

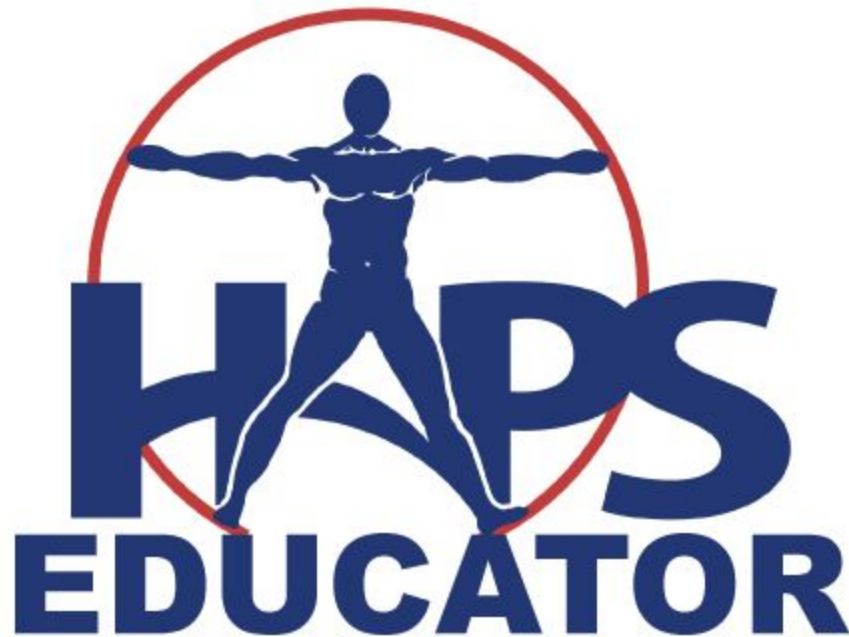
**Method For Production of 3D interactive Models Using
Photogrammetry For Use in Human Anatomy Education**

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Method For Production of 3D interactive Models Using Photogrammetry For Use in Human Anatomy Education

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Abstract

Despite a shift to use digital resources to supplement traditional anatomy education, institutions often rely upon external sources of digital materials. Such three-dimensional (3D) animations rarely resemble the anatomical models or cadaveric specimens used in the students' laboratories. Photogrammetry is a technique that generates an interactive three-dimensional model from a series of photographs. This study developed a simple and inexpensive method for using photogrammetry to produce interactive models that can be used by the anatomy educator. Only cell phone cameras were used, and the authors had no previous experience with photogrammetry. Such photo-realistic interactive models of cadaveric specimens or plastic anatomical models may allow learners to review and recall anatomical structures seen in the laboratory on any web-enabled device.

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Key words: anatomy education, digital anatomy, photogrammetry

Introduction

Undergraduate human anatomy courses are taught in a variety of educational institutions from two-year community colleges, to four-year colleges, to universities. A wide variety of instructional practices are common, including cadaveric dissection and prosection, physical models, and clay modeling (Lombardi et al. 2014; Motoike et al. 2009; Waters et al. 2005). Digital models are used to supplement or replace more established pedagogical tools (Fredieu et al. 2015; Saltarelli et al. 2014), and virtual reality and 3D printing are the newest additions to the toolkit of anatomy educators (Fredieu et al. 2015; McMenamin et al. 2014). From this great diversity of visualization tools, each institution makes choices based on pedagogical rationale, budgetary concerns, the educational level of the students, and/or the level of experience and expertise of those in the position to make such decisions.

Anatomy students may encounter major barriers to outside-of-class access to the same materials used in their laboratory instruction. Whether students are unable to access these materials because there are too many of them vying for laboratory time or their own busy academic and extracurricular schedules do not afford the time, limited access to the educational resources used in their laboratories can negatively impact their learning. Digital products, with their ubiquity in today's world, have entered to fill this void. Such applications allow students to learn or review anatomy on their own time and in any place. Sugand et al. (2010, p. 85) argued that "the future of anatomy teaching must rely more on visual aids outside the dissection room."

