The Application of 3D Printing in Anatomy Education

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A thesis presented in candidature for the degree of Master of Research

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Candidate Statement

This thesis represents research conducted at Macquarie University as part of the requirements for the Master of Research. I certify that the work incorporated in this piece has not been submitted for a higher degree to any other institution.

I certify that the work presented in this thesis is my own except as acknowledged in the text.

Ethics approval was obtained from Macquarie University's Human Research Ethics Committee. Approval number: 520-150-036-2 (see Appendix A)

Yousef AbouHashem

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Abstract

This thesis investigated the application of 3D printing in anatomy education and assessed attitudes of students towards 3D printing. The aims were accomplished in 3 stages. Namely assessing the accuracy and usefulness of 3D printed models, and assessment of student attitudes towards 3D image donation.

The project focussed on 3D printing of human vertebrae. A mixed method approach was utilised, combining concepts and methods from biological anthropometry, medical education and engineering.

Accuracy analysis showed minimal differences in the dimensional measurements between 3D printed and dry vertebrae. Formative assessment results also showed minimal differences in the students' performance on 3D printed vertebrae compared to performance on high-quality plastic and dry vertebrae. Results of the survey of students' attitudes toward 3D medical images donation and whole body donation suggest that the majority are more willing to allow capturing of 3D images of their body for 3D printing in anatomy education compared to whole body donation.

This study strongly suggests that 3D printed bones, at the current level of technological development, could be applied effectively in anatomy education, as they seem to be very similar to the real bones in their appearance and anatomical detail. In addition, there is a positive attitude of tertiary level students towards the donation of body images for 3D printing in anatomy education.

1. Introduction

1.1 Background

According to the Oxford Dictionary of English, anatomy is defined as: "*the branch of science concerned with the bodily structure of humans, animals, and other living organisms, especially as revealed by dissection and the separation of parts*" (1).

Human anatomy in its various approaches has been a cornerstone in the medical and allied health courses (2-5). The purpose of anatomy in the medical or allied health fields is to equip the students with sufficient and necessary knowledge to allow understanding of the bodily structures, their arrangements and to an extent, their function. Thus, without sufficient knowledge and understanding of anatomy, no subject in the medical science fields, be it basic or clinical in nature, can be comprehended fully (6). Throughout history, however, anatomy education endured numerous changes. This process particularly heightened in the last several decades resulting in considerable transformations in all aspects of curricula, including syllabus, methods of delivery and resources (7).

Anatomy is more or less, a "dense" subject. It is content driven and crowded with facts, causing overwhelm to students while learning its intricate details with a minimum understanding of relevance (8). The traditional teaching method of anatomy is by dissection supplemented with didactic lectures. This process of learning has been associated with significant weaknesses, including reliance solely on memory and failure to connect relevance (9). Therefore educational changes were essential to identify effective education methods needed for optimal knowledge acquisition (9). Such reforms resulted in the emergence of modern anatomy education with a focused, integrative and clinically relevant content designed to engage future health professionals and anatomy educators in their learning and teaching (10). Therefore, human anatomy education is considered nowadays a "multimodal discipline" (11).

1.2 Cadaver-Based Teaching

Despite the importance of anatomy, as a discipline it incurred controversial concerns over its methods of education, teaching resources and assessment tools, resulting in a paradigm shift and curricular change (7, 12). Alongside curricular reforms, resources required for the delivery of anatomy courses also changed. Traditionally, cadavers have been utilised as the primary teaching resource in anatomy education. Cadavers are used in the study of anatomy by dissection or by prosection (4, 13). Teaching anatomy using cadavers is claimed to be the most useful method in learning anatomy (14), promoting both knowledge acquisition and professionalism (15). However, for a number of reasons cadavers have lost the central place of being the only resource when it comes to anatomy education in many institutions.

Even with firm anatomy acts, some legal and ethical constraints related to obtaining dead human bodies and tissues to be used in the anatomy laboratory continue to be an obstacle. This is particularly true with respect to particular cultural, religious and social milieus. As a consequence, this has led to a decline in the availability of donated bodies (16, 17).

Furthermore, financial burdens play a huge part in reducing dissection-based anatomy teaching and even prosection-based to an extent. Maintaining a dissection laboratory is a considerable financial burden. Generally speaking, cadavers are costly to acquire, maintain, and dispose of in any form and they require large occupied areas for storage (18, 19).

Finally, significant health and safety considerations may arise from the use of cadavers. Preparation of a body to teach anatomy is a multistep process that involves dealing with a cocktail of chemicals. In some instances, inadequate preservation of cadaveric materials, and in rare occasions, the presence of transmissible infectious diseases (15, 20), may pose health risks to staff and students in the anatomy laboratory, requiring adherence to appropriate measures.

1.3 Multimodal Approach to Anatomy Education

A variety of additional resources have been developed to supplement the delivery of anatomy courses. It is argued that these resources and teaching methods make better use of the student learning time (7). Some of the resources include manufactured plastic models, medical imaging, plastinated specimens, and multimedia interactive learning (4, 9, 21). Other reported innovations in the methods of teaching anatomy include surface body painting (21), play dough activities and clay modelling (22) and even yoga exercises (23).

Many institutions have overcome some of the issues surrounding dissection by using plastic models (4). It is no doubt models are the second best alternative to hands-on approach after cadavers (11). They also possess longer shelf life compared to cadavers. However, there are issues surrounding their use. Because they are "moulded to represent the standard-normal shape", they are, therefore, theory based three-dimensional (3D) representation of what is otherwise encountered in anatomical textbooks as diagrams (9). Therefore, anatomical plastic models and textbook figures only give a limited representation of the real thing. Anatomical models have been reported to lack accurate representations of shape and detail, and most importantly they do not account for anatomical variations (24, 25).

Plastination is a relatively new method in anatomy that was introduced by Gunther von Hagens in 1987. It is an effective technique for tissue preservation, be it a part of the body or an entire cadaver (26). The polymers used in the process produce dry, odourless, and lifelike specimens. Plastinated cadavers are an invaluable resource for anatomy education. The main advantage of plastinated specimens is that they preserve prosected specimens of high quality, allowing them to withstand wear and tear while maintaining anatomical variance and realism (4). Their drawbacks are mainly the costs of preparation (27) and the cocktail of chemicals involved in the embalming process (28). Apart from their education value, there have been reports concerning some ethical dilemmas with plastination (29). Indeed, written consent must be given by the body donor before obtaining their human tissue for medical education and research. The donor’s body is used for a certain time before it is returned to their family for funeral services. Plastination, however, increases the lifespan of the cadaver or part of the cadaver. Once a cadaver is plastinated, its tissue is preserved. This means a longer duration and usability (30). In addition, plastinating body parts could mean a different disposal time for each body part (if it is disposed of), which further complicates the ethical issue.

Advances in computer software and development over the past few decades allowed the introduction of multimedia and computer assisted interactive learning in anatomy education. It is almost impossible to see classes without some virtual learning component (31).This has also occurred as a result of increased class size, curricular change, and reduction of time spent in the anatomy laboratory (9). Since learning and level of involvement are correlated, interactive learning is reported to aid in knowledge acquisition and retention in the long run (12).

3D digital anatomical models have become increasingly available as a consequence of the availability of interactive media and digital resources. They are found on many media platforms, from computers and the Internet to handheld personal assistant devices and smartphones. In their simplest forms, 3D anatomy models can be observed in live or animated videos on popular video sharing websites, namely YouTube™ (32). Furthermore, 3D anatomical models incorporated into computer software and tablet applications (for example *Visible Body 3D Human Anatomy Atlas* (33)) have superior educational advantages over the standard textbook representations (34). Anatomy applications and software are designed in a way that the user can manipulate and control the positioning of the 3D model to allow visualisation from different views (35-37). Furthermore, most of these programmes nowadays contain an optional layer view, where structural components of the viewed model can be added or removed, in addition to assembling and disassembling options (38, 39). The primary limitation of digital models, however, is visualising a 3D image on a two-dimensional (2D) screen (40). This proves to be a disadvantage because the digital models essentially lack haptic (tactile) value.

1.4 Rapid Prototyping Techniques

Recent developments in medical imaging enabled an unprecedented outlook into the structures of the human body. The momentum and desire to translate 3D images into physical models was made possible with technological advances in manufacturing technologies (41). Nowadays, medical-based modelling technologies allow the construction of 3D anatomical models derived from information obtained using medical imaging and scanning procedures (42). Physical models can be fabricated directly from 3D images by rapid prototyping (RP) techniques (43).

RP (also known as additive manufacturing or 3D printing) is a digitally directed layer-by-layer material deposition manufacturing process (44). RP began in the early 1980s, incurring widespread applications in the traditional engineering sector (44). Charles Hull first invented RP in late 19th century, which he referred to as “stereolithography” technique, while working on making plastic objects from photopolymers (45). He later founded 3D Systems, a company that developed the first 3D printer named “stereolithography apparatus”, and later the first commercially available 3D printer, the SLA-250 in 1988 (45, 46).

The merging between computer graphics software and various materials used in the manufacturing processes resulted in the emergence of various additive manufacturing techniques (47). RP technologies have recently entered the field of anatomy education (40-42, 47, 48). Only over the last two decades have these technologies begun to impact the biomedical fields (47).

RP techniques involve a number of technologies and manufacturing procedures. Amongst these techniques, the most common ones are: stereolithography, selective laser sintering, fused deposition modelling (FDM) and 3D printing (49). Their process is digitally directed, automated, and additive, where a layer-by-layer material deposition is carried out (42, 44). The final product is a replica or “prototype” of the complex geometrical 3D structure formulated from a computerised digital image of the chosen object. In a biomedical application, the 3D digital image can be obtained from computed tomography (CT) or magnetic resonance imaging (MRI) scans, or scans produced from a surface 3D scanner (50).

RP techniques only differ in few aspects including materials used, total costs, quality, production time and accuracy (40). Their biggest advantage is overcoming the limitation of having to view 3D images formulated from conventional imaging modalities on 2D screens (40). Thus producing a graspable 3D model (40).

1.5 Attitudes Towards 3D Images and 3D Printing

It is with no doubt that the advent of 3D technologies has generated novice ways of conceptualising the human body. Without advanced imaging modalities, formulating 3D accurate and realistic digital models of anatomical structures is almost impossible. Since 3D images formulated from digital data can be converted into tangible, solid physical models for visualisation, one might ask what are the social resonances and effects behind these "fabricated data bodies" (51) and what implications do produced 3D models have on the future of anatomy education?

Just like body donation in anatomy, there are cultural, societal and political implications of 3D imaging and 3D printing (51). The human body is being represented in a digital form and later transformed into a solid form. What is described in the literature as "patient specific anatomical replicas", are reproduced models from medical imaging and scans of various parts, which are essentially unique and specific to each person (52). While the potential of 3D printing in anatomy may overcome some of the ethical and cultural obstacles relevant to body donation and cadaver dissection (27), there are other ethical aspects relevant to 3D printing technology which have not been explored in depth yet that also requires appropriate regulations (53, 54).

Since 3D technologies are still fairly modern, critical sociology of 3D printing, in particular, is still at its infancy (52). Therefore, there is no reported relevant research on the willingness and attitudes of individuals towards donating medical images of their bodies and body parts for the purposes of anatomical study and 3D printing of anatomical models. However, the attitudes of individuals in many cultures around the world and their willingness to donate their bodies for anatomical dissection are well established in the literature (16, 17, 55-57). Furthermore, the associated factors that are thought to influence body donation have also been reported on and analysed (17, 58). Consequently, most educational institutions rely on the altruism and generosity of body donors (58), to the contribution towards medical sciences (59).

1.6 Summary

Human anatomy has been an important subject in the medical and allied health fields. Many changes in anatomy education throughout its time resulted in a substantial renovation of all aspects of programmes, means of delivery and resources. In particular, recent developments in medical imaging, allowed unique outlook into human body structures. Physical models can be fabricated directly from 3D medical images by RP techniques.

Attitudes towards body donation, the willingness of individuals to donate their bodies and the factors that influence these parameters have been well established in the literature. However, issues surrounding analytical and critical sociology of 3D printing are still at their beginning. Moreover, attitudes of individuals towards 3D printing and willingness to donate 3D images of the body, in particular, are yet to be explored.

2. Literature Review

This chapter aims to review the published work on the applications of 3D printed models in the discipline of anatomy, with a particular focus on anatomy education. Papers relevant to surgical training and education will also be reviewed. This is because the two disciplines (anatomy and surgery) overlap considerably and experiences in the usage of RP and 3D printing in the surgical field are relevant to anatomy education.

2.1 Applications of RP and 3D Printing in Anatomy Education

The literature reports minimally on the practical application of RP and 3D printing in anatomy teaching. The primary aims of many papers were directed towards producing 3D printed models and performing various accuracy assessments that are qualitative and descriptive in nature. A common trend is seen in the majority of the articles showing the benefits and advantages of 3D printed anatomical models over other teaching modalities, without objective practical assessment of efficacy.

Image acquisition of the anatomical part of interest can be obtained using many medical imaging modalities. CT and MRI are commonly used modalities for image acquisition (60, 61). Sliced images obtained by the scans are used to construct a 3D digital representation of the scanned specimen in the standard DICOM (Digital Imaging and Communications in Medicine) file format (62). The DICOM file is then imported into an image-processing software to remove the unwanted artefacts around the specimen of interest and to form the 3D data mesh (62). The mesh is then exported in the form of Standard Tessellation Language (.stl extension) file format, to be uploaded into a 3D printer to be 3D printed (63).

The utilisation of CT and MRI scans allows the representation of anatomical structures that are difficult to visualise. Kapakin described the production of 3D anatomical models of the ethmoidal air cells with the stereolithography technique (64). Benkhadra *et al*. described the production of a 3D printed model representing the neurovascular structures of the superior thoracic aperture with the surrounding bony structures (65). Acquiring commercial anatomical models representing these aforementioned structures is difficult because such models are rare, expensive and difficult to manufacture.

Acquiring the image is not only done using CT or MRI scans. Adams *et al*. produced 3D printed replicas of cadaveric orbital dissections in different planes, showing muscular, bony and neurovascular structures in the orbit (50). The images were obtained from a cadaver using a handheld surface 3D scanner with an accuracy of 0.1 mm, which is approximately similar to that of a CT scan. The scanner, however, only captures the surface features of the specimen only. Therefore, in order to visualise the internal structures, parts or layers of the specimen have to be removed and exposed.

The ease of replication and production is mainly in the final step of producing the 3D print, taking only a few minutes to hours. This is primarily dependent on the specimen size and the 3D printer used (66). In addition, there are multiple steps involved prior to the final step. Image acquisition and processing are the preceding steps, which can take up to a day or two, depending on the size of the scanned specimens and the quality the user is after.

Different materials can be used with 3D printing depending on the 3D printer used. Wurm at al. attempted cerebral aneurysm simulation surgery in one study. The authors created a skull with the complex cerebral vessels with an aneurysm defect in one of the vessels (67). The models were 3D printed in different materials; the skull and vessels were made from plastic and the aneurysm was made from rubber, to accommodate the multiple clipping procedures by practicing trainees (67) and to create a realistic hands-on experience (68). Furthermore, two studies by Waran *et al*. used multiple materials to create 3D models of the skull to add “realism” value to the models (69, 70). A similar approach was also seen in West *et al*. (71) and Zabaneh *et al*. (72). The results of all these studies prove to be beneficial in anatomy education when it comes to producing 3D models with varying consistencies and materials to make them more realistic, and importantly, more durable. However, the main drawbacks reported include the lack of extent of “realism” (73) compared with the same structures in cadavers (74). Depending on the 3D printer used, current printing technology, however, allows printing with a limited number of material types per printing job and to an extent, limited colours.

Unlike regular plastic anatomical models, accuracy is one of the main features of 3D printed models. The accuracy in 3D printed models is due to the nature of the utilised imaging modality. CT, MRI and high-quality 3D scanners can accurately capture the features of the required body part to be 3D printed. In order for the 3D printed model to be accurate, image input must be of good quality to produce a good output (50). Therefore, image acquisition is one of the most important steps in rapid prototyping and 3D printing (27).

The accuracy of the 3D printed models was reported on in descriptive terms with direct comparison to the original specimen. A study by Mottl-Link *et al*. reported on the accuracy of 3D printed models of congenital heart defects (75). Direct comparisons of the models were made with the patient's heart and were found to be relatively accurate, which aided in the localisation of the pathology in an intra-operative setting. Quantitative assessments of accuracy can be made with a measuring instrument, either manually or digitally. Using a ruler, Zein *et al*. assessed the geometries of 3D printed liver models via "direct comparative validation protocol" in an intraoperative setting and concluded that the models were highly accurate (76). McMenamin *et al*. used a Vernier calliper to measure the accuracy of their hand model (27). They reported an increase in error measurement when structures were below 10mm, primarily due to calliper and human errors (27).

