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Paul M. Rea *Editor*

Biomedical Visualisation

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Preface

The utilisation of technologies in the life sciences, medicine, dentistry, surgery and the allied health professions has been at an exponential rate over recent years. The way we view and examine data now is significantly different to what has been done perhaps 10 or 20 years ago.

With the growth, development and improvement of imaging techniques like CT, MRI and microscopic data visualisation techniques, the way we are able to interact with data is much more engaging than it has ever been.

Indeed, with immersive technologies like augmented, mixed and virtual reality, coupled with 3D printing technologies and new methods to scan, like photogrammetry, we are at a pivotal point.

These technologies have been used to enable improved visualisation in the biomedical fields but also how we engage our future generations of practitioners when they are students within our educational environment. Never before have we had such a wide range of tools and technologies available to engage our end-stage user. Therefore, it is a perfect time to bring this together to showcase and highlight the great investigative works that is going on globally.

This book will truly showcase the amazing work that our global colleagues are investigating, and researching in, ultimately to improve student and patient education, understanding and engagement. By highlighting innovative examples of co-creation approaches and engaging the learners and patient's, we can truly advance our engagement with everyone using these tools and technologies. By sharing best practice and innovation, we can truly aid our global development in understanding how best to use technology for the benefit of society as a whole.

Glasgow, UK
Paul M. Rea

Acknowledgements

I would like to truly thank every author who has contributed to the first ever edition of *Biomedical Visualisation*. By sharing our innovative approaches, we can truly benefit students, faculty, researchers, industry and beyond in our quest for the best uses of technologies and computers in the field of life sciences, medicine, the allied health professions and beyond. In doing so, we can truly improve our global engagement and understanding about best practice in the use of these technologies for everyone. Thank you!

About the Book

Biomedical Visualisation is a book which will truly showcase and highlight the innovative use of technologies in enabling and enhancing our understanding of the life sciences, medicine, allied health professions and beyond. This will be of benefit to students, faculty, researchers and patients alike. The aim of this book is to provide an easy access format to the wide range of tools and technologies which can be used in the age of computers to improve how we visualise and interact with resources which can improve education and understanding related to the human body.

Chapters 1 and 2

These chapters shall explore the use of virtual, augmented and mixed reality in clinical simulation, nursing education and applications of these technologies for patients with amputations.

Chapters 3–7

These chapters shall discuss how a variety of technologies can be used in enhancing education and engagement related to anatomy and embryology and visualising medical heritage items. In addition, it will discuss and critique the key pedagogies around the use of technology-enhanced learning and the evidence that is within the current literature.

The use of technologies like mobile applications and hand tracking technologies will also be explored, specifically related to those patients that have multiple sclerosis. Key studies will present materials which have been developed to create user-friendly, intuitive environments to improve understanding of drugs and their side effect. In addition, it will also demonstrate key ways to create a user interface in a virtual environment, which can be used to improve upper limb strength and mobility. It will also highlight the limitations and ways to further the development of these types of technologies in patient education and engagement.

Chapter 8

This chapter will highlight how to create interactive datasets from microscopes. By using confocal data, this chapter will highlight how 3D modelling, and virtual reality can be utilised to create an immersive learner experience never seen before.

Chapters 9 and 10

These two final chapters will show how photogrammetry can be used to create interactive materials. By literature searches and case examples, the ways and means of how to create the best imaging and processing will be demonstrated through the author's experiences and related scientific literature.

Contents

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About the Editor

Paul M. Rea is a medically qualified clinical anatomist and is a senior lecturer and licensed teacher of anatomy. He has an MSc (by research) in craniofacial anatomy/surgery, a PhD in neuroscience, a diploma in forensic medical science (DipFMS) and an MEd (Learning and Teaching in higher education), with his dissertation examining digital technologies in anatomy. He is an elected fellow of the Royal Society for the Encouragement of Arts, Manufactures and Commerce (FRSA), an elected fellow of the Royal Society of Biology (FRSB), a senior fellow of the Higher Education Academy, a professional member of the Institute of Medical Illustrators (IMI) and a fully registered medical illustrator with the Academy for Healthcare Science.

Paul has published widely and presented at many national and international meetings, including invited talks. He sits on the executive editorial committee for the *Journal of Visual Communication in Medicine*, is an associate editor for the *European Journal of Anatomy* and reviews for 20 different journals/publishers.