For many students, however, the available cadaver dissection software or 3D model may bear little resemblance to the materials used in their college or university's laboratory. Some colleges may use prosected cadaveric specimens in the laboratory but provide students with 3D models that bear more resemblance to cartoons than to their laboratory materials. Bridging the gap between the physical materials in the laboratory (e.g., model, prosected cadaver, or organ specimen) and a software package of idealized anatomy may be difficult, particularly for the novice learners of anatomy often found in undergraduate classrooms. These students would likely benefit from digitized images of their actual physical laboratory materials. However, 2D images may be difficult to use because they do not portray the spatial relationships visualized on a 3D model or specimen.

Photogrammetry is a tool that utilizes multiple photographs to generate a complex 3D surface model (Luhmann et al. 2006). Available software identifies points on a photograph, and matches them to similar points taken from a slightly different angle. With dozens of photographs, aligned points are used to generate a 3D representation of these points, a *point cloud*. From the point cloud, polygons are added to create a surface mesh. A texture is applied to the mesh, wherein the original photographs are "stitched" together to form a composite image for each of the polygons. Unlike surface scanning, photogrammetry does not use expensive laser scanners; instead modern mobile phone cameras are sufficient to take photographs. In addition,

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rather than simply provide a surface reconstruction, photogrammetry compilation software applies the color and simulated texture of the object. The result is a photo-realistic 3D model. Previously, this technique has been applied to modeling pathology specimens (Turchini et al. 2018), and to isolated human organ specimens (Petriceks et al. 2018). These studies required expensive rendering software and cameras; the latter utilized a proprietary multi-camera and lighting setup developed by Anatomage, Inc.

The purpose of this study was to develop a simple protocol to inexpensively create interactive 3D digital models of anatomical learning materials. This novel tool in anatomy education leverages the ubiquity of a web-based platform such as Sketchfab for viewing 3D models and virtual reality and allows students to see the very same cadaveric specimens or plastic models found in their laboratory. Importantly, we demonstrate that this approach can be used with very little financial commitment and with very little prior technical expertise, so it can benefit anatomy educators in institutions of any size.

Materials and Methods

To test the proof of concept that photogrammetry could generate accurate 3D models for use in anatomy education, two teaching resources were used: a cadaveric hand and forearm (used to demonstrate the muscles and tendons of the hand and wrist), and a model of the upper limb (3B Scientific, Germany). Figure 1 illustrates the workflow for producing the 3D models.

Specimen Preparation and Photography

Preparation for photography was minimal. A typical, unaltered teaching laboratory served as the location for photographs. Reflective surfaces in the room can create difficulty in the alignment process used to create 3-D images. It is recommended that mirrors or other reflective surfaces, such as a glossy whiteboard, should be covered or obscured. Additionally, the authors observed that an uninterrupted, expansive background of a single color that closely matches the color of the subject of photography might result in fewer matches in point alignment, so this was avoided. In the case of the cadaveric specimen, wet locations were blotted dry prior to photography to reduce the likelihood of reflection.

In positioning the specimen, it was desirable to have as much access around the specimen as possible in order to enable photography from a variety of perspectives. No lighting apparatus or backdrops were necessary to produce models of sufficient quality. Ambient laboratory lighting was sufficient, provided no distinct shadows were present on the object of photography. In preliminary trials, a mobile phone ring light (www.flawlesslighting.com) was used, but was found to be unnecessary. If a space with too much directional lighting cannot be avoided, a ring light might prove useful.

Specimen preparation

- Blot wet specimens dry to reduce reflection
- Cover reflective surfaces in the background

Photography

- Mobile phone camera, take 100-200 photos
- Remove out of focus images

Photogrammetry

Import photos

Generate sparse point cloud

- High accuracy setting

Refine sparse point cloud

- Reconstruction Uncertainty: value 10
- Projection Accuracy: value 10
- Reproduction error: value 1
- Re-alignment of camera (default selections)
- Adjust region of interest

Generate dense point cloud:

- Medium accuracy setting

Refine dense point cloud:

- Manual selection/deletion of erroneous points

Generate mesh

- Face count: 1,000,000

Generate texture

Export model and texture

Archive or Upload to hosting service

Figure 1. Workflow illustrating the generation of 3D models.