In terms of 3D printing application, the above-mentioned errors may only affect very fine structures, including minute terminal and continually dividing structures (50, 66). Li *et al*. performed digital measurements on two 3D printed anatomical models from corrosion casts of the human bronchial tree and its associated vasculature (66). Branches with diameters smaller than 1 mm in diameter were lost. However, the 3D printed models were was reported as fulfilling "the most basic educational needs". Although "rigorous scientific testing of the face validity of such replicas" and "how models can aid visualization of anatomy" is necessary (77), studies agree that the 3D printed models show an overall accurate representations when compared with their real counterparts, given that they come directly from the original specimen, or "patient file" (73, 74, 78, 79).

In surgical applications, 3D printed models are used for decision-making preoperatively and for surgical planning (76). The models are also used in an intraoperative setting to help with overcoming spatial orientation difficulties by allowing the easy localisation of the pathology to be treated (60, 61, 75, 80). The benefits reported were also improvement of the surgeon's confidence level and the reduction of time spent in the operating theatre (81). In addition, 3D printed models could prove to be more valuable in surgical training and anatomy education compared with virtual reality simulators or other forms of interactive media (70, 82, 83).

Regarding information delivery between practitioners and patients, it is easier to relay information between parties in the presence of a visual, haptic aid. Because of the ease in which they are produced, 3D printed models could be used in clinical settings to facilitate the communication between health professionals, but most importantly between practitioners and patients, aiding in patient education and in obtaining informed consent (61, 84, 85).

A dominant advantage of RP and 3D printing is the production of anatomically variant models. Patient-specific 3D printed models obtained from patient scans can be used to visualise anatomical and pathological variations (86). In a study by Windisch *et al*., the authors 3D printed clubfoot models obtained from CT scans, which demonstrated the complex malformations associated with each bone due to the disease process (87) Another study produced colour-coded heart models that were patient specific and representative of variations in congenital heart disease (88). Another study designed two 3D tracheobronchial models for the purpose of endoscopic training, with one of the models having an anatomical variant (89). Other studies produced 3D models of patient-specific abdominal anatomies (90) including variants of the abdominal aorta (91) and parts of the collecting systems of the renal organs (92) from CT scans. These studies concluded that the produced models were of significant value in teaching and training. This can an invaluable resource in anatomy education because most of these variations are absent on commercial anatomical models and are otherwise only encountered in textbooks as theory or as 2D representations.

3D printed models are reported to aid in visuospatial capabilities because of their haptic value (93). This is a significant advantage that is present in physical models, cadavers, and plastinated specimens but absent in digital models that are viewed on a 2D screen (40). In a study by Preece *et al*. the authors assessed the practical value of 3D printing in veterinary anatomy (93). A 3D printed equine foot model was produced from MRI scans of a cadaver horse foot. The efficacy of the 3D printed model was validated by comparing it with other teaching resources used: textbooks and 3D digital models. It was concluded that the physical models were superior to the other resource because of their haptic value. By physically touching the models the “visuospatial capabilities” of the students improved, which in turn allowed them to score higher in a formative test. This was due to the free ability of the students to manually manipulate the physical models in space (93).

3D printed models are reported to be durable. The durability of such models was put into practical perspective in surgical training studies. Hochman *et al*. produced "realistic" temporal bone models with four varying material infiltrates (82). Recruited subjects were instructed to evaluate the randomly assigned models using a surgical drill. Results of the study showed that the models were durable and that various material infiltrates do have an influence on the realism and durability of the 3D printed model, agreeing with the outcomes of a comparable study (94). Some of the reported results were measured with Likert-scale scores (95) and, therefore, caution is necessary when generalising the results due to their subjectivity. Further objective research is warranted to assess how such models are able to withstand certain physical and chemical impacts on the various materials used in the production.

A major advantage of the 3D printed models is the low production price. This is dependant on the level of detail, the number of anatomical structures included, the size of the model and most importantly, the RP technique used (27). The costs involved with producing 3D printed models, compared with other methods is noticeable. One study estimated the costs of 3D printing of anatomical models compared to cadaver plastination method (27). Apart from administrative staff and printer purchasing costs, 3D printing an entire upper limb with the neurovascular components would be between $300 and $350 (US dollars) in material cost whereas a plastinated upper limb would be around $14,000 (US dollars). Bustamante *et al*. presented aorta models with the celiac trunk at $250 (89). Hawkinson *et al*. models were third party printed with a 3D printer and later treated with a silicone coating to make them more realistic (96). The neonatal congenital defects prototypes made were between $90 and $140. A temporal bone model (used for surgical training) produced by Rose *et al*. was approximately $400 (74). Therefore, the relatively low costs involved and the ease of production means that students are able to acquire these models easily. The 3D models produced remain relatively at a low price compared to other modalities (92, 97).

Other benefits of 3D printed models include avoidance of health and safety issues related to the preparation of cadavers. They also do not require specialised storage or handling equipment compared to cadavers. 3D printing in anatomy may also overcome issues related to cultural or religious traditions in some countries or regions, where dealing with corpses or dead human tissue is frowned upon (50). However, the ethics and critical sociology of 3D printing (and even 3D bioprinting) are still at their infancy (98).

2.2 Study Aims

Based on the literature review findings, the main aim of this project was to test the applicability of 3D printing in anatomy education and to investigate the attitudes of a section of the general population (anatomy students) towards 3D medical images donation. The focus of the project was directed towards the 3D printing of vertebrae. The reason for this choice is two-fold. The monochromatic nature of bones makes them the easiest component in the human body to duplicate while maintaining the accuracy and the haptic value. The second reason for choosing vertebrae is the irregularity and complexity of the shape of these bones. Thus, if the vertebrae were to be 3D printed with a high degree of accuracy, the process would be basic for less complex bones.

The aims were accomplished in three stages. In the first stage the accuracy of the 3D printed vertebrae was tested. In the second stage, the usefulness of the 3D printed models was assessed through a practical application in a formative anatomy assessment. Finally, the attitudes of students towards 3D imaging donation and 3D printing versus body donation were assessed in a questionnaire.

In light of the above, it is hypothesised that the 3D printed vertebrae are a valuable resource in anatomy education and that 3D anatomical images for 3D printing will be obtained easier than bodies for dissection. To test this, three testable working hypotheses were formulated:

1. 3D printed vertebrae are as accurate as their real vertebrae and high-quality plastic vertebrae in representing anatomical features;
2. Students will obtain good scores in formative anatomy assessment where 3D printed vertebrae and real bones are used compared with plastic vertebrae; and
3. Positive attitudes will be expressed by a population of undergraduate anatomy students towards 3D medical image donation and 3D printing of body parts; willingness to donate 3D images of body and body parts for anatomy research and education is greater than willingness to donate body for anatomical dissection.

2.3 Summary

Based on the Literature Review, the impact of 3D printing technology on anatomy is undeniable. The evidence is lacking, however, on the practicality of 3D printing in anatomy education. The main theme of the published literature is towards RP and 3D printing in surgery and medical education. Articles relevant to anatomy education are also emerging.

The reviewed articles showed a common trend where their primary outcome was looking at aspects of the RP technique itself, exploring the advantages of the 3D printed models, their accuracy, methods of production, usefulness, costs and subjective feedback from participants. The reviewed articles explored 3D printing but did not assess the objective practicality of 3D printed models in anatomy education.

Based on these findings from the Literature Review, the present project will focus on the applicability of 3D printed vertebrae in anatomy education by assessments of accuracy and practicality in anatomy education. In addition, attitudes of students will be assessed towards 3D medical images donation compared with whole body donation.

3. Methodology

3.1 Ethics Approval

Ethics approval for the project was obtained from Macquarie University's Human Research Ethics Committee (MUHREC) on 12th June 2015.

Approval number: 520-150-036-2 (see Appendix A)

3.2 Methodology Overview

The project utilised a mixed method approach (99). The theoretical assumptions, methods and approaches from biological anthropology (anthropometry), medical education and engineering were combined. The project was divided into two phases: a preparation phase and an evaluation phase, each consisting of various designs and protocols to achieve the aims of the project.

3.3 Preparation Phase

Figure 1 shows the methodology overview for the preparation phase. Dry vertebrae were selected, scanned and 3D printed in the preparation phase.

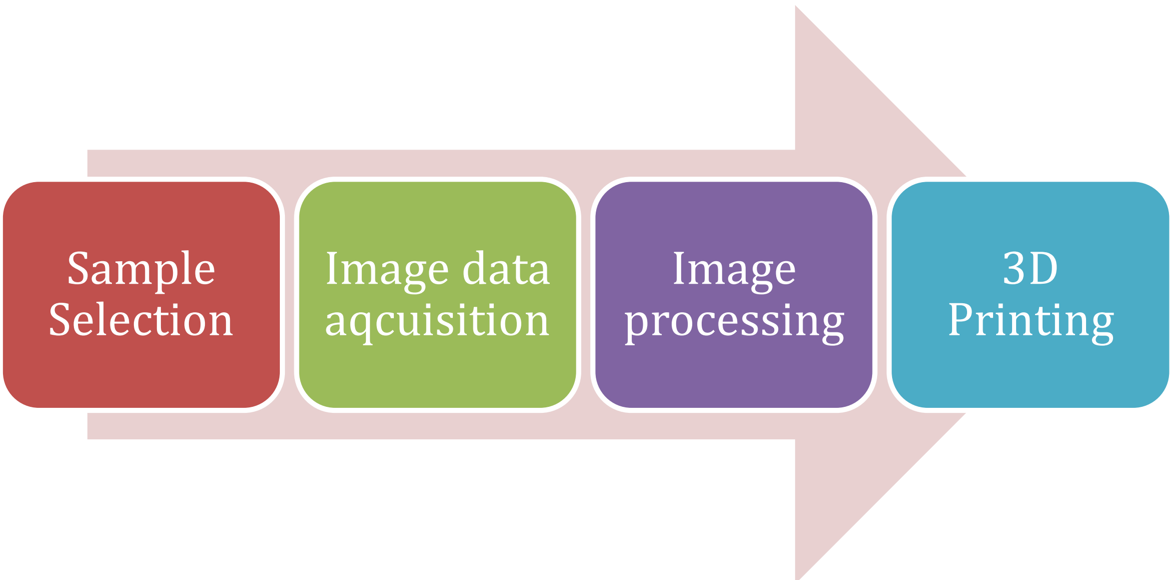


Figure 1: Overview of the preparation phase

Figure 2: Dry vertebrae

Figure 3: Plastic vertebrae

Sample Selection

Vertebrae from different regions of the vertebral column were selected from a larger collection of bones from the Department of Chiropractic, Macquarie University. The chosen samples contained real, dry adult human vertebrae that are used as an educational resource in the anatomy programmes at the institution. The chosen samples were symmetrical, pathology free and bearing of all identifiable anatomical features of a typical vertebra. The vertebrae included two typical cervical, two typical thoracic, and two typical lumbar vertebrae (Figure 2). Figure 3 shows the chosen plastic vertebrae, which were used for the formative anatomy assessment.

Image Data Acquisition

3D surface images of the selected dry vertebrae were obtained using the hand-held Artec Spider™ (Artec Group, Luxembourg) 3D surface scanner (Figure 4). The scanner is highly accurate with a 3D resolution of up to 0.1mm and 3D point accuracy of up to 0.05mm (100). Each sample was scanned multiple times. Multiple scans were performed to ensure all sides and features of the samples were captured. The vertebrae were turned during the scanning procedure to capture the inferior surfaces as well. The scanner was also held diagonally to the sample to ensure all features were captured. These steps were crucial in order to obtain all of the anatomical features because the quality of the 3D printed model relies heavily on the quality of the obtained image (27, 50). Scanning was performed at Western Sydney University, Campbelltown Campus (formerly, University of Western Sydney). The 3D data of the scans were imported into a computer for processing.

Figure 4: Artec Spider™ 3D surface scanner (100)

Image Processing

Images were processed with the compatible Artec Studio 9.2 software (figure 5). The software was provided with the scanner and is required for the scanner to operate. It enables the user to visualise the scanning process of the sample during the scanning procedure. The following steps were carried out in order:

1. The acquired scans were edited to remove any additional surroundings and unwanted scanned artefacts around the sample using the erase feature under the 'Editor' tab.
2. The scans were aligned together with the align feature in the software using the 'Align' tab.
3. A 'Global Registration' was applied after the samples were aligned to optimise the frames position within all scans. The feature is in tool panel under the 'Tools' tab.
4. Noise was eliminated and further unwanted scanned artefacts were erased with 'Outliers Removal' option in the tool panel under the 'Tools' tab.
5. A single surface model from the multiple scans was created using the 'Sharp Fusion' option from the tool panel in the 'Tools' tab.
6. Further flaws and outliers were erased when needed using the 'Defeature Brush' tool under the 'Editor' tab.
7. The 3D model was exported as a mesh in a .stl file format to be 3D printed.

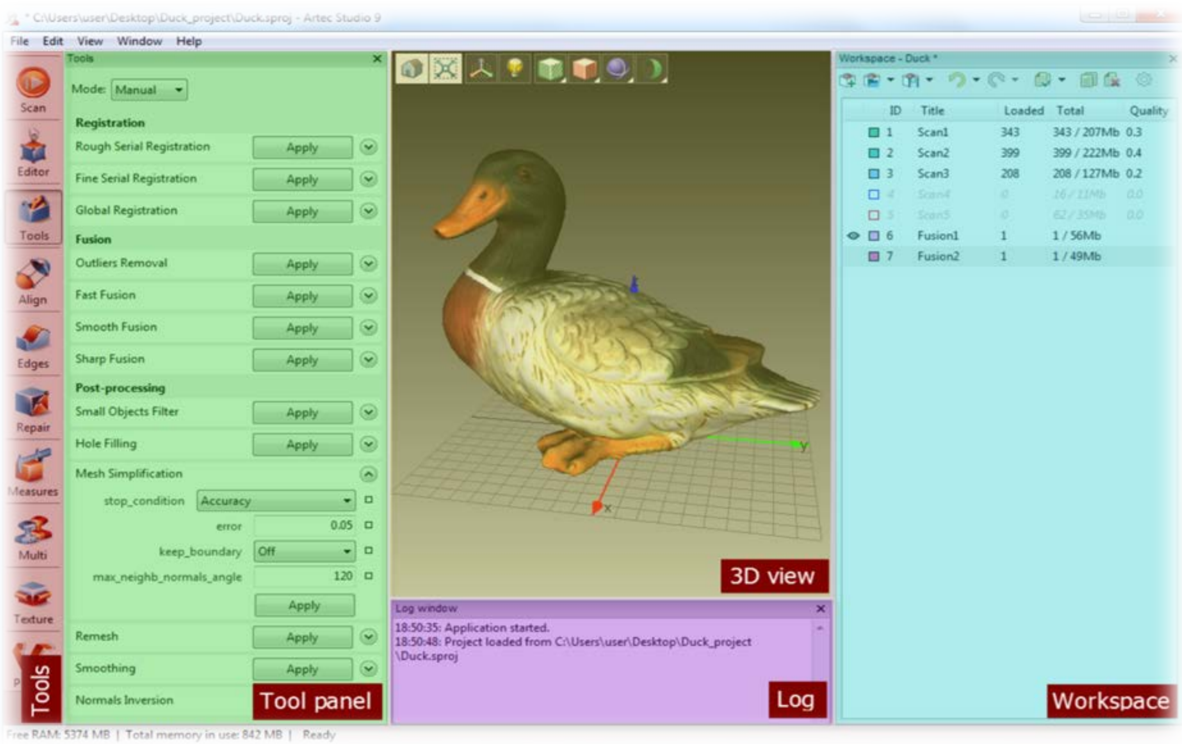


Figure 5: User interface for the Artec Studio software, version 9.2 (101)

3D Printing of Samples

A total of six 3D images (.stl file format) were acquired from 3D scanning and image processing. The images consisted of two cervical, two thoracic and two lumbar vertebrae scans. The 3D images were 3D printed at two locations, Macquarie University, North Ryde Campus, and Western Sydney University, Penrith (Kingswood) Campus. The printers that were used for this project were the desktop 3D printers MakerBot™ Replicator® 2 (figure 6) and the Mojo™ (figure 7).

Figure 6: MakerBot™ Replicator® 2 3D printer (102)

Figure 7: Mojo™ 3D printer (103)

The MakerBot™ Replicator® 2 (MakerBot Industries, New York) is a desktop 3D printer that uses FDM technique with biodegradable polylactic acid (PLA) filaments as its primary material. It has a large build volume (28.4 x 15.2 x 15.5 cm) and a high layer resolution of 0.1mm (102). The Mojo™ (Stratasys Ltd, Minnesota) is also a desktop 3D printer. It also uses FDM technology with Acrylonitrile butadiene styrene (ABS) thermoplastic polymer as its main material. The maximum part size that can be printed is 12.7 x 12.7 x 12.7 cm with layer thickness at 0.178 mm (103).

