paradigms – a traditional 2D monitor, a 3D TV with active shutter glass, and the DK2 version Oculus Rift, as well as two different user interaction devices – a space mouse and traditional keyboard controls

Keywords. learning and technology, medical simulation and modeling, virtual anatomy rendering, visualization, and manipuation, simulation design and evaluation, serious games

1. Introduction

Human Anatomy is an implicitly 3D problem yet even in the modern classroom, 2D oriented didactic tools are the predominate method of content delivery. A conventional anatomical lesson consists of group lectures, supplemented by 2D anatomical images and video, and self-study via review of atlases and 2D images or coloring black and white

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reference plates [1, 2]. This pedagogical convention — of teaching with 2D media — assumes that students can effectively and efficiently translate 2D information into a real-world, 3D setting. However, it has been shown that the process of making 3D interpretations from 2D anatomical datasets is not intuitive for audiences including clinicians [3], and can lead to complications in medical practice [4, 5]. For instance, clinicians largely use 3D data derived from 2D medical image slices such as X-ray, CT or MRI scans, to treat patients [5]. However, when clinicians are posed with the challenges of "stitching" together, spatially orienting and translating 2D data to reconstruct 3D scenes, misunderstandings and misdiagnosis often occur due to information lost in a clinician's interpretation between the 2D and 3D data. This is purportedly partially a result of insufficient exposure to 3D anatomies, due to a lack of accessible 3D didactic tools in anatomical education. Therefore, in order for students to have a better, and more applicable knowledge of anatomy, easily accessible 3D didactic tools need to be created. Furthermore, to inspire students in anatomical education, these didactic tools need to be made more entertaining — to provide an immersive educational experience which promotes the approachability and retention of the content delivered.

At or above the high school level, 3D methods such as the study of physical models are frequently used in anatomical education. Physical models attempt to assess the educational deficits of current practices but have several key limitations. They are expensive and non-extensible. Additionally, it's difficult to understand the more complex relationships between organ systems, because only the outer surface of the anatomy in a physical model is visible.

Another 3D method that is utilized in teaching are cadaver dissections. Cadaver dissections are only feasible for undergraduate and graduate level students, due to the required infrastructure. Additionally cadaver dissection may intimidate many young students. As such, cadaver dissections are reserved for students with extensive anatomical backgrounds, and are not suitable for early learning.

It is the "digital age" and the collection and availability of 3D, 4D (3D + time), and 5D (3D + time + function) data now coincides with the development and approaching ubiquity of stereoscopic displays, and the increasing popularity and legitimacy of serious games — games used to educate, train, and inform [6]. This emerging juxtaposition brings into question the utility of the stereoscopic display as a possible mainstream pedagogical tool for anatomy teaching, simulation and training. Affordable, accessible, and accurate 3D didactic tools can be implemented by incorporating anatomical datasets derived from **real** human anatomies using the mentioned display modalities, in the form of a *serious game*.

The use of stereoscopic displays with anatomical didactic tools is not commonplace, although there is other work investigating this topic. One group — Cyber Anatomy — released "3D anatomy", which is an application on the zSpace — a virtual holographic (stereoscopic) platform — that allows users to visualize and preform dissections on 3D anatomies [7]. There are more 3D didactic implementations of 3D anatomies being rendered on 2D displays (computer monitors, tv's, etc.), such as the Biodigital Human [8], and the Zygote Body [9] projects, which have very similar function to Cyber Anatomy's "3D Anatomy", but are not stereoscopic.

This study is a preliminary evaluation of our developed 3D virtual anatomy puzzle game implemented with an immersive stereoscopic head-mounted-display (hmd). This 3D puzzle is a serious game that is designed to teach anatomical annotation, and 3D spatial anatomy — the 3D orientation, position, and relation that [an] organ(s)/organ system(s) has/have with (an)other organ(s)/organ system(s). This functionality diverges from other work mentioned, with greater emphasis on guided, objective based interaction in contrast to un-moderated, exploratory exchange. The preliminary evaluation was inspired by data from users' playing the first alpha release of the developed game, with the intent of determining the pedagogical effectiveness of the game, and to determine the comforts and stresses associated with playing the game.