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Photographs were taken using a 2016 iPhone 7 (Apple, www.apple.com). The auto-adjustment of the native camera application's ISO (International Organization of Standardization – assesses the sensitivity of the image sensor) value resulted in highly variable photographs with regard to brightness. Depending upon which objects were present in the background with a particular camera angle (a black benchtop, a bright fluorescent light), the auto-adjustment of ISO affected the appearance of the object. Thus, the object's brightness was inconsistent when compared across photographs. Locking the ISO at a consistent value resulted in images of the object that were consistent in brightness regardless of the background. Subsequent photography was conducted using the Moment app (www.shopmoment.com), which allowed for the locking of ISO.

At least 100–200 photographs were taken, encircling the model as well as at multiple angles to capture the model from many visual perspectives. Figure 2 illustrates the calculated angles from which 167 photographs of the model arm were captured. No precise regimen of determining angles was necessary. The authors simply took small steps to encircle the object, taking 20–30 photographs; then, a higher or lower camera perspective was taken and another 20–30 photographs were taken encircling the object. In total, the authors found that four to six different angles with respect to the z-axis along with an approach to encircle the object at each of these angles provided sufficiently accurate and reproducible results. The photos were taken with an attempt to either fill the photograph with the entire region of interest or

with a slightly closer approach. In this study, the distance was approximately 30 cm. Photographs were 3024×4032 (12 megapixels); camera settings were 0.033 second exposure; ISO speed = 32; f 1.8. The photography of a single specimen took approximately 5 to 10 minutes. The resulting collection of digital photos was screened, and out-of-focus photos were deleted. Approximately 100 to 200 photos proved sufficient to produce high-quality 3D models.

Photogrammetry

Agisoft Metashape standard edition, version 1.5.0 (www.agisoft.com; subsequently referred to as Metashape) was used to compile the photographs, generate a point model, and produce the mesh model and its texture. This software is available for Microsoft Windows, Linux, and macOS. Other software is available at no cost, for example: Photomodeler (www.photomodeler.com), Meshroom (alicevision.org) and RECAP (www.autodesk.com). The authors found Metashape to have no compatibility issues with their laptop computers (Apple, www.apple.com), easy to use, and the one-time standard, educational license was \$59 at the time of this study. Tutorials are available on the Metashape web site (www.agisoft.com/support/tutorials/beginner-level/). After importing the approximately 100–200 photos into Metashape, they were aligned using the high accuracy setting to generate a sparse point cloud (Figure 2). The default selections were unmodified (generic preselection; key point limit = 0, unlimited; tie point limit = 1000; adaptive camera model fitting) for this step.