Both printers use materials that belong to the same family of thermoplastics, mouldable when heated and hard when cooled. However, few differences are present. ABS is a strong and a high temperature resistant material, making it ideal for making durable strong models. PLA, on the other hand, exhibits these properties but lower. PLA's main advantage is the smaller layer thickness (0.1mm compared to 0.178mm of ABS), which makes it more accurate and gives a sharper finish to the final geometry of the 3D printed model, making it ideal for showing bony features and landmarks (104)

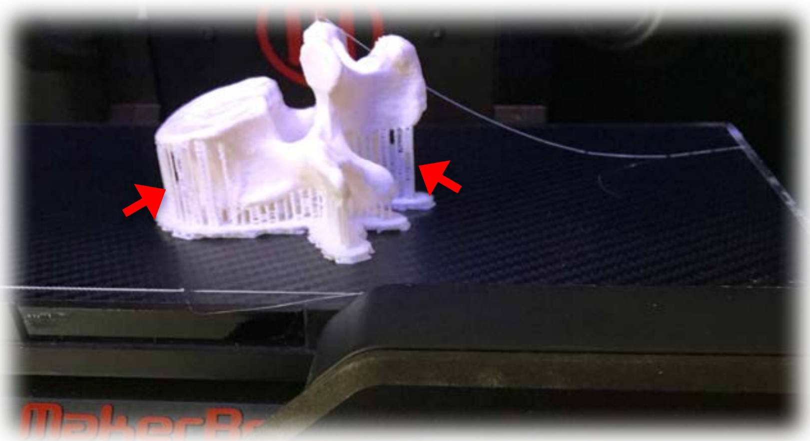


Figure 8: 3D printed model of lumbar sample 2 on the MakerBot™ Replicator® 2 build tray (support structures indicated by red arrows)

The files were opened using the printers' software. The scans were positioned as flat as possible on the virtual platform in the software in preparation for printing. This allowed for minimal 'Supports' to be used and also reduced the printing time for each vertebra (figure 8). 'Supports' are easily removable support structures deposited under overhanging parts of the scan (102). The MakerBot™ Replicator® 2 support structures are manually removed by hand without damaging the 3D printed model.

Because the Mojo™ 3D printer uses a different type of material for 3D printing, the supports are usually dissolved away in a water-based solution (103). The machine used for support dissolving is the WaveWash 55 removal system (figure 9). Since the whole process is automated, the 3D printed vertebrae were placed inside the WaveWash 55 where the support material was dissolved away.

Figure 9: WaveWash 55 support removal system for the Mojo™ 3D printer (103)

3.4 Evaluation Phase

Figure 10 shows an overview of the evaluation phase. Anthropometric measurements to assess the accuracy of the 3D printed vertebrae were performed. In addition, the 3D printed vertebrae with the selected dry and plastic vertebrae were used in a formative assessment (spot test). Questionnaire design and distribution were also addressed in the evaluation phase.

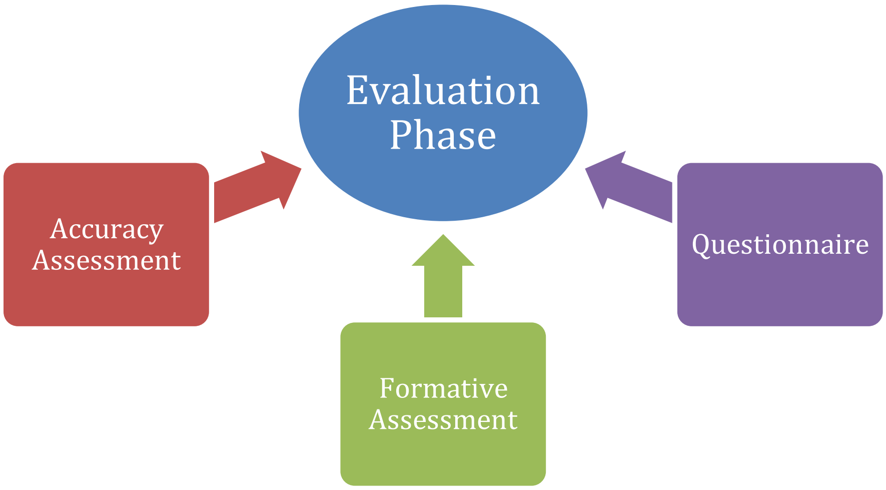


Figure 10: Overview of the evaluation phase

Accuracy Assessment

A total of twelve vertebrae were produced from the 3D printing of the scans; six vertebrae were made using the MakerBot™ Replicator® 2 3D printer and six were made using the Mojo™ 3D printer. Figures 11(a–f) show the 3D printed vertebrae with each corresponding dry vertebra. A series of linear measurements (figure 12 and table 1) were directly performed on the selected dry vertebrae and each of the 3D printed vertebrae by calculating the maximum distance between the two measured points using the following parameters (105-107):

- Anterior vertebral body height
- Spinous process length
- Vertebral foramen width
- Vertebral foramen breadth
- Pedicle height (right and left)
- Lamina height (right and left)
- Bi-transverse process length

a) Cervical Sample 1

b) Cervical Sample 2

c) Thoracic Sample 1

d) Thoracic Sample 2

e) Lumbar Sample 1

f) Lumbar Sample 2

Figure 11(a–f): 3D printed vertebrae with their original dry vertebra (Top: dry vertebra; Left 3D printed vertebra with MakerBot™ Replicator® 2 3D printer; Right: 3D printed vertebra with the Mojo™ 3D printer)

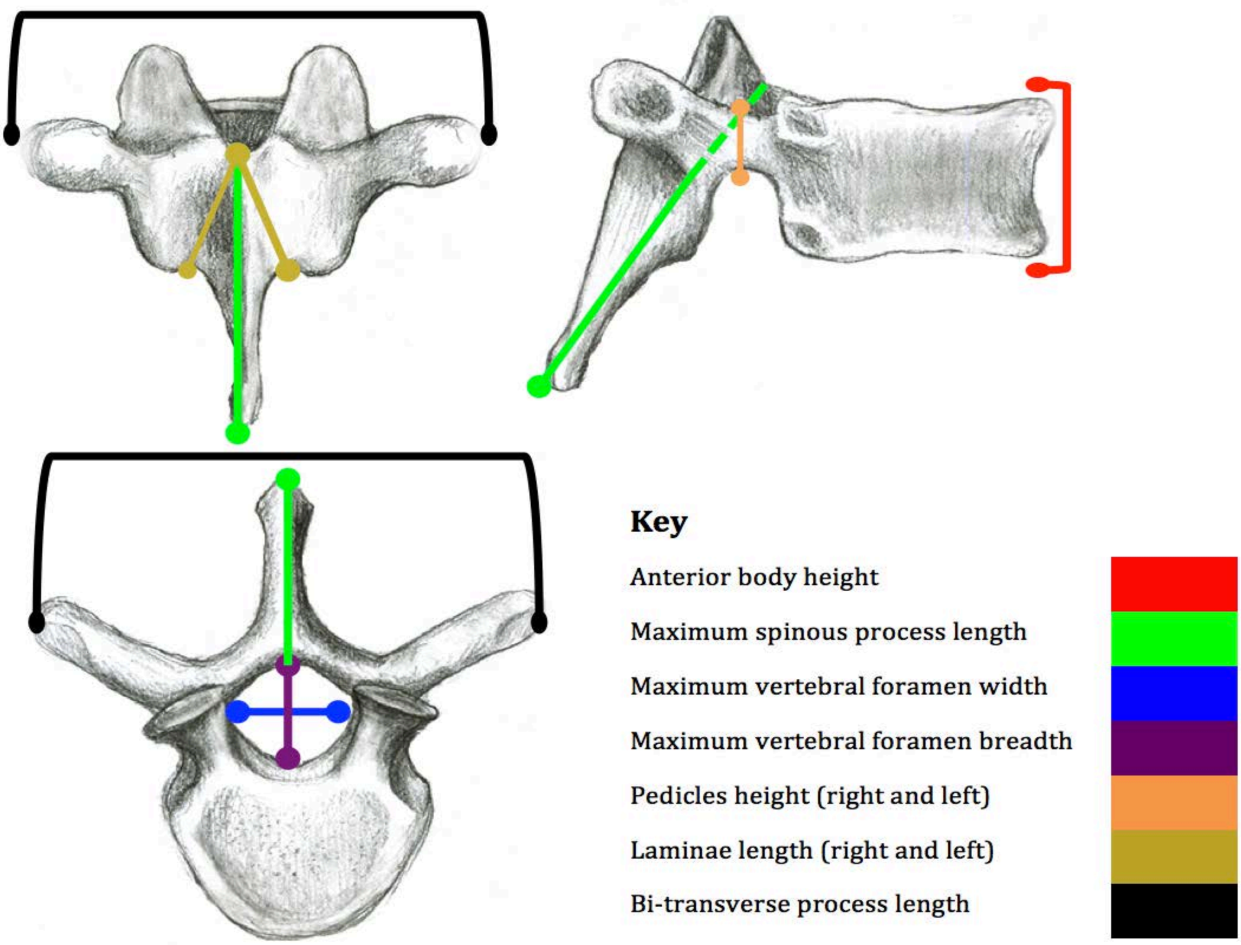


Figure 12: Orthogonal views showing dimensional measurements (108)

Table 1: Definitions and abbreviations for the measurements

Measurement	Abbreviation	Definition
Anterior body height	ABH	The most anterior distance between the superior and inferior endplates of the vertebral body (106)
Vertebral foramen width	VFw	The inner measured distances of the vertebral foramen (105-107)
Vertebral foramen breadth	VFb	
Spinous process length	SPL	Distance between the most anterior point of the spinous process (in the vertebral foramen) to the most posterior point (109)
Right pedicle height	PHr	The maximum perpendicular distance of the pedicles in relation to the horizontal (105-107)
Left pedicle height	PHl	
Right lamina length	LLr	The maximum length of the laminae
Left lamina length	LLl	
Maximum bi-transverse process length	TVPL	Maximum vertebral width distance from the most lateral points of the right and left transverse processes (106)

Figure 13: Digital calliper

Measurements were performed using the digital calliper shown in figure 13 (Mitutoyo Corporation, Japan). The instrument has a reported precision of 0.01 mm and an accuracy of 0.02 mm (27). Each measurement was performed by one observer three times on three separate days, with a one-week interval between each day to minimise bias, and to ensure consistency and repeatability (106). Thus, a total of three measurements were performed for each category. The mean was calculated from the total of each measurement parameter. Paired sample *t*-test was used to compare the means of each measurement obtained from the dry vertebrae to the 3D printed vertebrae. For each linear measurement, dimensional error was calculated in accordance with Choi *et al*. (2002) and Chang *et al*. (2003) methods, as cited in Silva *et al*. (110), using the following equations:

- Mean absolute difference (mm) = 3D printed vertebrae – dry vertebrae
- Mean relative difference (%) = $\frac{\text{(3D printed vertebrae – dry vertebrae) x 100}}{\text{dry vertebrae}}$

Formative Assessment (Spot test)

The 3D printed, the dry and the plastic vertebrae were applied in a formative anatomy assessment called the spot test. Spot tests (also known as tag tests) are traditional practical anatomy assessments that take the form of a "steeplechase" (111). Spot tests consist of a stream of anatomical structures (prosections, images, models *etc.*…) placed on 'stations' (112). Students are assessed on the ability to identify anatomical landmarks that are highlighted (with pins, labels or colours) to be identified (113). Students rotate from station to station and are required to answer the questions within a 60 to 120 seconds timeframe (111).

Figure 14 shows an outline of the spot test for the present study. The spot test consisted of nine stations. Each station had a vertebra model placed. Each vertebra was placed randomly on one of the nine stations, and remained consistent throughout the test day. Therefore each station had a dry, a 3D printed or a plastic vertebra.

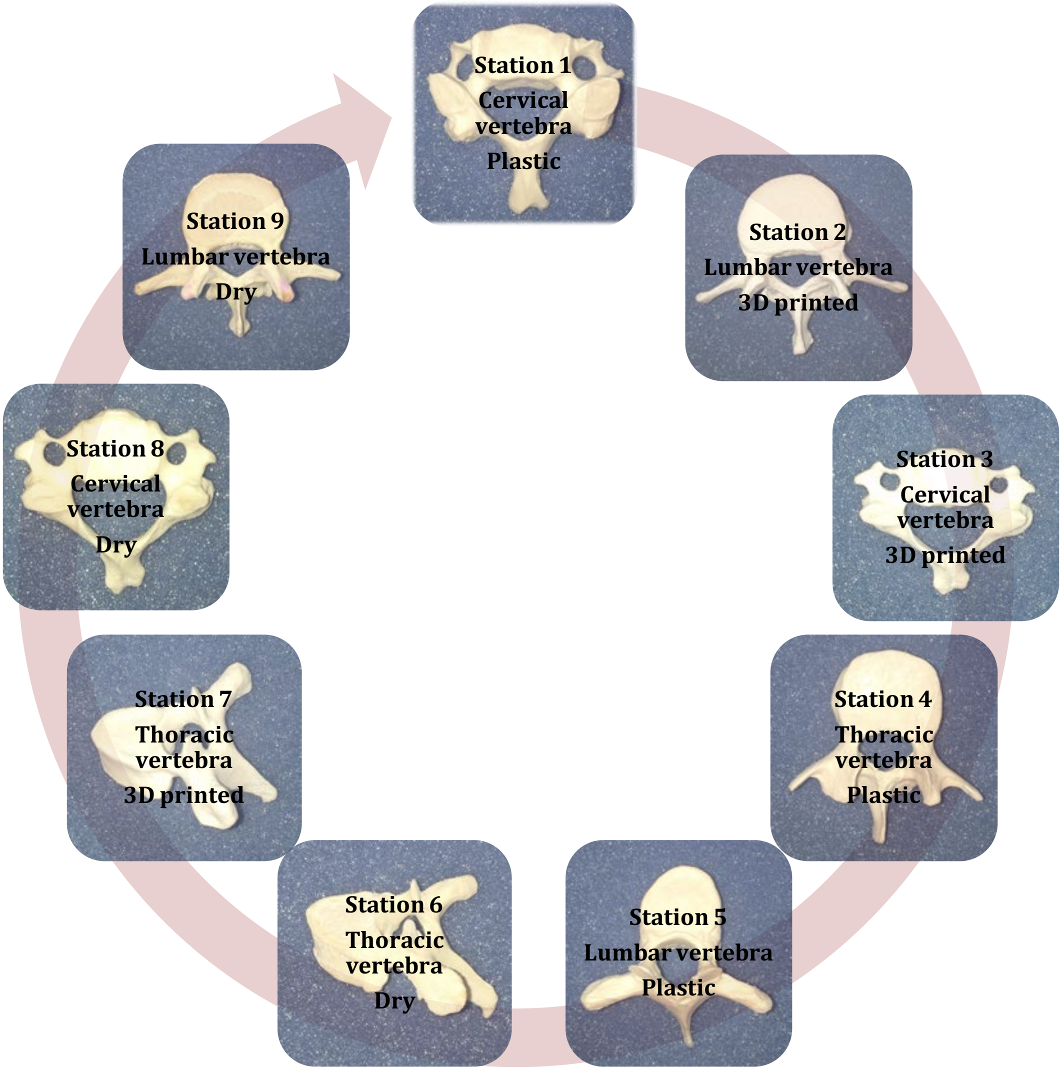


Figure 14: Spot test overview

The assessed participants were undergraduate anatomy students who were enroled in the anatomy course "*Anatomy of the Limbs and Back*". The assessed students were only exposed to bones of the vertebral column and their morphological features and differences in the previous course "*Introduction to Anatomy*" as part of their learning outcomes. Thus, the knowledge of the participants about vertebrae is basic. The spot tests were conducted in concurrence with the students' regular anatomy classes. Nine students performed the test at every session. One mark was allocated for every correct answer. Therefore, the maximum achievable score was nice correct answers out of nine. Each student had 30 seconds per station to answer one question: To which region of the vertebral column does the vertebra shown belong to?

Every participating student received a participant information sheet (see appendix B) and a spot test answer sheet (see appendix C) before the spot test. Participants were not informed about the spot test prior. They were made aware that participation was anonymous and voluntary and no penalties were incurred for choosing not to participate.

Questionnaire Design, Measures and Administration

The questionnaire was designed to assess the attitudes and willingness of individuals to donate 3D medical images of their body and body parts to be 3D printed into anatomical models for anatomy education and research. The responses were contrasted to the attitudes of the same group towards whole body donation (56).

Expert opinion on the questionnaire items was obtained from six academics in the Chiropractic Department at Macquarie University. The academics have had long and extensive experience in questionnaire design in the fields of anatomy, anthropology, education and manual therapies. This step was done to ensure the relevance of the construct to the topic and to validate the content (114). There is no consensus in the literature as to the number of experts that should be used for content validation (115).