2. Methodology

To further promote the effort of introducing 3D virtual and augmented anatomical representations as part of the education curricula, we have developed a virtual, fully immersive 3D anatomy puzzle that prompts the user to assemble various anatomical systems in a 3D virtual environment (**Fig. 1**).

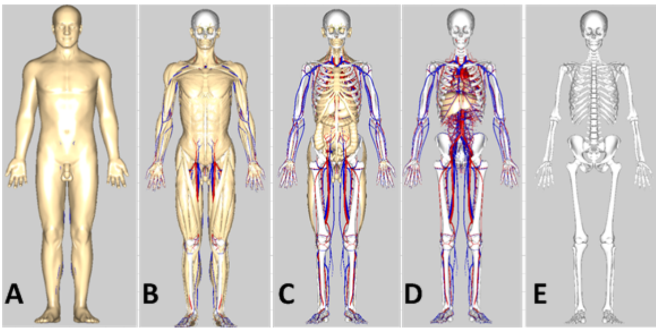

Figure 1. Presentation of the BodyParts3D anatomical dataset layers: **A)** BodyParts3D dataset (version 4.0) in its entirety; **B)** illustration of the integumentary system removed exposing the muscular system; **C)** skeletal, reproductive, gastro-intestinal (GI), and circulatory systems; **D)** skeletal and circulatory systems and the liver; **E)** inner-most layer of the dataset — the skeletal system.

2.1. Virtual Anatomy Puzzle Overview

The Virtual Anatomy Puzzle game currently consists of three functional modes. The first mode is a tutorial aimed to familiarize the user with the interface hardware and control mappings. This tutorial consists of a series of alignment tasks with an asymmetrical singleton object, progressively introducing the user to all degrees of freedom (DoFs) in the control scheme that will be later encountered during the anatomy puzzle.

The second mode is a so-called *Free Play Mode* that allows unguided and unlimited exploration of the anatomical dataset, with annotations on all models. This exploratory free play is intended to facilitate user preparation and training prior to assessments, especially for those who embark the game with a highly limited knowledge base. Exploratory free play is a functionality commonly found in existing digital anatomical tools.

Lastly, the assessment or *Quiz Mode* is a highly controlled and guided experience challenging the user to recall both name and position of anatomical entities selected at random relative to its neighbours in the fully completed assembly. The task begins by loading three ”keystone” models at random, that are permanently grounded to be unmovable by the user. A queue of five adjacent models are then loaded, from which the user is prompted to select a specific model to add to the grounded assembly. The user is given four attempts to maneuver the model into the proper position and trigger a ”snap” event to check the solution. If a correct solution has not been achieved by the fourth attempt, the model is automatically snapped to the correct orientation and no points are accrued. This puzzle assembly task is the basis from which this “serious game” aims to serve as a useful pedagogical tool (**Fig. 2** and **Fig. 3**).

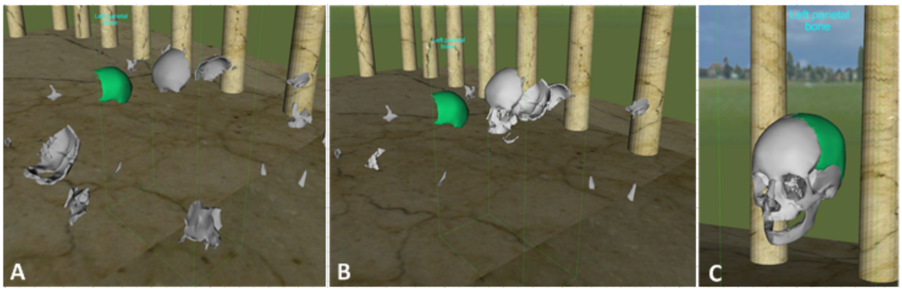

Figure 2. Images of the rendered **Skull dataset** in the puzzle game. These images were taken in *Free Play mode*. The currently selected bone, the **Left Parietal Bone**, is highlighted in **Green**. **A)** shows the rendered skull components placed in a circle around a randomly selected keystone, which in this case the KEYSTONE is the **Ethmoid Bone**. **B)** presents the skull in the progress of being puzzled together. **C)** shows the completed puzzle of the **Skull dataset**.