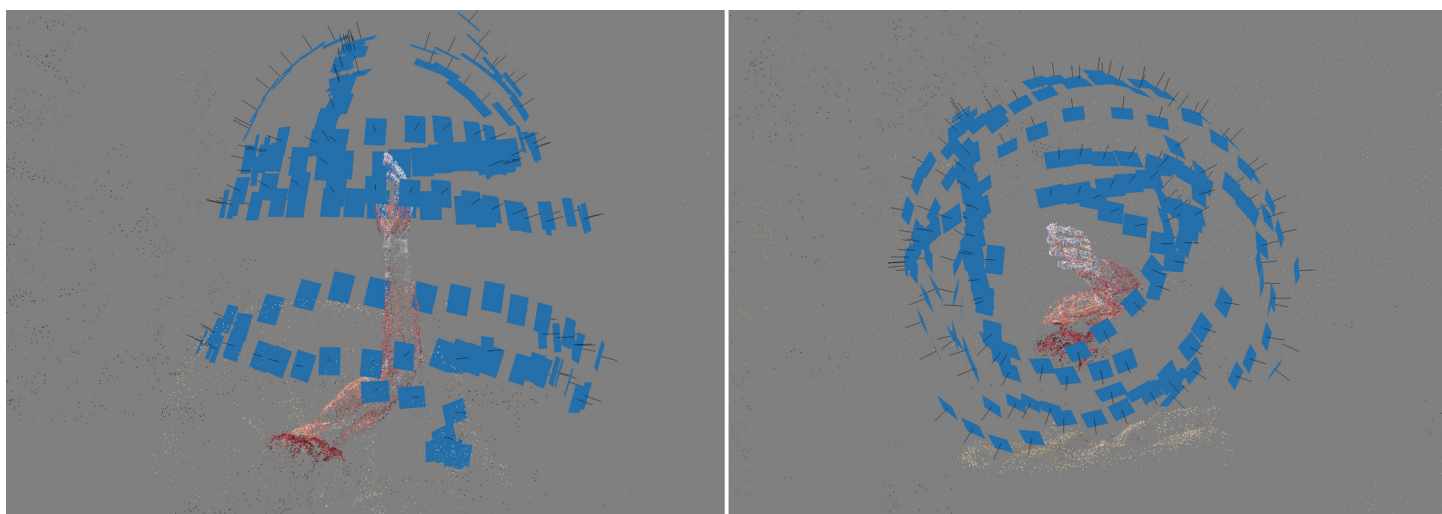


Figure 2. Sparse point cloud generated from 167 photographs of an anatomical model in Metashape (www.agisoft.com). Matching points in photographs are compared to calculate the position of the camera in space (blue rectangles), and a 3D representation of the mapped points is generated. An effort was made by the authors to methodically encircle the model at a variety of perspectives, as can be seen by the illustrated camera positions. Left and right panels show the same sparse point cloud from two perspectives.

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The sparse point cloud that was generated was then edited to remove points not related to the object. Options for reducing error were performed: reconstruction uncertainty (value chosen: 10), projection accuracy (value chosen: 10), and reproduction error (value chosen: 1). The photos were then realigned with the remaining points and the region of interest was defined by resizing the bounding box to include only the specimen. A medium accuracy dense point cloud was then generated (Figure 3A). Processing time for higher accuracy density point cloud generation was significantly higher and produced results that did not justify the additional processing time. The resulting dense point cloud was manually edited to remove any erroneously identified points, not part of the anatomical specimen or model. A mesh was generated from the points with a target of 1,000,000 faces (Figure 3B). Meshes with many more faces produced files that were too large, and the added detail was not relevant for this

application. Other settings were left as default (Surface type = arbitrary 3D; Interpolation = enabled; Calculate vertex colors). A texture was applied to the mesh using the default settings (Mapping = generic; Blending = average; Texture size/count = 4096 x 1; Hole filling = enabled).

The resulting model (Figure 3C) was exported in OBJ, JPG, and MTL file formats. The OBJ file contains the mesh, the JPG and MTL files contain the texture and its properties. Decimation of the resulting mesh was not performed since the mesh was originally created with a 1,000,000 face target, but excessively large models can be slightly simplified within Metashape or other meshing software without obvious effect on model quality. Models with 100,000 to 1,000,000 faces were determined to be of excellent quality for the proposed application.