The surveyed population was an undergraduate anatomy students enroled in the course "*Introduction to Anatomy*" at Macquarie University. The questionnaire was administered to the students before their regular tutorial classes. Each student received one hard copy of the survey (see appendix D) with the attached participant information sheet (see appendix E). Students were made aware that participation in this study was completely voluntary and anonymous and that no associated risk was involved in choosing not to participate in the study.

A total of six dependent variables were assessed for the questionnaire. All the responses from the dependent variables were rated on a three-point Likert type scale (1=No, 2=Undecided and 3=Yes). The questionnaire items asked the respondents to which extent they agreed with the following questions:

1) "Would you donate your body for anatomical education and research?"
2) "Would you support a family member's decision in donating their body for anatomical education and research?"

3) “Would you support a stranger in donating their body for anatomical education and research?”
4) “Would you allow 3D images of your body, body parts or organs to be 3D printed and used for anatomical education and research?”
5) “Would you support a family member’s decision to allow his or her 3D body images to be 3D printed and used for anatomical education and research?”
6) “Would you support a stranger’s decision to allow his or her 3D body images to be 3D printed and used for anatomy education and research?”

The first and fourth questions contained additional items to indicate the reasons for the choice made (see appendix D). The independent variables were measured with single items, which included age, religion and ethnicity. The latter two were pooled into the largest and most meaningful categories that facilitated the statistical testing.

3.4 Statistical analysis

Statistical analyses were performed using IBM® SPSS® Statistics, Version 22 (IBM Corporation, New York). A significance level (*p*-value) of 0.05 was used when multiple comparisons were made. For accuracy assessment, results were analysed using the paired sample *t*-test (Student’s *t*-test) for each measurement parameter to compare the differences of the means between the dry vertebrae and each of the 3D printed vertebrae. The differences in student performance in the spot test were analysed using Pearson’s Chi-Square (χ^2) test. Survey results were also analysed using χ^2-test for the relationships of categorical data. Regression analysis was used to assess the influence of the independent variables on the choices of surveyed participants. Microsoft® Excel® 2011 (Microsoft Corporation) was used to present the results in graphs. Other results were presented in tabular formats where appropriate.

3.5 Summary

This project employed a hybrid method approach applying concepts from biological anthropology (anthropometry), medical education and engineering. The project was divided into a preparation phase and an evaluation phase to accomplish the project goals.

Three primary assessments were performed. Anthropometric assessment was performed on the dry and the 3D printed vertebrae. A Spot test was performed using the 3D printed vertebrae on undergraduate anatomy students. The third part of the project was a questionnaire that assessed the attitudes of undergraduate anatomy students towards 3D image donation and body donation.

4. Results

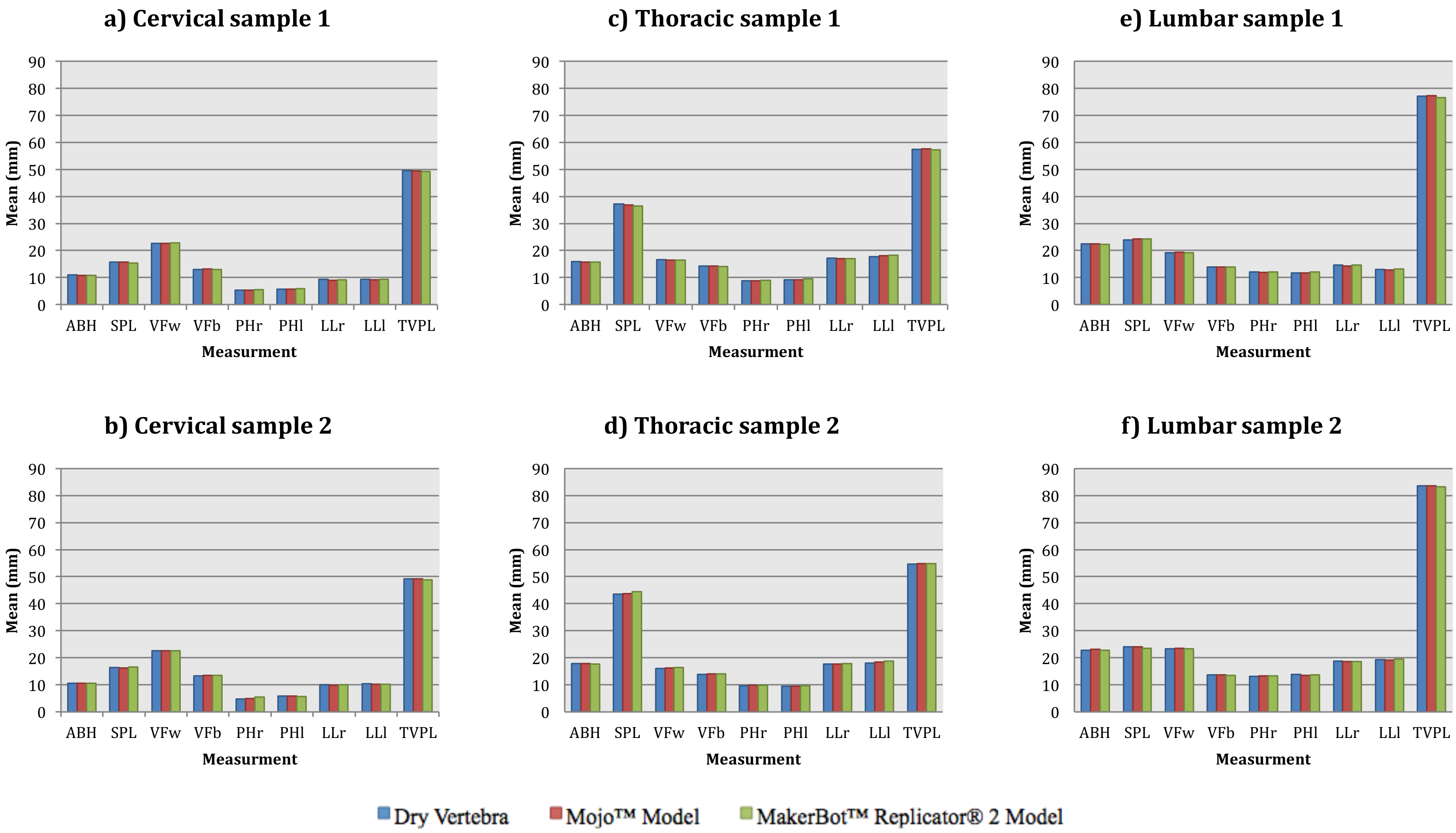
The results chapter will be divided into three parts. The first part will focus on the results of the dimensional accuracy of the 3D printed vertebrae compared to their real counterparts. The second part of the results chapter is concerned with the results of the anatomy formative assessment, with particular focus towards the 3D printed vertebrae compared to the dry and the plastic vertebrae. The final set of results will be relevant to the questionnaire on the attitudes of students towards 3D medical images donation compared to whole body donation.

4.1 Accuracy Assessment

The means of the measurements results are presented in Figures 15(a-f). As it can be observed from the diagrams, the 3D printed vertebrae show overall greater dimensions in the observed measurements compared to those of the dry vertebrae. No specific trend is present however concerning the effect of this overestimation of dimension on particular measurements.

Relative assessment of the differences in the means of the 3D printed vertebrae compared to the dry vertebrae is presented in table 2. Overall, the absolute dimensional error of the measurements means for the 3D printed vertebrae from both 3D printers is 0.188mm (0.01%). Further analysis revealed that the Mojo™ 3D printed models showed less relative error (0.148 mm; 0.99%) compared to the MakerBot™ Replicator® 2 (0.227mm; 1.49%). This result is in fact interesting considering that the layer thickness of the material of the MakerBot™ Replicator® 2 3D printer is thinner than the Mojo™ 3D printer.

Overall, there appears to be no significant differences between the dry vertebrae and the 3D printed models, except where indicated (Table 3). Few statistically significant results were observed in the spinous process length, pedicles heights, and bi-transverse process lengths measurements. In addition, the Mojo™ 3D printer shows statistically less significant differences overall compared to the MakerBot™ Replicator® 2. These preliminary results indicate that the 3D printed vertebrae are relatively accurate and are sufficient for use in anatomy education.



Figures 15(a-f): Means of linear dimensions of the dry vertebrae and the 3D printed vertebrae. Abbreviations: ABH=Anterior body height, SPL=Spinous process length, VFw=Vertebral foramen width, VFb=Vertebral foramen breadth, PHr=right pedicle height, PHl=left pedicle height, LLr=right lamina length, LLl=left lamina length, TPL=bi-transverse process length.

Table 2: Absolute means and percentages for the linear dimensions differences of the 3D printed vertebrae compared to the dry vertebrae. Abbreviations: ABH=Anterior body height, SPL=Spinous process length, VFw=Vertebral foramen width, VFb=Vertebral foramen breadth, PHr=right pedicle height, PHl=left pedicle height, LLr=right lamina length, LLl=left lamina length, TPL=bi-transverse process length.

Mojo™ 3D printer																		
	ABH		**SPL**		**VFw**		**VFb**		**PHr**		**PHl**		**LLr**		**LLl**		**TVPL**	
	mm	%	mm	%	mm	%	mm	%	mm	%	mm	%	mm	%	mm	%	mm	%
Cervical sample 1	0.060	0.55	0.043	0.28	0.013	0.06	0.133	1.02	0.09	1.70	0.037	0.65	0.357	3.80	0.0217	2.31	0.167	0.37
Cervical sample 2	0.113	1.07	0.110	0.67	0.023	0.10	0.060	0.45	0.103	2.17	0.080	1.38	0.187	1.87	0.050	0.49	0.123	0.25
Thoracic sample 1	0.167	1.05	0.300	0.81	0.077	0.46	0.023	0.16	0.013	0.15	0.060	0.65	0.190	1.11	0.357	2.00	0.133	0.23
Thoracic sample 2	0.010	0.06	0.173	0.40	0.087	0.54	0.057	0.41	0.120	1.24	0.007	0.07	0.787	4.46	0.413	2.29	0.117	0.21
Lumbar sample 1	0.073	0.33	0.343	1.44	0.093	0.48	0.097	0.70	0.207	1.71	0.113	0.97	0.337	2.31	0.240	1.84	0.210	0.27
Lumbar sample 2	0.293	1.28	0.043	0.18	0.107	0.46	0.097	0.71	0.130	0.99	0.310	2.24	0.260	1.38	0.160	0.83	0.010	0.01
Overall mm and %	0.119	0.72	0.169	0.63	0.067	0.35	0.078	0.58	0.111	1.33	0.101	0.99	0.353	2.49	0.207	1.63	0.127	0.22
MakerBot™ Replicator® 2 Vertebrae Models																		
	ABH		**SPL**		**VFw**		**VFb**		**PHr**		**PHl**		**LLr**		**LLl**		**TVPL**	
	mm	%	mm	%	mm	%	mm	%	mm	%	mm	%	mm	%	mm	%	mm	%
Cervical sample 1	0.14	1.29	0.27	1.72	0.073	0.33	0.021	0.20	0.173	3.21	0.157	2.18	0.197	2.18	0.013	0.15	0.293	0.59
Cervical sample 2	0.08	0.76	0.103	0.64	0.023	0.10	0.077	0.57	0.643	13.2	0.227	3.95	0.080	0.82	0.143	1.40	0.333	0.68
Thoracic sample 1	0.200	1.28	0.697	1.89	0.100	0.61	0.157	1.10	0.120	1.36	0.387	4.25	0.203	1.2	0.380	2.09	0.133	0.23
Thoracic sample 2	0.193	1.08	0.973	2.23	0.290	1.80	0.113	0.81	0.203	2.08	0.207	2.18	0.177	1.00	0.663	3.60	0.207	0.38
Lumbar sample 1	0.260	1.16	0.347	1.43	0.087	0.45	0.070	0.50	0.037	0.31	0.407	3.46	0.033	0.23	0.063	0.50	0.577	0.75
Lumbar sample 2	0.130	0.56	0.503	2.10	0.127	0.54	0.153	1.12	0.113	0.86	0.137	1.01	0.197	1.06	0.157	0.82	0.410	0.49
Overall mm and %	0.167	1.02	0.482	1.67	0.117	0.64	0.099	0.72	0.215	3.50	0.254	2.84	0.148	1.08	0.237	1.43	0.326	0.52

Table 3: Differences between means of the dry and 3D printed vertebrae. Abbreviations: ABH=Anterior body height, SPL=Spinous process length, VFw=Vertebral foramen width, VFb=Vertebral foramen breadth, PHr=right pedicle height, PHl=left pedicle height, LLr=right lamina length, LLl=left lamina length, TPL=bi-transverse process length.

Vertebra	3D Printer	Significance of Measurement (*p*-value)*								
		ABH	SPL	VFw	VFb	PHr	PHl	LLr	LLl	TVPL
Cervical Sample 1	Mojo™	0.438	**0.023**	0.889	0.059	0.381	0.680	0.149	0.130	0.399
	MakerBot™ Replicator® 2	0.667	0.567	0.705	0.133	0.154	**0.028**	0.552	0.428	0.201
Cervical Sample 2	Mojo™	0.342	0.792	0.893	0.753	0.061	0.353	0.426	0.392	0.064
	MakerBot™ Replicator® 2	0.335	0.751	0.539	0.222	**0.037**	0.214	0.463	0.439	**0.011**
Thoracic Sample 1	Mojo™	0.563	**0.011**	0.730	0.644	0.716	0.683	0.406	0.065	0.193
	MakerBot™ Replicator® 2	0.241	0.304	0.149	0.247	0.390	0.093	0.653	0.093	0.136
Thoracic Sample 2	Mojo™	0.828	0.305	0.096	0.173	0.095	0.919	0.099	0.063	0.574
	MakerBot™ Replicator® 2	0.273	**0.026**	0.084	0.144	**<0.001**	**0.007**	0.245	0.298	0.103
Lumbar Sample 1	Mojo™	0.536	0.188	0.076	0.668	0.147	0.508	0.185	0.135	**0.014**
	MakerBot™ Replicator® 2	0.111	0.174	0.065	0.641	0.781	0.174	0.289	0.210	**0.007**
Lumbar Sample 2	Mojo™	0.399	0.655	0.456	0.779	0.506	0.076	0.249	0.724	0.742
	MakerBot™ Replicator® 2	0.106	**0.028**	0.308	0.400	0.497	0.050	0.489	0.329	**0.028**

**p*-value<0.05 is considered significant; Bolded *p*-values are statistically significant

4.2 Formative Assessment (Spot Test)

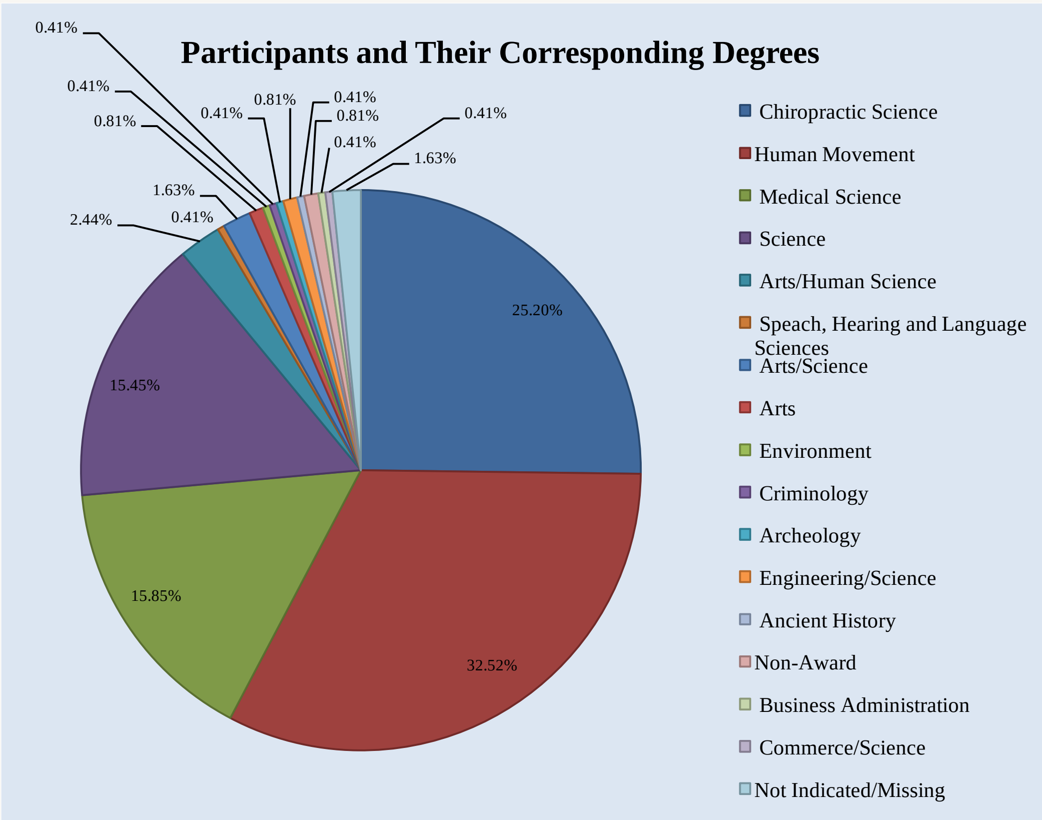


Figure 16: Study participants and their corresponding degree

The number of participants was 246, which makes up 71% of the total number of students enroled in anatomy course "*Anatomy of the Limbs and Back*". The diversity of participating students is evident (Figure 16). Approximately 58% (*N*=142) of the students were enroled in an undergraduate allied health program (Bachelor of Chiropractic Science and Bachelor of Human Movement), 30% (*N*=77) were in general science and medical science undergraduate programs, and 5% (*N*=13) were enroled in combined undergraduate degrees.