He is the public engagement and outreach lead for anatomy coordinating collaborative projects with the Glasgow Science Centre, NHS and Royal College of Physicians and Surgeons of Glasgow. Paul is also a STEM ambassador and has visited numerous schools to undertake outreach work.

His research involves a long-standing strategic partnership with the School of Simulation and Visualisation – the Glasgow School of Art. This has led to a multimillion pound investment in creating world leading 3D digital datasets to be used in undergraduate and postgraduate teaching to enhance learning and assessment. This successful collaboration resulted in the creation of the world's first taught MSc medical visualisation and human anatomy combining anatomy and digital technologies. The Institute of Medical Illustrators also accredits it. This degree, now into its 8th year, has graduated almost 100 people and created college-wide, industry, multi-institutional and NHS research-linked projects for students. Paul is the pathway leader for this degree.

Enhancing Nursing Education Through Affordable and Realistic Holographic Mixed Reality: The Virtual Standardized Patient for Clinical Simulation

Sean W. Hauze, Helina H. Hoyt, James P. Frazee,
Philip A. Greiner, and James M. Marshall

Abstract

Nurses serve a valuable role in the healthcare industry. Nurses are trained with the skills and knowledge to thrive in a fast-paced, evolving environment. In order to meet the complex and diverse needs of patients, nurses must be able to assess and prioritize care to produce safe and high-quality outcomes. Simulation is an established method of educating nursing students and preparing nurses to respond appropriately to situations they are likely to encounter in practice. Traditional nursing simulation devices are prohibitively expensive for many nursing education institutions. The development of augmented, mixed, and virtual reality simulation delivery offers a new platform for simulation, known as *immersive simulation*. Immersive simulation can virtually place nursing students in situations that are difficult to arrange in actual clinical practicums or that occur rarely but for which nurses need to be prepared. Additionally, the hardware required to deliver immersive simulation is much cheaper than that of traditional nursing simulation devices. This chapter describes the virtual standardized patient application delivered via mixed reality immersive simulation. This chapter also discusses the research initiative currently underway to assess student perceptions to this modality of health training simulation.

Keywords

Nursing education · Technology · Mixed reality · Immersive simulation · Assessment

1 Introduction

Simulation is an important aspect of training nursing students. Once education is complete and licensure is obtained, professional nurses function in an industry that is high-stakes, rapidly changing, and technology-driven (American Association of Colleges of Nursing 2016; National League for Nursing 2015). Pre-licensure nursing education encompasses both theoretical and clinical development. A debate exists about the best method for helping nursing students transition from a novice to a professional role that is safe for students and produces quality outcomes for students and future employers alike (American Association of Colleges of Nursing 2016; Benner et al. 2010; National League for Nursing 2015).

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Nursing educators have embraced simulation as a safe and realistic teaching methodology to help support the clinical development of nursing students for over a decade (National League for Nursing 2015). A study was conducted in the United States by the National Council of State Boards of Nursing (NCSBN) to explore the role and outcomes of simulation in pre-licensure nursing education. This landmark research provided substantial evidence to support simulation being used as a substitute for up to 50% of traditional clinical experiences when delivered through evidence-based methods (Hayden et al. 2014a; National League for Nursing 2015).

Guidelines by the National League for Nursing (2015) articulated that technology alone does not provide a realistic simulation experience. Evidence-based methods surrounding simulation should include a situation that is purposeful, requires student preparation, involves debriefing, and is related to student learning outcomes (National League for Nursing 2015). Well-designed simulation experiences are built upon concepts of active learning and student mastery. These concepts have repeatedly demonstrated the importance of aligning what is learned in theory to authentic, real-world scenarios (Bandura 1977; Benner et al. 2010; Bloom 1968; Dewey 1938; Ericsson et al. 1993; Freeman et al. 2014; Knowles 1973). A vast array of nursing and non-nursing educational research has shown that simulation can engage students in authentic active learning that is motivating, relevant, and builds confidence (Keller 1987; Larue et al. 2015; Vaughn et al. 2016; Weaver 2011).

1.1 Shortage of Nursing Faculty

Multiple competing forces are creating a need to transform the nursing educational system in the United States (American Association of Colleges of Nursing 2016; Benner et al. 2010). A current shortage of nurses is being compounded by an insufficient number of faculty (American Association of Colleges of Nursing 2016, 2017). According to the American Association of Colleges of Nursing (2017), the professional nursing workforce is expected to have more than one million job openings as 2020 approaches. The nursing faculty shortage is attributed as one of two critical reasons for the looming shortage (American Association of Colleges of Nursing 2016). The faculty shortage is complex and perpetuated by multiple factors. These include an aging faculty, looming retirements, non-competitive faculty salaries, burdensome workloads, and insufficient educational pathways for nurses to obtain the appropriate credentials to serve as nursing faculty (American Association of Colleges of Nursing 2016; National League for Nursing 2015).