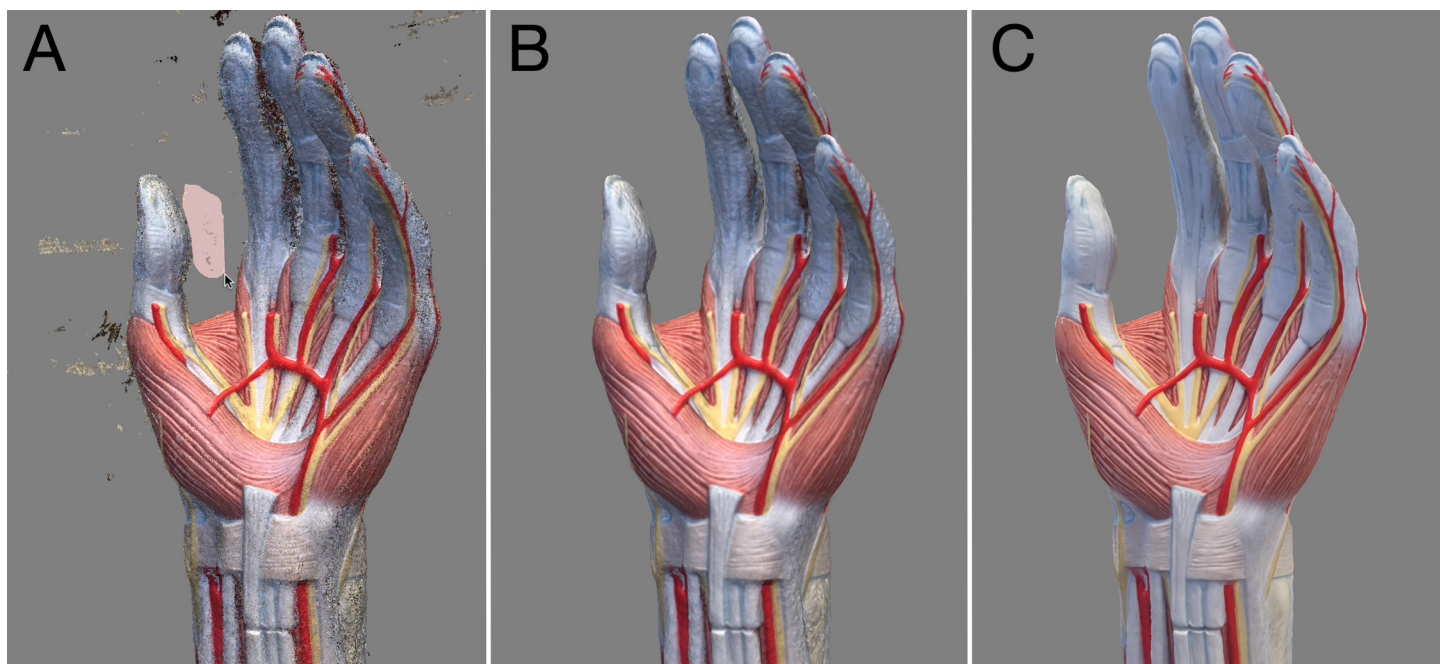


Figure 3. Refinement of the model. (A) Dense point cloud is manually edited by selecting erroneous points with mouse cursor. Points that are obviously not a part of the original object are evident when rotating the dense point cloud. The authors found it unnecessary to remove erroneous points internal to the model. (B) A 1,000,000 face mesh is produced from the dense point cloud. Metashape assigns a single color to each polygonal face, but only is a more photorealistic model produced when (C) a texture is applied; each face of the mesh receives an image derived from the original photographs.

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Archival and retrieval

OBJ, MTL, and JPG files were imported into the web service, Sketchfab (www.sketchfab.com), which provides a "Pro" account for educators at no cost. Within Sketchfab, 3D objects were manipulated to remove the defaults for lighting, position, and other aesthetic factors. If desired, these variables can be adjusted to the instructor's preference. Additionally, labels can be attached to the model from within the Sketchfab web interface. An instructor-provided URL was generated to enable student access to interactive 3D models in Sketchfab. URLs could be provided directly to students or, alternatively, links to the models could be embedded in an HTML-based webpage using an embed code generated by Sketchfab. The 3D models were viewable on any web-enabled device, regardless of platform, and virtual reality could also be used. Additionally, download of the file for 3D printing could be enabled. A website was developed for students, allowing easy access to all models made using the same methods: <https://anatomy.web.unc.edu>