The overall percentage of correct answers in the spot test was 65%. Figures 17 and 18 show the performances of participants in the spot test. The average percentage of correctly identifying the cervical vertebrae was 78%, followed by the lumbar and the thoracic vertebrae (63% and 54%, respectively). The average total score of the test was 5.87 (SD=2.40) out of 9. Approximately 2% of participants (*N*=5) did not manage to identify any of the vertebrae correctly while 17% (*N*=40) identified one to three models correctly, 38% (*N*=94) managed to identify four to six models and 44% (*N*=107) correctly identified more than six models.

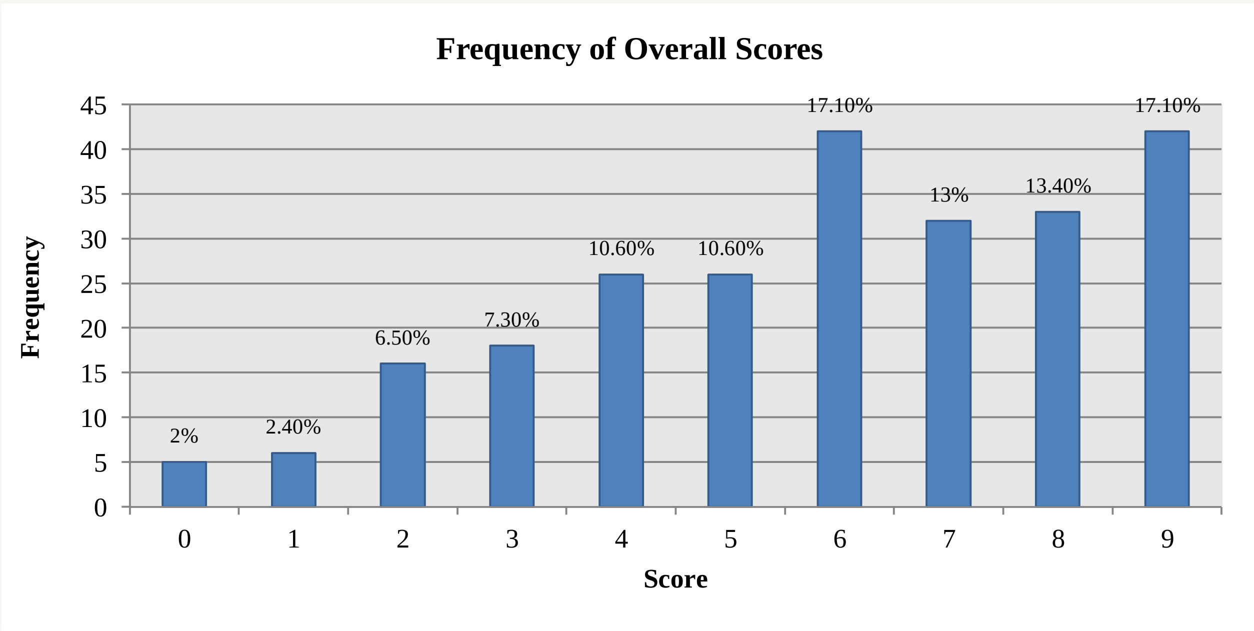


Figure 17: Frequency of overall scores of participants

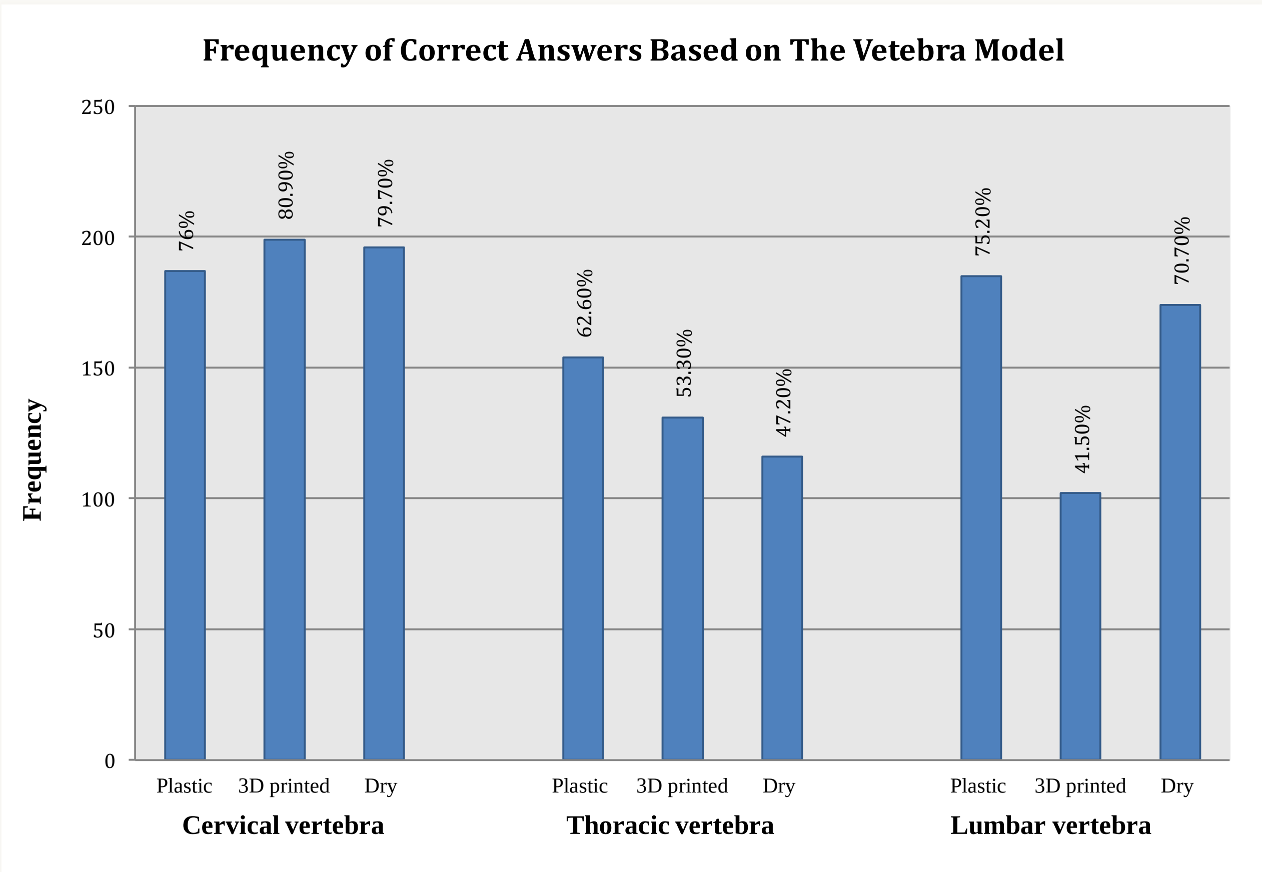


Figure 18: Frequency of correct answers based on the vertebra model

Table 4: Difference in performance between specific models

Vertebra	Model Type	Pearson χ^2-value	Significance (p-value)*
Cervical	Dry and 3D	0.116	0.734
	Dry and Plastic	0.955	0.329
	3D and Plastic	1.732	0.188
Thoracic	Dry and 3D	1.829	0.176
	Dry and Plastic	11.853	**0.001**
	3D and Plastic	4.412	**0.036**
Lumbar	Dry and 3D	42.783	**<0.001**
	Dry and Plastic	1.247	0.264
	3D and Plastic	57.608	**<0.001**

*p-value<0.05 is considered statistically significant; Bolded p-values are statistically significant

Analysis of the total average performance showed that students were capable of correctly identifying the plastic vertebrae (71.4%), followed by the dry (65.9%) and the 3D printed vertebrae (58.6%). In addition, analysis of correlation showed that performances across all vertebrae models were significantly correlated. Performance on the dry vertebrae showed a positive correlation with the 3D printed vertebrae (r=0.646) and the plastic vertebrae (r=0.515). Similarly, performance on the plastic and the 3D printed vertebrae showed a significantly positive correlation (r=0.463).

Table 4 shows the differences in performance across different vertebrae models. No significant results were observed in the performance between the dry vertebrae and the 3D printed vertebrae of the cervical and thoracic regions. However, significant results were present in the lumbar region between the dry vertebrae and the 3D printed vertebrae. In addition significant results were seen between the 3D and plastic vertebrae of the thoracic and lumbar regions, but not for the cervical. Lastly, a significant result was observed between the dry and the plastic vertebrae of the thoracic element, but neither to the lumbar nor the cervical region.

4.3 Questionnaire Results

The total number of responses collected for the survey was 368. According to gender, 49% of respondents indicated they were female (n=181), 40% were male (n=148), 1% indicated other (n=3) and 10% (n=36) left the response space blank or chose not to indicate gender. The population age as a whole was relatively young (figure 19). The average age of respondents was 19.95 (SD=3.90). 2% were under the age of 18 (n=8), 86% (n=317) were between the ages of 18 and 24, and 8% (n=28) were 25 year of age and older. Regarding ethnicity, 51% (n=189) of respondents were Australian, 23% (n=87) self-reported as Asian, and 5% (n=18) as European. With respect to religion, 56% (n=205) assented themselves into an organised religion and 29% (n=105) were atheists and agnostics (figure 20).

Overall, the support for 3D medical image donation was favoured by respondents compared to body donation (table 5). The averages of responses in both categories were consistently higher for support of a stranger donating their 3D medical images and donating their body (2.90 and 2.83. respectively). The averages of responses for supporting a family member donating their medical 3D images and donating whole body was 2.87 and 2.73, respectively. Lastly support for own 3D images and whole body (2.77 and 2.19 respectively) were least favoured compared to support for a family member or a stranger (2.77 for own 3D image donation and 2.19 for whole body donation).

Table 5: Frequency of responses for body donation and 3D image donation

	Yes	Undecided	No
Body Donation for:			
Own	42.7% (*N*=157)	32.6% (*N* =120)	23.9% (*N* =88)
Family	78.3% (*N*=288)	15.8% (*N* =58)	5.4% (*N* =20)
Stranger	85.3% (*N* =314)	11.7% (*N* =43)	2.4% (*N* =9)
3D Image Donation for:			
Own	81% (*N* =298)	13.6% (*N* =50)	4.9% (*N* =18)
Family	89.1% (*N* =328)	8.2% (*N* =30)	2.2% (*N* =8)
Stranger	90.8% (*N* =334)	7.3% (*N* =27)	1.4% (*N* =5)

*1=No, 2=Undecided and 3=Yes

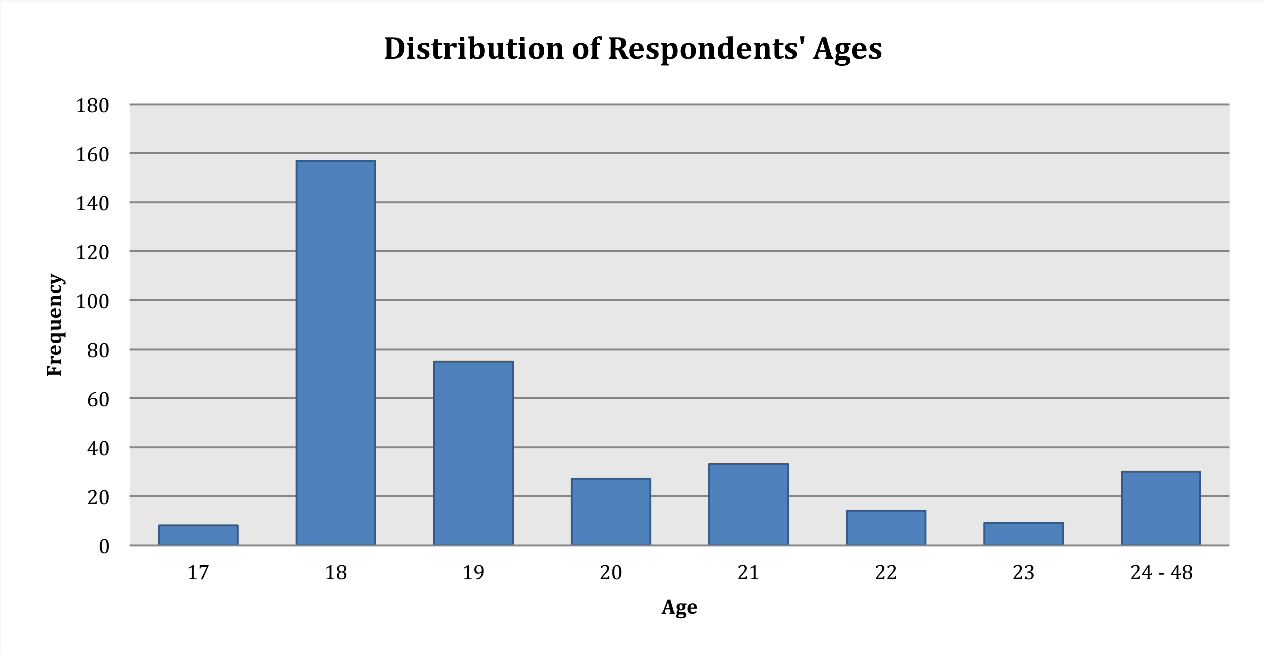


Figure 19: Distribution of respondents' ages

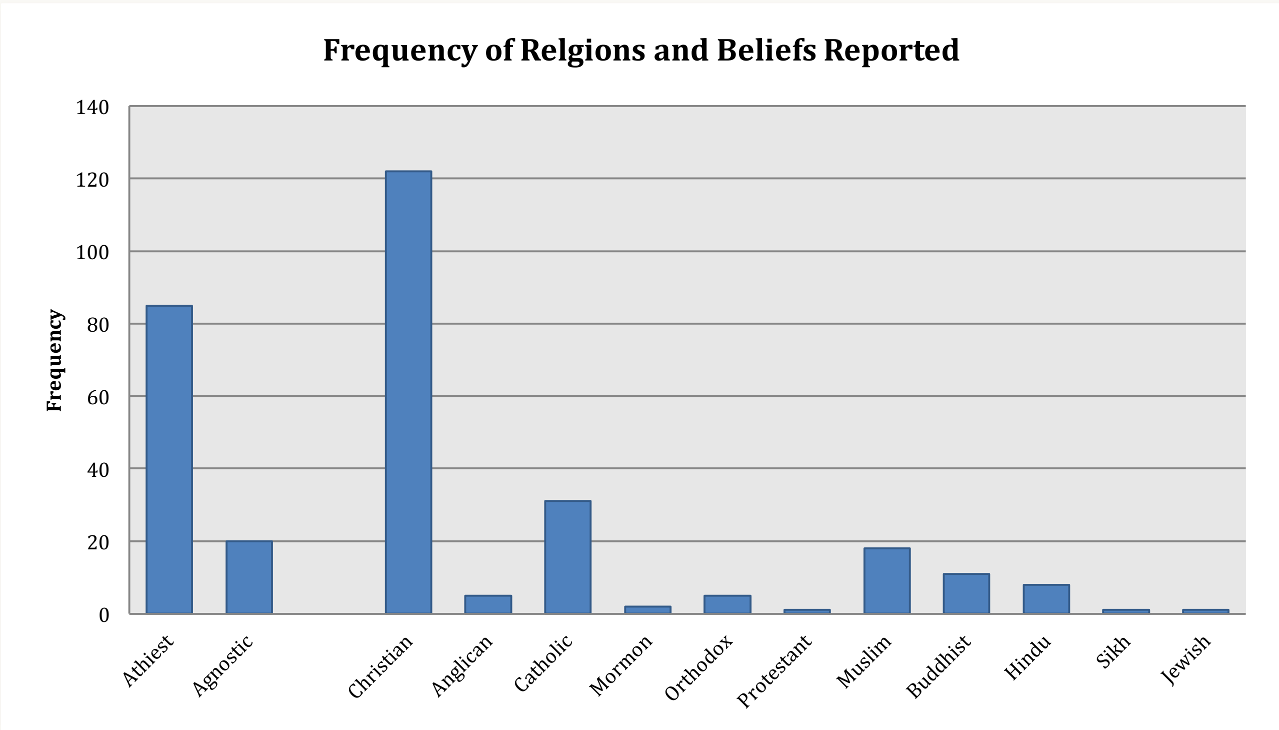


Figure 20: frequency of religions and beliefs as reported by respondents

Figures 21(a-c): Reasons stated by respondents for choices made

Figures 21(a-c) show the reasons stated by respondents for body donation compared to 3D medical images donation. Approximately 75% of respondents, who are in support of own 3D image donation, indicated the main reason for donating was to help education and research in science and medicine. The observed was slightly less in own body donation for the same reason, where approximately 40% of respondents who are in support of whole body donation indicated that they are willing to do so to help research and education in science and medicine. Another motive for donating one's own body was justified by wanting to feel useful after death (18.20%). Religious reasons were less of a motive when it came to both aspects of own donation. 0.80% for indicated they are in support of donating their own body for religious reasons and 1.40% indicated the same reason for 3D image donation.