2.2. Platform Architecture

Our software platform was built using the WorldViz Vizard toolkit. The Vizard toolkit provides platform-agnostic development with built-in support for all chosen interface hardware, while supporting a multitude of other hardware which will be explored as part of our future work, such as 3D TVs, Optical Motion trackers, etc. Vizard also provides convenient Python bindings to the programming language.

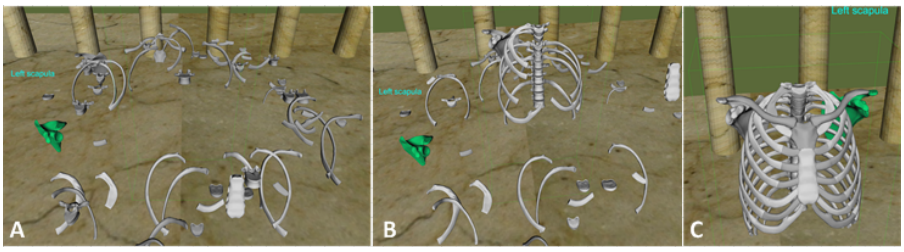

Figure 3. Images of the rendered **thorax dataset** in the puzzle game. These images were taken in *Free Play mode*. The currently selected bone, the **Left Scapula**, is highlighted in **GREEN**. **A)** shows the rendered thorax components placed in a circle around a randomly selected KEYSTONE, which in this case the keystone is the **10th thorasic vertebrae**. **B)** presents the **thorax** in the progress of being puzzled together. **C)** shows the completed puzzle of the **thorax dataset**.

The incorporated hardware interface consists of two display modalities — a traditional 2D display monitor and a virtual, fully-immersive, stereoscopic head-mounted display — the Oculus Rift, and two input modality options — a 3-DoF keyboard mapping and a 3-DoF 3DConnexion SpaceMouse.

2.3. *Testing Procedure*

We conducted a preliminary assessment of the designed virtual anatomy game puzzle in which two users of slightly different expertise levels in anatomy knowledge and familiarity with the interface and visualization systems were asked to perform the following tasks. The scope of the experiments consisted of several goals:

- Provide the users with a pre-determined, consistent training period to explore the anatomy puzzle *Free Play Mode* on the skull dataset and evaluate their performance in the virtual anatomy puzzle game in *Quiz Mode* using Oculus Rift/space mouse display/interface combination;
- Quantify the users' productivity given selected interface and display technology independent of the anatomy puzzle, hence using the asymmetric singleton object in the *Tutorial Mode*;
- Quantify the effect of the training on the users' performance in both the *Tutorial Mode* and *Quiz Mode*;
- Quantify the extent of *Mental Demand, Physical Demand, Temporal Demand, Performance, Effort*, and *Frustration* associated with the entire user experience, including the task at hand, manipulation hardware and display paradigm according to the NASA-TLX index on a scale from 1 to 10, where 10 implies a high level of demand, effort or frustration.

Participants began by completing a written "fill-in-the-blank" screening test to assess baseline knowledgeably in the subject area. The interface tutorial was then conducted four times, completing a full factorial design of the 2 x 2 interface and display modality experiment.

The anatomy puzzle game was then played three times. The first run was conducted in *Free Play Mode*, allowing the participant to explore the dataset without time constraints. After the participants declared themselves sufficiently confident to progress further, the second run resumed the game in *Quiz Mode*. The third run was a replica of *Quiz Mode*. Following completion of *Quiz Mode* runs, the same screening test was administered a second time. Following the screening test, a second full factorial of the interface tutorial was run.