Student Perceptions of Usefulness

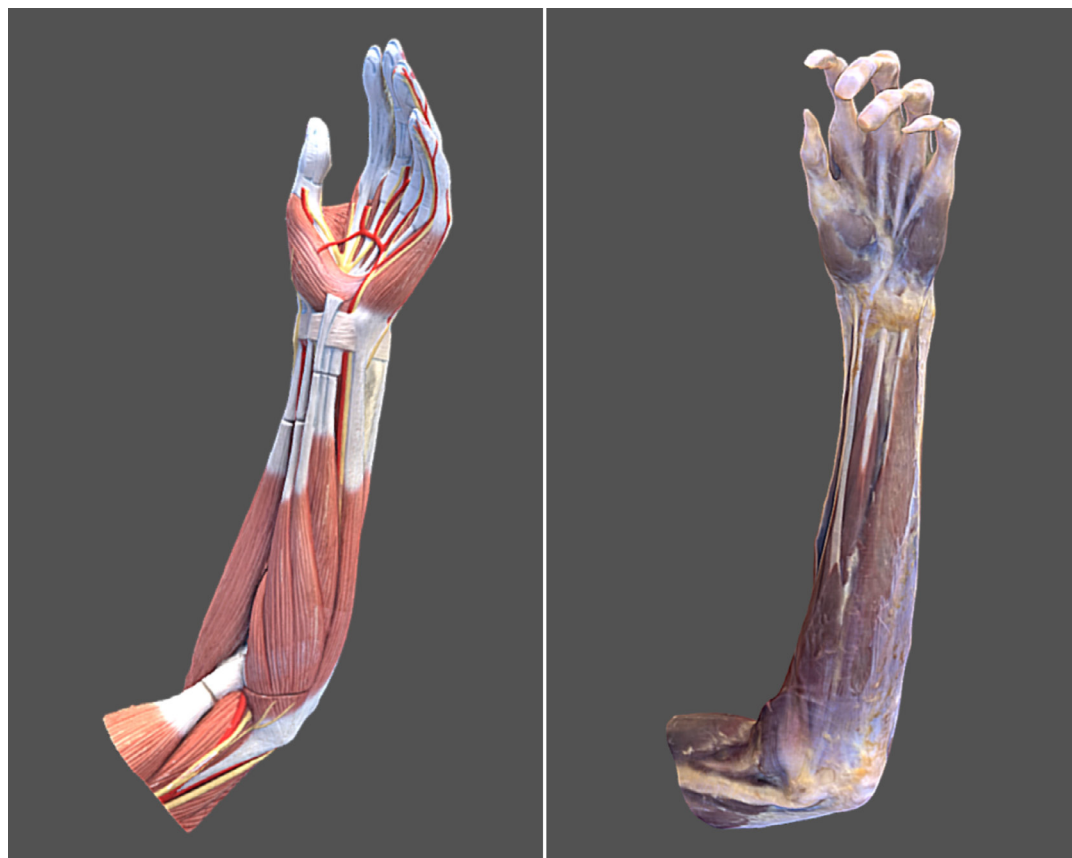
An anonymous end-of-semester evaluation was included as a component of a larger course and instructor evaluation. Students were asked to evaluate the usefulness of various provided or linked resources

within the course management system. In addition to the 3D virtual models described in this paper, the items to be evaluated included: a custom laboratory text, a slide deck that was also used in each laboratory lecture period, online flashcards customized to the content of the laboratory, and various online videos, websites, or mobile apps deemed to be relevant to the content of the laboratory. Suggested mobile apps were free of charge. With the exception of the lecture slides, all of the resources were presented as materials for students to study outside of laboratory and not used directly in laboratory instruction.