Strategies to overcome the nursing faculty shortage have centered around both short- and long-term approaches to the problem. Short-term strategies involve the use of academic innovation that could increase the effectiveness of undergraduate nursing education through immersive and standardized simulation experiences (American Association of Colleges of Nursing 2016). The use of simulation to enhance teaching and clinical experiences despite a shortage of faculty could prove beneficial for regions that are especially hit hard by the shortage, such as rural communities.

1.2 Lack of Clinical Placements

A lack of undergraduate student nursing clinical placements is the second critical constraint to increasing student enrollment for nursing schools across the United States (National League for Nursing 2015). The National League for Nursing (NLN) and the American Association of Colleges of Nursing (AACN) are the two professional organizations that monitor pre-licensure nurse training programs and provide data about the obstacles to expanding educational capacity within the United States. A study among various types of pre-licensure nursing programs from 2012 to 2014 indicated 49% of Associate Degree Nursing programs and 41% of Bachelors of Science in Nursing programs have turned qualified applicants away because of the inability to provide appropriate clinical placements within their respective region (National League for Nursing 2015). Similarly, AACN conducts an annual survey of pre-licensure baccalaureate nursing programs. In their 2016 Report on Enrollment and Graduations in Baccalaureate and Graduate programs in Nursing, a majority (72.9%) of pre-licensure baccalaureate nursing programs reported insufficient clinical sites as a reason for not admitting more students (AACN 2016). Without alternative solutions to the clinical placement constraint, the impact will be potentially catastrophic (National League for Nursing 2015).

Simulation may provide a solution to this shortage in clinical placements. In a study by (Hayden et al. 2014b), findings concluded that simulation can be a successful substitute for traditional clinical experiences. This landmark study provided the basis for the National Council of State Boards of Nursing (NCSBN) to allow state boards and schools of nursing within the United States to substitute up to 50% of traditional clinical experiences when delivered through an evidence-based framework. The NLN has further developed a simulation framework that is widely used as the theoretical foundation for nursing simulation development and conducting research in the field around simulation use and its effectiveness (Jeffries 2005; Jeffries 2012; National League for Nursing 2015).

1.3 Potential for Immersive Simulation

Recent advances in immersive technologies makes possible a new kind of simulation, with potential to transform health education simulation. Virtual reality (VR), augmented reality (AR), and mixed reality (MR) technologies enable the user to interact with and control virtually-displayed components within virtual and physical environments. The combination of both physical and virtual components enables the user to practice low-frequency, high-risk scenarios within the safety of the classroom or clinical skills lab. While the research on such technologies is limited, early studies of immersive technology devices, such as Google Glass, showed positive effects on nursing student confidence (Vaughn et al. 2016).

Traditional simulation falls short in addressing the lack of available clinical placements due to the cost-prohibitive nature of high-fidelity manikin simulators, space and maintenance costs, and costs related to staffing. Innovation in the field of immersive technology provides a promising new alternative for high quality simulation at an affordable price. While this approach is attractive in terms of portability and affordability, the effectiveness of this immersive technology simulation to provide a motivating learning experience has not been thoroughly investigated.

2 Background

2.1 History of Simulation in Nursing Education

There is a rich history of simulation being used in nursing education. “Mrs. Chase” was the first patient simulator on record being used in the Hartford Hospital Training School for Nurses in 1911 (National League for Nursing 2015). Mrs. Chase was a life-sized adult doll with movable joints. Nurse educators used the doll to allow nursing students the ability to practice safely turning patients within a hospital bed. There was no interaction or realistic-feel to the original “Mrs. Chase.”

Several advances have been made in technology and the use of simulation since Mrs. Chase. Nurse educators built upon previous simulation research that centers on student satisfaction and confidence to continually improve simulation so that it is more realistic and interactive (Hayden et al. 2014a). New methods provide not only learning opportunities for students but evaluation opportunities as well. There is a call for educators to continue to measure student satisfaction and confidence with simulation, as well as develop methods to measure knowledge and skill acquisition (Hyaden et al. 2014a; National League for Nursing 2015).