Finally, the participants were asked to complete the NASA Task Load Index (TLX) assessment. For the novice reader, the NASA-TLX scoring system is a widely-used, subjective, multidimensional assessment tool that rates perceived workload as a means to assess a task, system, or user's effectiveness or other aspects of performance.

3. Results

As previously stated, **two users** were tested in our experiments. **Subject 1** had the least amount of background anatomy knowledge, and had the least familiarity with the interface and visualization systems. **Subject 2** had a greater amount experience and familiarity in both areas of interest.

The metrics used to evaluate performances of our subjects were the average time per move (i.e, the time required to execute each of the maneuvers required to complete the 3D virtual anatomy puzzle), total completion time, and total score. Score was computed by rewarding the user with fewer points as additional maneuvers were required at each step, with the best score being 200 (i.e., 10 points for each maneuver if completed correctly in the first attempt, 5 points for the second attempt, 2 points for third attempt and no points if additional attempts needed for maneuver completion).

$$S_{total} = 10m_0 + 5m_1 + 2m_2 + 0m_3 \tag{1}$$

Eq. 1 is a representation of the scoring algorithm used to calculate total score: S_{total} is the total calculated score; m_n denotes the total number of rounds with n failed attempts before successfully completing the requested move. As such, a high score and low average maneuver time and overall completion time would imply ideal mastering of the anatomical relationships between the puzzle components and familiarity with the manipulation and display interfaces.

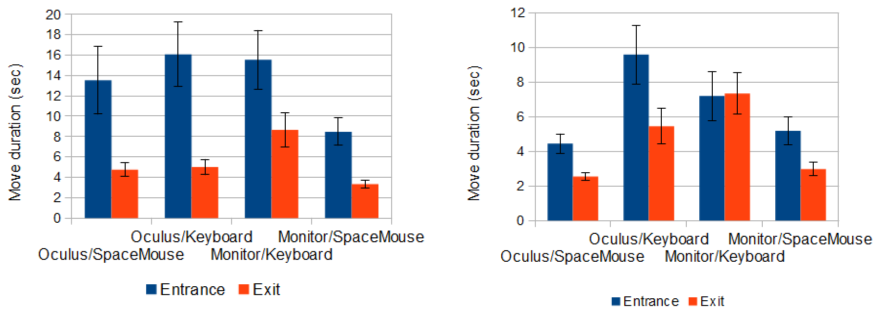

Figure 4. Plot of mean task completion time across all four combinations of user interface in *Tutorial Mode*. Left and right panel show data from two separate participants. The **ENTRANCE** label refers to data from the user **before** the use of the anatomy game. The **EXIT** label refers to data from the user **after** the use of the anatomy game to show the impact of training on the user's familiarity with the input and display devices.

To identify the user's most productive manipulation and display interface, as well as differentiate between their dexterity with the interfaces independent of the anatomy learning task and observe the effect of the training via the *Free Play Mode*, we analyzed the users' performance using the asymmetric singleton object prior to and after "free-play" training. **Fig. 4** suggests a strong training effect, with overall decrease in move duration between entrance and exit samples while an interface combination yielding maximum productivity is not apparent.

Fig. 5 illustrates the results of the NASA-TLX assessment across all ranking criteria for both users for the 3DConnexionSpaceMouse and Oculus Rift interface modalities used during *Free Play Mode* and *Quiz Mode*.

Furthermore, **Fig. 6** illustrates the score and average maneuver time recorded by the test subjects during the two runs of the 3D virtual anatomy puzzle game in *Quiz Mode*.