Results

The methods employed in this study successfully produced 3D digital models of a plastic anatomical model and of a cadaveric prosection. Screenshot images of the completed models are shown in Figure 4, and the interactive 3D models can be accessed with the following links: arm dissection: <https://sketchfab.com/3d-models/ac0b6ada828349b99d4e9fa6a9cc4fbd>; arm model: <https://sketchfab.com/3d-models/1d75fd9232144f1b9467b6d2d1639b48>. The interactive 3D models can be rotated in three axes, scaled up or down, and moved in a planar dimension. Students were provided with access to the models through links in their course management system, so they could use them for review of structures seen in the laboratory.

Figure 4.
Screenshots of final 3D
interactive models.



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The level of detail provided excellent visualization for the purpose of learning and reviewing anatomical structures inside or outside of the laboratory. The cost of producing interactive 3D models using photogrammetry may differ according to existing supplies. However, for the current study and using materials that were previously purchased for common computing tasks, the only monetary cost of producing the interactive models was the one-time purchase of the photogrammetry software.

End-of-semester evaluations revealed that 73.6% of 413 respondents found the 3D virtual models to be either very useful or somewhat useful resources (Table 1). A small number of respondents found them unhelpful or very unhelpful, numbers commensurate with those of the other resources. The laboratory text was more highly rated, but all other resources did not achieve the same usefulness ratings as the 3D virtual models.

	No answer	N/A, didn't use	Unhelpful	Somewhat unhelpful	Neither helpful nor unhelpful	Somewhat helpful	Very helpful
Lab text	0.2	0	6.5	1.7	0	19.9	71.7
Lab lecture slides	0.5	0.7	5.1	11.9	13.1	48.9	19.9
3D virtual lab models	0.5	4.1	3.6	6.8	11.4	31.7	41.9
Online flashcards	1.0	13.1	3.4	8.0	16.9	31.2	26.4
Anatomy videos	0.5	36.1	3.1	7.0	26.6	18.6	8.0
Anatomy websites	0.2	31.7	4.1	8.0	26.6	20.3	9.0
Anatomy Apps for mobile devices	0.5	39	4.1	7.5	22.5	16.0	10.4

Table 1. Summary of end-of-semester student evaluation of lab resources. Values indicate percentage of 413 anonymous evaluations of the usefulness of provided resources for a 1 semester undergraduate anatomy laboratory.

Discussion

The aim of this project was to develop a simple methodology for the production of interactive 3D models of laboratory materials. We have demonstrated that accurate, interactive 3D models of anatomical teaching specimens can be produced for the benefit of students in undergraduate anatomy courses at two-year community colleges, four-year colleges or universities. Using inexpensive software and common laptop computers and mobile phones, instructors with no photogrammetry experience will be able to produce realistic digital models that are accurate reproductions of laboratory models, prosected cadaveric materials, human or animal organs, or even regional dissections of a cadaver.

Apart from the ability of students to review a virtual replica of their laboratory models or specimens, the interactive models also have potential use in instruction. The web platform described allows users to easily generate a code to embed the interactive 3D model in HTML-based instructional materials. The authors have opted to leave their virtual models unlabeled, for the purpose of post laboratory review, however instructors may label their models with terminology, origins/insertions/actions of muscles, or simply number anatomical structures for short formative assessments. Such instructional and assessment tools would be available to students on any device capable of rendering

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HTML. Alternatively, the generated OBJ files can be inserted into a PDF document format capable of rendering 3D for distribution to students.

Student evaluations indicate that respondents generally found the 3D virtual models useful. The laboratory text had the highest rating of usefulness, likely as a result of its central role in defining the course's content. Among the other resources, the 3D virtual models were clearly valued by most students in their out-of-classroom study. This novel learning tool allows undergraduate or medical anatomy students to have access to the exact laboratory specimens or anatomical models that they use in the laboratory. Thus, with the development of photogrammetry-based interactive digital 3D models, students out of the classroom have additional tools to support their success in anatomy courses with minimal effort from course instructors.

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Zachary J. Burk is a recent graduate of the University of North Carolina, with a BS in Biology. He is an Internet entrepreneur and he has been teaching human anatomy and physiology for two years. Zach is currently a first year DDS student in University of North Carolina's School of Dentistry.

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