Religious reasons showed a slightly higher number of responses when it came to rejecting both aspects of donations (6.80% for body donation and 3.30% for 3D image donation). Concern for respect was the main reason for not supporting own body donation (6.80%) Reasons for being undecided about body donation were the individual being either uninformed (16.30%) or undecided about donating (18.50%).

Table 6: Pearson's χ^2-test of body donation compared to 3D image donation

Body donation vs. 3D image donation	Sample Size (*N*)	χ^2- value	*p*-value*
Own	365	118.743	**<0.001**
Family	366	16.650	**<0.001**
Stranger		5.417	0.067

**p*-value<0.05 is considered statistically significant; Bolded *p*-values are statistically significant

Support for donating medical 3D images compared to whole body donation was consistently high and notably significant in all two groups (Table 6). Statistically significant results were observed for individuals donating their own body for anatomical education and research. Respondents also showed greater support for family members donating their 3D medical images compared to their bodies for anatomical education and research. However, no significant results were observed in participants response in supporting a stranger donating their 3D medical images compared to donating their body for anatomical research and education.

Table 7: Pearson's χ^2-test for of religion's effect on body donation 3D image donations

Religiosity	Body donation vs. 3D image donation	χ^2-value	Sample Size (N)	p-value*
Religious	Own	29.529	203	**<0.001**
	Family	13.344	204	**0.001**
	Stranger	5.485		0.064
Non-Religious	Own	41.514	105	**<0.001**
	Family	2.979		0.225
	Stranger	1.233		0.540

*p-value<0.05 is considered statistically significant; Bolded values are statistically significant

Table 8: Regression analysis of the religion's effect on body and 3D image donations

	Body Donation			3D Image Donation		
	Own	Family	Stranger	Own	Family	Stranger
Regression coefficient (β)	-0.279	-0.148	-0.0122	-0.146	-0.039	-0.030
R-squared value (R^2)	0.078	0.022	0.015	0.021	0.002	0.001
Significance (p-value)*	**<0.001**	**0.009**	**0.032**	**0.010**	0.494	0.600

*p-value<0.05 is considered statistically significant; Bolded values are statistically significant

The same pattern is noted with respect to the effect on religion on the decisions made (table 7). Individuals who affiliated themselves with an organised religion showed significantly more support for donating one's own 3D medial images compared to whole body. Non-religious individuals (i.e. atheists and agnostics) also showed more support towards donating own 3D images compared to own body. Religious individuals showed significant support towards a family member donating their medical images. However, non-religious respondent did not differ in their level of support towards a family member donating either their body or 3D image. Both groups showed greater support for strangers donating their 3D medical images compared to their bodies.

Simple linear regression analyses were used to test if religion predicted the decisions of the study participants. It was found that religion significantly predicted the person's choice in donating one's own body, as well as the decision to support to a family member or a stranger in doing so (table 8). Therefore, individuals who belonged to an organised religion were less likely to support body donation, for own and for family members or strangers. The same trend was seen in donating one's own 3D medical images. However, it was found that religion did not significantly predict support for a family member or a stranger donating their 3D medical images.

Table 9: Pearson's χ^2-test for ethnicity's effect on body and 3D medical image donations

Ethnicity	Body donation vs. 3D image donation	χ^2-value	Sample Size (*N*)	*p*-value*
Australian	Own	51.589	189	**<0.001**
	Family	6.159		**0.046**
	Stranger	1.990		0.370
Asian	Own	29.265	85	**<0.001**
	Family	7.870		**0.020**
	Stranger	3.269		0.195
European	Own	3.600	18	**<0.001**
	Family	7.200		0.289
	Stranger	1.596		0.2064

*p-value<0.05 is considered statistically significant; Bolded values are statistically significant

Table 10: Regression analysis of ethnicity's effect on body and 3D image donations

		Body Donation			3D Image Donation		
Australian profile vs.		Own	Family	Stranger	Own	Family	Stranger
Asian	Regression coefficient (β)	-0.182	-0.351	-0.266	-0.138	-0.271	-0.218
	R-squared value (R^2)	0.023	0.104	0.062	0.020	0.067	0.044
	Significance (p-value)*	**0.002**	**<0.001**	**<0.001**	**0.020**	**<0.001**	**<0.001**
European	Regression coefficient (β)	-0.189	-0.177	-0.101	0.150	-0.066	-0.045
	R-squared value (R^2)	0.058	0.134	0.072	0.020	0.072	0.046
	Significance (p-value)*	**0.001**	**0.002**	**0.081**	0.794	0.253	0.444

*p-value<0.05 is considered statistically significant; Bolded values are statistically significant

Regarding ethnicity, respondents were grouped into the largest and most meaningful categories. These were Australian, Asian and European. Australian and Asian individuals showed statistically significant results when it came to body donation and 3D image donation. They were more likely to support donating their own images and were more willing to support a family member in doing so. All ethnicities showed no differences in response when it comes to supporting a stranger donating their 3D images or their body (table 9).

Australian ethnicity and national identification was used as a base line measure for regression analysis to compare with Asians and Europeans as the dummy coded variables (table 10). Statistically significant results were observed in the Asian and European ethnicities when compared to Australians; Australians being more likely to support body donation in general compared to Asians and Europeans.

4.4 Summary

Relative assessment of accuracy found an absolute dimensional error of 0.188mm of 3D printed vertebrae when compared to the dry vertebrae. Furthermore, there is no significant difference between the dry vertebrae and the 3D printed ones, except in few parameters. Preliminary results indicate that the 3D printed vertebrae are relatively accurate and are sufficient for use in anatomy education.

Furthermore, assessment on the practicality of the 3D printed models found a difference in the student's performance. A statistically significant difference was found between the 3D printed lumbar vertebra and the dry vertebra with respect to students' performance; students were able to identify the dry model as a lumbar vertebra but not the 3D printed model. No reported statistical significance in the performance between identifying the 3D printed and the dry cervical and thoracic vertebrae.

Results from the survey showed that students are more willing and support 3D image donation compared to body donation. Furthermore, results showed that both religion and ethnicity predicted the population's decision. Thus, religious individuals were less likely to donate in their body for dissection compared to non-religious individuals. In addition, regression analysis results indicated that Asians are less likely to support 3D medical images donation and body donation when compared to Australians. Europeans were in favour of donating 3D medical images, similar to Australians.

5. Discussion

Chapter five will discuss the findings and results of the project in three parts. Discussion will begin with by addressing the results of the accuracy assessment of the 3D printed vertebrae. The second part of the chapter will review the results of the spot test. The final part of the discussion will explore the results of the questionnaire on the attitudes of students towards 3D medical images donation compared to whole body donation.

5.1 Accuracy Assessment Discussion

The aim of this part of the project was to assess the accuracy of the 3D printed vertebrae to establish if the level of precision in printing is adequate for the needs of efficient anatomy teaching. Overall, the 3D printed vertebrae produced in the present study are accurate with few statistically significant results observed in pedicles heights, spinous processes lengths and bi-transverse processes lengths. The overall appearances of the 3D printed vertebrae when compared to the dry vertebrae are identical. The 3D printed vertebrae tend to show morphological landmarks and features similar to the ones seen on the dry vertebrae. Thus, based on these observations, the 3D printed vertebrae are adequate for utilisation in anatomy education.

The results of this study are supported by a current study in the literature. Ogden *et al*. assessed the dimensional accuracy of 3D printed vertebrae compared to dissected specimens vertebrae (106). The authors reported an overall accuracy in the 3D printed vertebrae, with statistically significant results in the anterior body height and pedicles height measurements, when compared to the real vertebrae. Several studies looking at 3D printed skulls and mandibles reported significant differences in certain measurements but report an overall accuracy of the 3D printed models (110, 116-118). A study by Frame and Huntley reported that no statistically significant differences existed between their 3D printed models and the original CT scans (63). The 3D printed models were a radius and an ulna bones. Indeed, both bones are simple shaped and structurally less complex compared to the bones of the vertebral column and the skull that contain more convoluted surfaces with complex geometrical landmarks such as intricate projections and smaller foramina. Therefore, there is a relationship between the structural complexity of the 3D printed anatomical model and its dimensional accuracy. Thus, the more structurally complex the 3D model is, the more likely it is for dimensional errors to be present.

A high degree of linear dimensional accuracy is not particularly very necessary for anatomy education; given most anatomical models contain the basic morphological features of anatomical structures. Accuracy is, however, a crucial factor in medicine. Medical models manufacturing accuracy has not been explored sufficiently (118). Because 3D anatomical models are also used in preoperative planning, surgical simulators and implant manufacturing, dire consequences may occur if the 3D printed models or implants are not accurate (118). The main factors that determine the accuracy of the 3D printed models are the manufacturing steps themselves, which are reported to be sources of errors (119), derived mainly from the image acquisition and processing steps (106).

The majority of the studies utilised 3D medical imaging data from CT and MRI scans to produce 3D anatomical models (106, 119-122). Studies that utilise surface scanners are scarce (50). Indeed, the main advantage of the medical imaging procedure is capturing the internal detail of the structure being scanned. However, the handheld scanner used in this study is relatively cheaper than the sophisticated medical imaging equipment. In addition, it eliminates exposure to radiation. Being handheld in nature, however, it may have contributed to the geometrical inaccuracies of the produced models (50). Furthermore, the image-processing step is also a source of error. In the present study, the obtained scans were aligned using the native software Artec Studio. Choosing the points of alignment on the scans is a manual step. Therefore, precise alignment is hindered if the points of alignment on the scans are not chosen appropriately. Appropriately aligning the scans and obtaining sufficient number of scans are equally important to reduce the number of encountered errors.

With respect to the 3D printed vertebrae in the present study, they do not show observable signs of surface defects, except at sites where manual removal of the support material was required for the 3D printed vertebrae on the MakerBot™ Replicator® 2 3D printer. In addition, the results of the accuracy assessment of the 3D printed vertebrae in the present study showed an overestimation of dimensions in some measurements, but with no particular observable trend. Some studies reported on overestimation and increased global errors at areas of curvature on the 3D printed models (119, 123). The observations reported are consistent with the findings of the present study where significant results were observed in the pedicles height measurements of the 3D printed vertebrae when compared to the dry ones, which explains the presence of error in this measurement. In the present study, the 3D printed vertebrae were all produced at a “High” quality setting with 0.1 mm layer thickness. It is reported that increasing the layer thickness increases the global error and overestimation (123). Thus choosing a “High” quality setting for 3D printing process reduces layer thickness and in turn reduces dimensional overestimation.

With respect to the manufacturing process itself, the 3D printer and materials used can be a source of error. Physical and chemical properties of heating and deposition and how it reacts to the ambient temperature by contraction or expansion may explain some of the geometrical inaccuracies and coarse spatial resolution (121, 122). Furthermore, anecdotal evidence shows that 3D printing the same 3D image with the same 3D printer multiple times will show inconsistent results. Further research is warranted regarding accuracy and reliability of 3D printers and materials used.

Quantitative evaluation of measurements of 3D printed models using digital and Vernier callipers was reported in the literature (27, 106, 110, 120, 124). In addition, it was reported that structures above 10 mm were accurate in size. However, errors in the measurements increased when structures were below 10 mm (27). This may be due to the measuring instrument itself having relatively larger errors when measuring smaller structures. In addition, the measurement technique may qualify as an additional contributor to error, which may also explain the significant results in the present study. This can be overcome by performing multiple measurements by one (106, 110) or many observers (120) to reduce intra-observer and inter-observer errors, respectively. In addition, When measuring anatomic points in the human body it is difficult to allocate an exact measuring point and difficult to determine with commonly used measuring equipment (118). Currently, there is no reported gold standard for the accuracy measurements of medical models (118). Further research is warranted to develop standardised methods for measuring and validating anatomical models (118).

5.2 Formative Assessment (Spot Test) Discussion

The working hypothesis of this part of the project stated that the student performance in an anatomy spot test situation would be the same on the 3D models compared to the dry and high quality plastic models. Although basic in nature, this study was one of the first preliminary studies to compare performances between three different physical 3D models. In the present study three types of 3D physical models were utilised in a formative spot test. Two of these models (i.e. dry vertebrae and plastic modelled vertebrae) are commonly used in anatomy education and have been utilised as teaching resources in the anatomy courses at Macquarie University. 3D printed vertebrae were utilised for the first time in a formative practical examination on a volunteered sample of first year anatomy students at Macquarie University.

In particular, results showed significance in performance difference between the dry and the 3D lumbar vertebrae, with the students readily identifying the dry and plastic lumbar vertebra compared to the 3D printed one. No significant difference in the performance was observed between the dry and the 3D printed vertebrae with respect to the cervical and thoracic regions.

Perhaps the reason for the significance in the performance relevant to the lumbar vertebrae was because of the size difference of the vertebrae models used. Both the plastic lumbar vertebra and the dry lumbar vertebra that were used in the anatomy assessment were relatively larger in size than the 3D printed one. This explains why students readily recognised the plastic vertebra and the dry vertebra as belonging to the lumbar region and found difficulty in recognising the 3D printed lumbar vertebra. The difference in performance may also be explained by that fact that students rely on the simplicity of the plastic models (which is disadvantageous) rather than looking at the morphological features.

Few studies reported using an assessment procedure similar to the one used in this study. Myer *et al*. compared two assessment modalities and how they affected student performance (125). The authors compared the traditional spot test approach to an online version of the test. It was concluded that the assessment method did not influence performance. This is because cognitive processes were similar between students when viewing the examinable specimens on screen or during traditional spot test (111, 125). A study in the field of veterinary anatomy reported on the advantages observed from utilising 3D printed physical models in a formative assessment compared with other teaching methods: textbooks and 3D computer model (93). Students who revised using the 3D printed model scored higher results in the formative test. Also students who utilised the physical model showed a significant confidence in identifying the structures compared to the other groups.

Students were allowed to touch the vertebrae models during the test. This allowed them to receive visual and haptic feedback from all dimensions on the structure. This sort of hands-on approach can be effective with learning complex 3D anatomy. A study by Estevez *et al*. reported a positive relationship between manipulating a physical model in space with the formation of an internal mental model, which would allow easy recognition of the model and surface structures (126). This may not be the significantly related to the present study due to its basic nature and easy difficulty of the assessment question. However, the concepts can be assessed with respect to 3D printed models in a more comprehensive assessment.

Traditional anatomical models are viewed as excellent teaching resources for anatomy (4, 11) There is, however, a noticeable lack in the pragmatic evidence relating to their efficacy (127). Majority of the studies that utilised or manufactured a 3D printed anatomical specimen did not objectively assess the practicality or the efficacy of the produced models (See Chapter 2). Therefore the incorporation of the 3D printed models should be encouraged, and their assessment could also incorporate student feedback rather than just spot tests.

One of the main limitations in the present study is the basic nature the assessment. The spot test had only one question, "To which region of the vertebral column does the vertebra shown belong to?". Although the question was very basic, it did give insight into the student's ability to retain such basic knowledge. Furthermore, the 3D printed vertebrae were to shown to be accurate in the previous part of this project. Therefore, further research is warranted with respect to assessing morphological features of the vertebrae and other 3D printed models to further validate the efficacy of 3D printed anatomical models.

Furthermore, the formative test was unannounced to students. It was run in concurrence with their regular weekly anatomy laboratory session. In addition, students were exposed to vertebrae in the previous course "Introduction to Anatomy", where they were taught the regional differences of vertebrae using primarily plastic models. Therefore students had to rely almost completely on memory to retain relevant knowledge from the previous semester on vertebrae. Indeed, individuals vary when it comes to retaining information. This process does not only rely on memory recall, but on the student's learning approach and cognition (125). An important concept to note as well is that the variability of visuospatial capabilities fluctuates between individuals. Since it is important in learning anatomy, it may affect the student's performance in assessments (128).

With respect to anatomy assessment tools in general, no golden rule, type of assessment instrument or specific format is reported in measuring all anatomical educational objectives (9, 129). The spot or spotter test as an assessment tool has been used traditionally as an anatomy assessment tool. Compared with other traditional assessments (oral or multiple choice question assessments), the spot test can prove to be more practical in the fact that it emphasises assessment of visual recognition and spatial knowledge (13). However, the major disadvantage that stems from such assessment is the "negative steering effect" where rote memorisation and recall of knowledge is consistently required by the examined individuals (113). Perhaps the nature of the study permitted the use of the spot test.