Lastly, as mentioned in the methodology section, we also attempted to identify the users' knowledge of anatomy before and after being exposed to and exploring the 3D virtual anatomy puzzle game. **Fig. 7** shows the entrance and exit survey score for both

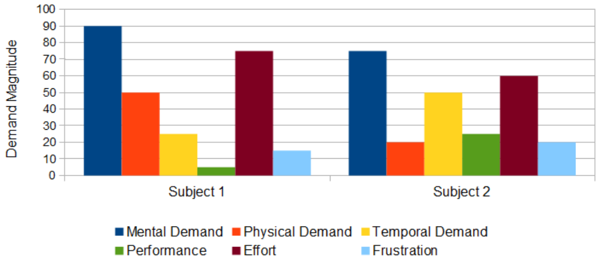

Figure 5. NASA Task Load Index ratings from subjects, which assess overall experience. In DARK BLUE is the MENTAL DEMAND; in ORANGE is the PHYSICAL DEMAND; in YELLOW is the TEMPORAL DEMAND; in GREEN is the PERFORMANCE; in MAGENTA is the EFFORT; and in LIGHT BLUE is the FRUSTRATION.

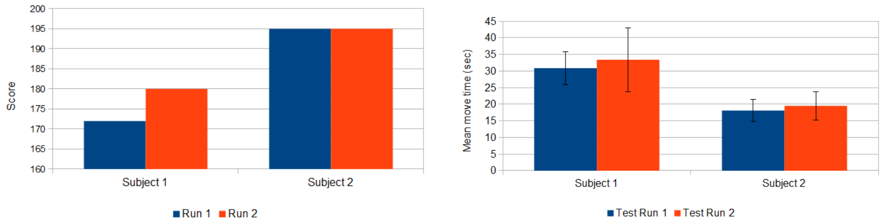

Figure 6. The LEFT PLOT shows the scores the subjects received from playing *Quiz Mode*: FIRST TRIAL scores are shown in BLUE and the SECOND TRIAL scores are shown in RED. The RIGHT PLOT illustrates the average maneuver duration across both runs of the *Quiz Mode* for both subjects.

users. **Subject 1** had no previous knowledge of anatomy, he/she demonstrated moderate learning, while **Subject 2** also demonstrated improvement following exposure to the didactic tool.

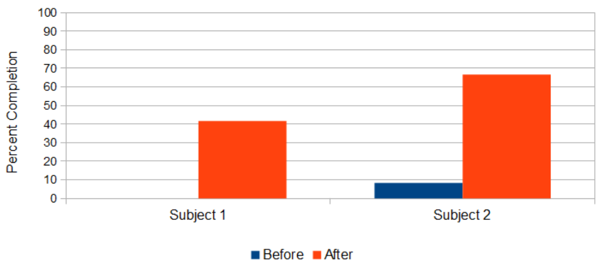

Figure 7. Plot of written "fill-in-the-blank" format assessment prior to and following exposure to and exploration using the developed 3D virtual anatomy puzzle game.

4. Discussion, Conclusion and Future Work

In this paper we have described the design, development, implementation and preliminary assessment of a 3D virtual anatomy puzzle game as a potential didactic tool for exposing students to the intrinsic relationships between the anatomical components of various organ systems. In its current form the application has been demonstrated using a skull and thoracic cavity assembly and ongoing efforts are are focused on exploring the tool to include other, more complex organ systems.

In terms of user interaction with and visualization of the virtual anatomy, our users have reported adequate, favourable comfort with using the 3DConnexion SpaceMouse and Oculus Rift for interaction and visualization, respectively, as shown by their performance results. Moreover, the added training showed beneficial to both the users' dexterity and learning, as suggested by the average maneuver time, overall score, total game completion time and entry and exit assessment survey.

As part of our future endeavours, we intend to expand the study to include additional test subjects featuring different levels of expertise in both hardware (manipulation and visualization interfaces) and anatomy knowledge, A larger and more diverse pool of users will enable us to conduct sufficient experiments and perform a more detailed statistical analysis that can clearly demonstrate the benefits of the proposed 3D virtual anatomy puzzle game as a pedagogical tool.

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