5.3 Questionnaire Discussion

The aim of this part of the project was to investigate the attitudes of anatomy students towards the donation of 3D medical images for the purposes of 3D printing of anatomical models. The responses were contrasted to the attitudes of the same group to whole body donation. It was found that respondents were more in favour of donating 3D medical images for anatomical research and education compared to whole body donation. In addition, the students supported a family member or a stranger in donating their 3D medical images was also more likely compared to whole body donation. These preliminary findings of the present study corroborate the original hypothesis of this part of the project.

Although the literature is abundant with studies that look at the attitudes towards whole body donation (55-57, 130-132), it appears that the present study is the first to investigate the attitudes of a section of the general population towards medical images donation for the purposes of 3D printing and anatomical education. Indeed, issues pertaining to acquiring such images (both from living individuals and cadavers) and the permission to 3D print them remain a legally and ethically undefined area (51). Therefore, insight into the attitudes towards 3D image donation for the purposes of 3D printing and anatomy education might help shed some light on relevant issues.

The results of the present study showed an overwhelming support towards donating 3D medical images compared to body donation. Respondents even showed greater support when it came to a family member or a stranger donating their medical images compared to body donation. This may be explained by the fact that body donation in its own, is rather a sensitive topic that has a potential emotional impact on the individual because of its association with death (133). Body donations is also important because it is where “boundaries and ethnic identity takes on special significance” (134). Many factors have been proposed to influence people’s opinions towards body donation, including age, religion, culture, personality characteristics, views on death and mortality, body image, and humanitarian concerns (135).

The most common stated reasons for support of donating 3D images and whole body were helping education and research in science and medicine. Consistent with the findings of the current study, these reasons were frequently encountered in other studies that assessed the attitudes towards body donation (58, 59, 133). Wanting to feel useful after death was another reason frequently associated with body donation in the present study and in other studies as well (17, 58, 59). Some of the respondents reported answers in the current study stating support for body donation, which can be summarized as follows: they do not need the body and that they do not have any use or need for it anymore, so therefore, why not donate. A similar finding was reported by Richardson and Brian in a UK survey, where 39% of their surveyed respondents indicated that the body is just an organic waste and 10% reported no significance for the body after death (133).

Although some of the aforementioned responses for donating one’s body are both humane and altruistic in nature, not everyone qualifies for body donation. There are factors that may render the body unacceptable as a “silent virtuous teacher” (131). Some of the reasons for rejecting a cadaver include autopsied and decomposed bodies, extremely obese or extremely emaciated bodies and the presence of infectious of communicable diseases in the cadaver (16, 55). While the former may not directly be applicable to image donation, it may be of relevance where individuals (both diseased and healthy) are given a better chance at donating their images to be 3D printed for anatomical education and research.

In addition, while the literature is void of studies relevant to this area, some of the respondents indicate interesting reasons for supporting the idea behind it. One respondent indicated the “the chance to be immortalised and help others” as the main reason. Another had a future outlook, where their main reason to donate would be “when 3D [printed] organs become acceptable replicas for persons in need”. Furthermore, 3D image donation would enable the 3D printing of certain anatomies that would otherwise be problematic to be exposed to or to acquire, such as viewing the pathological process of an organ or a body part. Such exposure may prove to be of great health risk. However, 3D printed anatomical model representing such pathology removes the health risk factor out of the equation.

Many reasons were reported by respondents justifying the unwillingness to either donate whole body or to donate medical images. Religious reasons were amongst the top stated reasons in the present study for lack of support of both components of donating. The results of the present study indicated that individuals who belonged to an organized religion were less likely to support body and 3D image body donation compared to non-religious persons.

While the influences of religion and culture may not seem to affect body donation in many of the Western world regions (58, 130, 136), Australia is rather a multi-cultural society. According to the Australian Bureau of Statistics (ABS) 2011 census, as cited in Alexander *et al*., 7.2% of the total population of Australia belong to a non-Christian faith, while 22% report no religion, and 26% were born overseas (56). In addition, the same consensus showed that 28% of higher education students (universities and colleges) in Australia are international students (56). These figures show the great diversity among Australian university students, which in turn may explain our study results with respect to religious influence on the two aspects of donations. Comparable results were observed in Alexander *et al*. survey of Australian chiropractic students with respect to the influence of religion and to an extent, culture, on the unwillingness of individuals to donate their body (56). Similar conclusions were also reported in studies from Libya, Turkey, Italy, Greece and India (134, 137-

140). What these studies have in common is that they all report on the strong influences of both religion and culture on the individuals in these societies when in it comes to body donation (136).

Relevant to the discussion, it is argued that major religions either both approve of and take a positive stance on body donation, or have at least a neutral, undefined stance (55, 58, 141). In the present study, very few people indicated that the main motive for donating either their body or medical images was for religious reasons. Despite this, the main conclusions derived from this study and other relevant studies indicate a strong relationship between the "religiosity" of the individual and the unwillingness to donate (58). Thus the decision of an individual not to donate could be based on the assumption or limited knowledge that his/her belief does not approve of body donation or image donation (55).

An important reason for the unwillingness to donate was the concern that the donated body will not be respected. It cannot be denied from anatomists and medical professionals that mistreatments have been either reported or witnessed, considering such fears also exist in the general and the professional population (17, 133). In addition, professionals often expressed in these studies the anxiety of potential disrespect from students as a reason for not donating (17, 139). However, the nature of this disrespect was not addressed in the studies and still remains elusive. Fear of being dissected in general was also indicated by medical professionals in other studies (17). In the present study, 2.7% of individuals who said no to body donation or were undecided about it stated similar fear and anxiety about "being cut open".

Some students expressed their unwillingness to donate because they were uninformed about body donation, but less so for 3D medical image donation. Others took a neutral stance because they never thought about body donation or 3D medical image donation. Studies looking into the awareness of individuals about body donation reported on similar findings to the present study. Alashek *et al*. reports lack of awareness of 43.8% of their study respondents, making them undecided in their decision (140). Rockade and Gaikawad observed similar results in their study where 66.9% of respondents of the general population were not aware of body donation (17). Sehirli *et al* concluded a combination of lack of awareness with a lack of religious knowledge to justify donating were the main reasons for being undecided about donating (139). This trend seems to be less evident in places where cultural norms and religious influences do not predominate.

The roles the media plays and the powers of advertisement both have an influence on informing individuals about body donation. Cornwall *et al*. reports that individuals in their study knew about body donation a decade before registering (58). In the Netherlands, donation to science is flagged as a third option (after burial and cremation) for body disposal in the Burial and Cremation Act (136). Nowadays, many institutions even hold memorial ceremonies to honour those who donated their bodies for anatomy and to raise awareness about the importance of body donation (131, 142, 143). Other reported sources from which awareness was raised and obtained include the television documentaries and Internet (58), printed literature (59) and celebrity publicity (131).

No significant correlation was observed between age and body donation in the current study. However, there was positive correlation between age and own image donation. Similar results were reported with respect to body donation in Nigeria, where there was no significance between age and body donation (144). In other studies, younger age groups were reported to be more inclined towards willingness to donate their bodies (16, 17, 140). A study from Greece reported that younger aged individuals were less likely to donate their bodies (137). The reason for the observed results in the current study is because the surveyed sample distribution is relatively young. Furthermore, a possible reason for the variety of results observed is that age may be influenced by other outweighing factors, such as educational experiences (57, 145) and level of knowledge (139, 140).

Our surveyed population was undergraduate university students. Most of them have completed secondary school education or equivalent. Therefore, the surveyed students are assumed to have the same educational level. Although it may not be possible to draw conclusions on body donation and image donation from the level of education of the study's respondents (134), it is a common agreed on finding that education level significantly influences the willingness to donate. Thus highly educated persons are more likely to donate compared to minimally educated or uneducated persons (16, 58, 137). Additionally, students in previous studies were reported to be more inclined to donation compared to others (140). The reasons for such observations are because the educated groups are open to change; more inclined towards free modes of thinking and are therefore more receptive to modern ideas (17). In addition, the influence of religion and old traditions to an extent diminishes amongst highly educated persons (56).

An interesting trend with respect to ethnicity was observed from the present study. In the current study, Australians were more willing to support both aspects of donations than the other ethnicities studied. Asian individuals were less likely to support both body donation and 3D medical image donation in all aspects compared to baseline Australian individuals. Similarly, European individuals showed less support to body donation, but a less conservative stance when it came to 3D medical image donation. Supporting these findings with respect to body donation is the study by Alexander *et al*. on Australian chiropractic students (56). The authors concluded that both Europeans and Asians were less likely support body donation compared to Australians. Although these results may be opposed by Halou *et al*., where they found no statistically significant results between ethnicity and body donation (137).

Cornwall *et al*. assessed the ethnic profiles of body donors in South Africa, Ireland and New Zealand (58). South Africa was reported to be statistically significant with respect to ethnicity, where 5% of "peoples" were of "black" or "coloured", compared to 95% "whites". Interestingly, Boulware *et al*. reported that older aged African-American persons were 60% less willing to donate (16). However, these figures are influenced and further complicated by other factors. Reliance on unclaimed cadavers for teaching has been reported from multiple schools in Africa, and is still a common practice, which was reported to negatively influence the decision to donate (146). Furthermore, survey respondents in Boulware *et al*. study stated certain discriminatory issues in health care settings, which may also influence the degree to which the person feels about donating their body (16, 56).

With respect to the Asian ethnic profile, there is an undeniable interplay between cultural, societal and religious perspectives. It is worth noting that in Asia, there is an extremely wide variation in the aforementioned factors and perspectives between individual countries (147). Thus, this diversity should be taken into thought when possible discussion points are made.

In the literature it has been shown that Asians are generally unwilling to donate compared to other ethnic profiles (147). The beliefs of many Asian individuals in Asia and to an extent, around the world, are closely related to or indirecrly influenced by principles from Confucianism (131). Benevolence, courtesy and most importantly filial piety, are amongst the fundamental values in Confucianism (131). This explains the significance in results, not just for body donation, but also for 3D image donation in the present study. Furthermore, Confucianism places particular emphasis on the integrity and maintenance of the human body. Therefore, most respondents would justify the reason for the unwillingness to donate whole body or organs because of the importance of the maintenance of an intact body for respect towards ancestors and nature (143). However, Chen *et al*. found that university students were more willing to donate their organs (143). This corroborates the finding stated earlier that higher education and knowledge levels are associated with positive attitudes towards donation in general.

The present study has several limitations. The analysed sample was a subsection of the general population (i.e. undergraduate anatomy students) who were considerably at a young age (19.95±3.90). Thus the results from this study should not be generalised. A diversified sample population would definitely add significant value to the research.

With regards to both ethnicity and religion, no appropriate categories were predefined for respondents to select from but rather respondents were allowed to self-report. Ethnicity has been a long debated topic in anthropology (148). A classic review by Isajiw looked at 65 studies on ethnicity in the fields of sociology and anthropology, only 13 gave definition to the term (149). Perhaps leaving the question open for respondents gave them the chance to freely affiliate themselves with the ethnic identity that was most meaningful to them. This may have led to some inconsistency in the present study. As a result, the “Asian” group consisted only of 85 persons and the ”European” group consisted only of 18. Minority groups and people who indicated dual, triple or even quadruple “ethnicities” were excluded from the analysis.

Furthermore, in this study, ethnicity may have gotten caught in “cross-fire” with nationalistic identity and race. Ethnicity in its most basic forms, refers to “the social reproduction of basic classificatory differences between categories of people and to aspects of gain and loss in social interaction” and involves multitude of interactions of sociocultural phenomena (150). Nationalistic profile, derived from nationalism, is rather political in nature is based on the ‘nationality’ profile of the individual (151). Race is rather a broad, elusive term, not only in anthropology, but does not have scientific validity and is not a dichotomous variable, which really affects the objectivity of the inquiry (152). These concepts should be established well before questionnaire design. A good solution would be pre-categorising these profiles in the survey before distribution.

The religions variable had also few limitations. Similar to ethnicity it was left free for individuals to self-report. Some respondents indicated dual religions or belief systems, which contradicted one another. Thus, when the effect of religion on body and 3D medical image donations was analysed, these groups were excluded from the sample due to their contradictory reporting. Furthermore, in the present study, individuals who affiliated themselves to an organized religion were placed in one category and those who indicated being atheist, agnostic and having no religious affiliation were placed in one category. Although this facilitated the statistical analyses, it resulted in some inconsistencies. To elaborate, most major religions consist of more than one branch. Christianity’s three main branches (Catholicism, Protestantism and Orthodox) support and encourage body donations. Other groups (Assemblies of God, Mennonites, and Mormons) have no official policy about the topic, and as a result affiliated individuals are left confused about what to do (141). Similar findings were reported about Islam, where the religion supports donation, but unanimous decision tends to be absent, resulting in confusion (16, 139, 140). The same concepts are seen with respect to Judaism, Buddhism, Sikhism and Hinduism where branched within have either positive, neutral or negative stance about body donation (153).

5.4 Summary

The discussion chapter analysed the findings from the three parts of the project. The accuracy of the 3D printed vertebrae models were reported to be adequate for the utilization in anatomy education. In addition, observed errors from dimensional measurements were not sufficient to cause major disruption to the overall appearance of the 3D printed vertebrae or affect the morphological landmarks of the models. Overestimation was commonly observed in 3D printed models, which was due to the manufacturing process itself; the 3D printer quality and accuracy and the type of material used for manufacturing. Other sources of errors in that may have contributed to the accuracy of the 3D printed models were errors in scanning procedure, image processing and the measuring techniques.

The 3D printed vertebrae were successfully applied in a practical formative (spot test) assessment. Students rather rely on the simplicity of the structure allocated, which is a typical characteristic of the plastic anatomical models. Furthermore, students were primarily exposed to plastic specimens in their introductory anatomy course. This explains why plastic models outperformed the other physical models. Overlying on plastic models could potentially steer the student in the wrong direction with respect to their realistic accuracy and how well these models demonstrate the anatomical structures.

Lastly, the attitudes of a section of the population (i.e. students) were positive towards 3D medical images donation compared to whole body donation. Indeed, there are many factors that influence these decisions such as religion and ethnicity. The concept of 3D image donation has been coined for the purposes of this study. Issues pertaining to acquiring such images (both from living individuals and cadavers) and the permission to 3D print them remain a legally and ethically undefined area warranting further research.

6. Conclusion

The thesis investigated the application of 3D printing in anatomy education. Previous studies looked at the aspects of accuracy and potential usefulness of such innovation. However, scarce practical application was reported on the efficacy of 3D printed anatomical models.

The aims of the project were to objectively apply 3D printing in anatomy education. In addition, the project looked at an elusive area with respect to 3D medical images donation for the purposes of 3D printing anatomical models. The aims were accomplished by first assessing the accuracy of the 3D printed models. These models were then practically applied in a formative anatomy assessment (spot test). In addition, attitudes and willingness of students to donate 3D images of their body and body parts were contrasted to whole body donation of the same population.

The main findings from this project were:

1. 3D printed vertebrae can be 3D printed with the current technological capabilities. In addition, the ability of the 3D printer to print complex bones (i.e. vertebrae) accurately means that basic bones would also 3D print with brilliant accuracy as well.
2. No significant differences in the overall performance of students in the formative anatomy assessment when comparing 3D printed vertebrae to the dry or plastic vertebrae. 3D printed anatomical models can be utilised in teaching and as an assessment tool in anatomy
3. Students showed more willingness to donate 3D medical images for anatomy education and for the purposes of 3D printing of anatomical models, compared to whole body donation.

The findings from this project are preliminary in nature, which will open doors for future comprehensive research potentials. Research is further warranted in the areas of accuracy assessment of 3D printed anatomy models. This should incorporate various 3D printers and different materials, in addition to finding the most suitable measurement guidelines and tools. Furthermore, an objective assessment of 3D printed models is further warranted by conducting such assessment on larger and diverse samples of both students and academics, and utilising various 3D printed anatomical models. With respect to the attitudes towards image donation, research should be directed at expanding the diversity of the sample population and further explore the ethics involved with incorporating 3D printing in medical and allied health fields.

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Appendix A – Ethics approval for the project

MACQUARIE UNIVERSITY

Dear A/Prof Strkalj

RE: Ethics project entitled: "The Application of 3D Printing Technology in Anatomy Education"

Ref number: 5201500362

The Faculty of Science Human Research Ethics Sub-Committee has reviewed your application and granted final approval, effective 12 June 2015. You may now commence your research.

This research meets the requirements of the National Statement on Ethical Conduct in Human Research (2007). The National Statement is available at the following web site:

http://www.nhmrc.gov.au/_files_nhmrc/publications/attachments/e72.pdf.

The following personnel are authorised to conduct this research:

A/Prof Goran Strkalj
Mr Yousef Abou Hashem
Manisha R. Dayal

NB. STUDENTS: IT IS YOUR RESPONSIBILITY TO KEEP A COPY OF THIS APPROVAL EMAIL TO SUBMIT WITH YOUR THESIS.

Please note the following standard requirements of approval:

1. The approval of this project is conditional upon your continuing compliance with the National Statement on Ethical Conduct in Human Research (2007).

2. Approval will be for a period of five (5) years subject to the provision of annual reports.

Progress Report 1 Due: 12 June 2016
Progress Report 2 Due: 12 June 2017
Progress Report 3 Due: 12 June 2018
Progress Report 4 Due: 12 June 2019
Final Report Due: 12 June 2020

NB. If you complete the work earlier than you had planned you must submit a Final Report as soon as the work is completed. If the project has been discontinued or not commenced for any reason, you are also required to submit a Final Report for the project.

Progress reports and Final Reports are available at the following website:

http://www.research.mq.edu.au/for/researchers/how_to_obtain_ethics_approval/human_research_ethics/forms

3. If the project has run for more than five (5) years you cannot renew approval for the project. You will need to complete and submit a Final Report and submit a new application for the project. (The five year limit on renewal of approvals allows the Committee to fully re-review research in an environment where legislation, guidelines and requirements are continually changing, for example, new child protection and privacy laws).

4. All amendments to the project must be reviewed and approved by the Committee before implementation. Please complete and submit a Request for Amendment Form available at the following website:

http://www.research.mq.edu.au/for/researchers/how_to_obtain_ethics_approval/human_research_ethics/forms

5. Please notify the Committee immediately in the event of any adverse effects on participants or of any unforeseen events that affect the continued ethical acceptability of the project.

6. At all times you are responsible for the ethical conduct of your research in accordance with the guidelines established by the University. This information is available at the following websites:
http://www.mq.edu.au/policy/

http://www.research.mq.edu.au/for/researchers/how_to_obtain_ethics_approval/human_research_ethics/policy

If you will be applying for or have applied for internal or external funding for the above project it is your responsibility to provide the Macquarie University's Research Grants Management Assistant with a copy of this email as soon as possible. Internal and External funding agencies will not be informed that you have final approval for your project and funds will not be released until the Research Grants Management Assistant has received a copy of this email.

If you need to provide a hard copy letter of Final Approval to an external organisation as evidence that you have Final Approval, please do not hesitate to contact the Ethics Secretariat at the address below.

Please retain a copy of this email as this is your official notification of final ethics approval.

Yours sincerely,
Peter Busch, Chair
Faculty of Science and Engineering
Human Research Ethics Sub-Committee
Macquarie University
NSW 2109

Appendix B – Spot test information sheet

Department of Chiropractic
Faculty of Science and Engineering
MACQUARIE UNIVERSITY NSW 2109

Phone: +61 (0) 2 9850 6197
Fax: +61 (0) 2 9850 9389
Email: goran.strkalj@ mq.edu.au

Chief Investigator's / Supervisor's Name & Title:
Associate Professor Goran Štrkalj

MACQUARIE University SYDNEY · AUSTRALIA

Participant Information

The Application of 3D Printing Technology in Anatomy Education (Anatomy Test)

You are invited to participate in a formative anatomy spot test, which is a part of a study that investigates the usefulness of the 3D printing in anatomy education.

The study is being conducted by A/Prof. Goran Štrkalj (Department of Chiropractic; phone: 9850 6197; e-mail: goran.strkalj@mq.edu.au) and Dr Manisha Dayal (School of Biomedical and Health Sciences; phone: 4620 3493; e-mail: m.dayal@uws.edu.au) and Mr Yousef Abou Hashem (email: yousef.abouhashem@mq.edu.au). The study is being conducted to meet the requirements of Master of Research degree for Yousef AbouHashem under the supervision of the aforementioned academic staff.

If you decide to participate, you will be asked to participate in an anatomy spot test. This test will last no longer than 10 minutes. This test is anonymous, it is not part of the formal (summative) assessment and it will not influence your marks.

Any information or personal details gathered in the course of the study will remain private and confidential, except as required by law. No individual will be identified in any publication of the results. Individuals who have access to research data are only the research personnel involved directly in the research project. All personal information will remain anonymous. A summary of the results of the data can be made available to you on request by contacting the chief investigator on their contact details. The data, results of this study or both may be made available for use in future Human Research Ethics Committee-approved projects.

Participation in this study is entirely voluntary: you are not obliged to participate and if you decide to participate, you are free to withdraw at any time without having to give a reason and without consequence.

The ethical aspects of this study have been approved by the Macquarie University Human Research Ethics Committee. If you have any complaints or reservations about any ethical aspect of your participation in this research, you may contact the Committee through the Director, Research Ethics & Integrity (telephone (02) 9850 7854; email ethics@mq.edu.au). Any complaint you make will be treated in confidence and investigated, and you will be informed of the outcome.

Participant Information and Consent Form

Appendix C – Spot test answer sheet

Degree Enrolled in: ……………………………

Please write down your answer to the following question in the answer column for each station regarding the vertebra model shown:

To which region of the vertebral column does the vertebra shown belong to?

Station No.	Answer
1	
2	
3	
4	
5	
6	
7	
8	
9	

Please place answer sheet in the box provided when completed.

Thank you for participating.

Appendix D – Questionnaire

WHOLE BODY/THREE-DIMENSIONAL IMAGE DONATION QUESTIONNAIRE

General Information

Age: .... years

Gender: Female / Male / Other

Ethnicity (*e.g. Australian, Brazilian, Chinese, Italian, Lebanese, etc.*): ....

Religion (*e.g. Atheist, Buddhist, Christian, Muslim, etc.*): ....

Whole Body Donation

Whole body donation refers to the donation of one's body after death for the purposes of anatomical education and research.

1) Would you donate your body for anatomical education and research? (Please circle the appropriate answer)

Yes No Undecided

1.1) From the following, please select the reasons that best explain why (you may select more than one):

I WOULD donate my body:
- For religious reasons ☐
- To help education in science/medicine ☐
- To help research in science/medicine ☐
- Because I want to feel useful after death ☐

Other (please specify) ....

I would NOT donate my body:
- For religious reasons ☐
- For concern that my body will not be respected ☐
- Because I am not well informed about this ☐

Other (please specify) ....

I am UNDECIDED (you may select more than one):
- Because I have never thought about this ☐
- Because I am not well informed about this ☐

Other (please specify) ....

2) Would you support a family member's decision in donating their body for anatomical education and research? (Please circle the appropriate answer)

Yes No Undecided

3) Would you support a stranger donating their body for anatomical education and research? (Please circle the appropriate answer)

Yes No Undecided

3D Image Donation

Three-dimensional (3D) image donation refers to allowing one's body, body parts or organs images, obtained through techniques such as Computed Tomography and Magnetic Resonance Imaging, to be used to produce 3D printed models for anatomical education and research.

4) Would you allow 3D images of your body, body parts or organs to be 3D printed and used for anatomical education and research? (Please circle the appropriate answer)

Yes No Undecided

4.1) From the following, please select the reasons that best explain why (you may select more than one):

I WOULD allow 3D printing from my body's images:
- For religious reasons ☐
- To help education in science/medicine ☐
- To help research in science/medicine ☐

Other (please specify) ....

I would NOT allow 3D printing from my body's images:
- For religious reasons ☐
- For concern that my body will not be respected ☐
- Because I am not well informed about this ☐

Other (please specify) ....

I am UNDECIDED (you may select more than one):
- Because I have never thought about this ☐
- Because I am not well informed about this ☐

Other (please specify) ....

5) Would you support a family member's decision to allow his or her 3D body image to be 3D printed and used for anatomical education and research? (Please circle the appropriate answer)

Yes No Undecided

6) Would you support a stranger's decision to allow his or her 3D body to be 3D printed and used for anatomy education and research? (Please circle the appropriate answer)

Yes No Undecided

Appendix E – Questionnaire information sheet

Department of Chiropractic
Faculty of Science and Engineering
MACQUARIE UNIVERSITY NSW 2109

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Email: goran.strkalj@mq.edu.au

MACQUARIE University SYDNEY·AUSTRALIA

Chief Investigator's / Supervisor's Name & Title:
Associate Professor Goran Štrkalj – Macquarie University

Participant Information

The Application of 3D Printing Technology in Anatomy Education (Attitudes Towards Whole Body Donation and 3D Image Body Donation)

You are invited to participate in a survey of attitudes towards whole body donation and 3D image donation for 3D printing. This survey is a part of the study which investigates the usefulness of 3D printing in anatomy education. The aim of this segment of the project is to establish the willingness to donate whole body after death and to donate 3D images of the body, body parts or organs to be 3D printed, for the purposes of anatomical education and medical research.

The study is being conducted by A/Prof. Goran Štrkalj (Department of Chiropractic; phone: 9850 6197; e-mail: goran.strkalj@mq.edu.au) and Dr Manisha Dayal (School of Biomedical and Health Sciences; phone: 4620 3493; e-mail: m.dayal@uws.edu.au) and Mr Yousef AbouHashem (email: yousef.abouhashem@mq.edu.au). The study is being conducted to meet the requirements of Master of Research degree for Yousef AbouHashem under the supervision of the aforementioned academic staff.

If you decide to participate, you will be asked to fill out a short, one-page questionnaire. Please attempt to answer the questions truthfully and to the best of your knowledge. The participation is anonymous and entirely voluntary, you are not obliged to participate and if you decide to participate, you are free to withdraw at any time without having to give a reason and without consequence.

Any information or personal details gathered in the course of the study will remain private and confidential, except as required by law. No individual will be identified in any publication of the results. Individuals who have access to research data are only the research personnel involved directly in the research project. No information identifying participants will be released without the explicit consent of the participants concerned. All information will remain anonymous. A summary of the results of the data can be made available to you on request by contacting the chief investigators and/or supervisors on their contact details. The data, results of this study or both may be made available for use in future Human Research Ethics Committee-approved projects.

The ethical aspects of this study have been approved by the Macquarie University Human Research Ethics Committee. If you have any complaints or reservations about any ethical aspect of your participation in this research, you may contact the Committee through the Director, Research Ethics & Integrity (telephone (02) 9850 7854; email ethics@mq.edu.au). Any complaint you make will be treated in confidence and investigated, and you will be informed of the outcome.

Appendix F

Paper "The Application of 3D Printing in Anatomy Education" published in Medical Education Online journal

Medical Education Online co-action

LETTER TO THE EDITOR

The application of 3D printing in anatomy education

Modern medical education relies on a wealth of resources as one of the key elements in developing students' clinical competencies. Acquiring these resources represents a considerable challenge for many medical schools, not only for financial but also a variety of other reasons, including ethical, legal, and cultural. Obtaining human tissue, in particular, faces many constraints, which, in some countries and cultural circles, create serious problems for medical educators. However, modern technology seems to offer solutions in acquisition of at least some of the resources. Among the new technologies that have in recent years entered the biomedical fields in research, practice, and education are the rapid prototyping techniques, particularly as applied in three-dimensional (3D) printing (1, 2).

In this paper, using an example from Australia's Macquarie University and Western Sydney University, we outline how 3D printing can be successfully used in anatomy education. Utilisation of 3D printing is a part of the long-term educational project at both these institutions, including fields as diverse as medicine, arts, and sciences. In anatomy, the first stage of the project, described here, focused on producing highly accurate 3D prints of human bones.

Educational resources

Acquiring in-depth knowledge of human structures and the ability to apply this knowledge within the clinical context is an imperative in many medical disciplines (3, 4). At Macquarie University and Western Sydney University anatomy instruction is provided to a diverse group of students enrolled in medical and science degrees. Teaching is carried out through the utilisation of a variety of resources. In the anatomy laboratory various medical images are utilised, together with anatomy models, prosected cadavers, and human bones. To the existing resources, a new addition was made this year – 3D prints of selected bones. These prints were made from the 3D surface scans of the bones from the Macquarie University Skeletal Collection.

There were several reasons for the decision to start the 3D-printing project with human bones. First, bones almost naturally lend themselves for printing as they are generally monochromatic and made of hard tissue. Technically, this makes them the easiest component of the human body to duplicate in 3D printing, with high levels of accuracy, preserving both visual and haptic values of the real tissue.

Second, obtaining bones for anatomical study is a complex process. Although obtaining cadavers for anatomy education (with time restrictions because of the legal requirement to cremate the body within the maximum of 8 years) does not represent a problem, thanks to the well-developed whole body donation programmes in Australia, the acquisition of bones for a permanent collection is constrained by ethico-legal norms. The main resources used for teaching osteology are thus anatomical bone models and bones already acquired for the university's collection (mainly past donations from health professionals' private collections). Although both institutions have large collections of models, these are not sufficient for teaching purposes. Indeed, anatomical models, even those of high quality are rather schematic and do not show the range of variation present in different human populations in health and disease (5, 6). The Macquarie collection of human bones, however, although relatively small, contains a considerable number of anatomical variants and pathologies that are essential in education. Many of these valuable bony elements are rare; some are quite fragile and were up to now used only in demonstrations, with very limited opportunities for students to handle and examine them directly. Through the advent of 3D printing, students are now able to handle and examine their exact replicas which are printed in several copies.

Finally, an important reason for printing bones is financial in nature. Once the appropriate infrastructure is in place, printing is the most cost-effective way of acquiring a large and representative osteological sample.

3D printing and its application

3D printing has, in the last two decades, been successfully utilised in different medical fields, including education. In anatomy, high-quality 3D-printed replicas of cadaveric material were recently produced for teaching purposes (7, 8). Following these pioneering enterprises, in the project described here, 3D prints of bones were produced and introduced to students in anatomy education. This was accomplished in several steps through a community of practice between the two participating universities (9). The project was a continuation of an existing collaboration between the two universities in the field of biomedical education. It capitalised on the existing resources and infrastructure (3D surface scanners, printers, skeletal collections, etc.), as well as the expertise at both universities, enabling production of high-quality scans and prints

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(page number not for citation purpose)

and increasing the number and variation of the osteological samples.

Bones were scanned using the handheld Artec Spider 3D surface scanner. The obtained 3D images in themselves represent useful educational tools as they can be easily downloaded from the universities' databases and manipulated by students (e.g., enlarged, viewed from different perspectives, and annotated). 3D replicas were then printed at both universities using the following 3D printers: Objet Connex, Mojo, and the MakerBot Replicator. Osteometric analysis was carried out and revealed that there were no significant differences in the shape and dimensions of the prints when compared to the real bones upon which they were made. Similar results were obtained in an earlier study that examined the accuracy of the 3D prints of cadaveric material (8).

The obtained 3D prints of bones were then used in anatomy laboratories at both participating universities. Students had a chance to handle and examine all specimens, including the rare and fragile elements previously not available for inspection. It is planned that 3D prints will also be utilised in pathology and radiology classes at both Macquarie University and Western Sydney University. Currently, another study is underway that focuses on the usefulness of these 3D prints in education. The study includes an investigation of students' and teachers' perceptions of the educational value of the 3D prints and projects in which volunteers will complete a series of anatomy tests on the anatomy models, 3D prints, and real bones.

Future plans regarding this stream of 3D printing include scanning and printing of other anatomical structures, particularly those not easily visible on cadavers and difficult to visualise. These will include, but not be limited to, small elements (bones of the middle ear), cavities (sinuses, ventricles of the brain), and anatomical variations and pathologies. These 3D prints will be used in anatomy and a number of clinical subjects.

Furthermore, as 3D-printing technologies evolve and continue to reduce in cost, alternative printers and techniques will be explored. A range of options, such as vat photopolymerisation, binder jetting, and powder bed fusion, will allow printing of structures that more closely mimic the original resource. For example, choice of materials and printer options can customise anatomy prints to match the weight of the original model. In addition, some newer 3D printers such as the CubePro C and the Connex series enable affordable 3D prints in full colour.

Another improvement that can be made in this preliminary study is to reduce the effort of using a handheld 3D surface scanner and instead use a micro-CT like the Quantum GX creating images that can be converted to .STL files ready for 3D printing. This technology lends itself well to human bones as images are of very high resolution and the scans produced include the internal structure of the bones which will also then mimic the actual weight of human bones if an appropriate consumable is used for printing. This also eliminates the extra step of scanning bones and then using the software to create a 3D file, thus saving time and increasing the resolution for printing.

Conclusion

3D-printed bones are being successfully applied in anatomy education at Macquarie University and Western Sydney University. The application of 3D prints will further ramify and expend into other subjects. Furthermore, the 3D-printing project will soon involve other anatomical structures, particularly those that are difficult to observe and manipulate. The resources for medical education will continue to develop and evolve following both technological development and increasing educational demands for the development of clinical competencies which, just as the world we live in, constantly change and increase in their complexity.

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All authors made equal contribution in writing this paper.

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