Currently, nurse educators utilize multiple modalities of simulation to enhance student learning and encourage skill mastery. A robust body of evidence exists surrounding use of traditional methods of simulation in nursing education. It showcases the rich learning opportunity for students to enhance assessment skills, develop the ability to become adept at clinical reasoning, work in teams, and receive immediate feedback on care provided during the simulation (National League for Nursing 2015).

Nursing simulation has helped bridge the gap between theory and real-time clinical decisions in an environment that is risk-free to patients and students. Evidence based methods of delivering simulation in an effective manner are rapidly changing. Not all schools have faculty who are experts in simulation or the ability to benefit from the latest equipment that offers better integration of simulation into the curriculum and to substitute for real-world clinical experiences (American Association of Colleges of Nursing 2016; National League for Nursing 2015).

The International Nursing Association for Clinical Simulation and Learning (INACSL) identified key concepts that guide simulation in nursing education. According to INACSL (2016), a consistent terminology is important to guide simulation experiences, research, and literature. The following definitions from INACSL (2016) are commonly used:

- AR technologies overlay digital objects into the real-world physical environment.
- Clinical relates to learning in a real or simulated environment and provides opportunities for students to apply knowledge, skills, and attitudes.
- Clinical judgement involves a process of making decisions and taking action.
- Clinical reasoning is identified as the capability of a person to gather and understand data while remembering certain knowledge, skills, and attitudes, about the situation as it develops.
- A clinical scenario gives the context for a particular simulation and can vary in length, difficulty, and design based on student learning outcomes.
- Clinical thinking is a disciplined process that allows an individual to be purposeful, goal-oriented, and scientific in methodology.
- Evaluation is the appraisal of data and involves a judgment that is based upon quality measures versus a standard measure.
- Fidelity is the degree to which a simulation experience is authentic. Creating fidelity that is realistic involves several dimensions (environment, equipment, psychological factors, social factors, culture) and an element of trust between participants.
- High-fidelity simulation involves large scale computer driven experiences such as patient simulators, virtual reality, or standardized patients. These experiences seem realistic and are highly interactive.
- Low-fidelity simulation involves experiences that are naturally static like manikins, use of case studies and role-playing.
- Mixed reality (MR) devices provide an ability to combine both the physical and virtual worlds and create a realistic and immersive experience.
- Pedagogy is the art and/or science of teaching.
- Simulated-based learning experience involves a combination of strategic activities that recreate real-world situations in a pretend environment with a case study that unfolds.
- A standardized patient is a person trained to act as a patient with a scripted scenario.
- Virtual reality (VR) is a term that can be used for virtual, augmented, and mixed reality. This technology is unique in that it transports the user into a constructed reality environment outside of the current physical environment.

2.2 Nursing Simulation Modalities

Nursing education relies heavily on simulation as a proven method for nursing students to master objectives to achieve safe, high quality care practices (McGaghie et al. 2011). These nursing sim-

Table 1 Nursing simulation modalities

Modality	Cost	Definition	Example
Partial task trainer	\$500–\$20,000	Low-tech simulation manikins and models used for specific scenario training	Plastic arm for intravenous procedures
High-Fidelity Manikin	\$10,000–\$200,000	Computerized patient simulation manikins used for a wide array of critical medical scenarios	SimMan simulation manikin
Standardized Patient	\$20–\$40 per hour	A patient actor trained to role-play specific medical scenarios	A patient actor with makeup displaying symptoms of anaphylaxis

ulation modalities are employed across all levels of nursing education, spanning the continuum of nursing fundamentals to advanced nursing courses. Along with coursework and clinical experience, simulation is a key component for transforming nursing students from novice to expert (Benner et al. 2010). Simulation requires nursing students to acquire knowledge, make sense of the learning, make use of the learning, assimilate learning, and transfer the learning into the patient care setting (Decker et al. 2008).

Table 1 outlines costs, definitions, and examples of commonly utilized nursing simulation modalities, including partial task trainers, high-fidelity computerized simulation manikins, and standardized patients (Decker et al. 2008; Jeffries et al. 2009).

The challenges nursing education faces to meet increasing demand with limited resources makes traditional simulation cost-prohibitive for many institutions, particularly those in rural areas (Lapkin and Levett-Jones 2011; National League for Nursing 2015). For example, nursing students at the San Diego State University – Imperial Valley campus do not have access to high-fidelity nursing simulation, with the nearest high-fidelity simulation center located over 100 miles away. The recent innovation in the field of immersive technology may provide a new modality for high quality simulation for institutions in need of high-quality simulation at an affordable price.

2.3 Immersive Technologies: Virtual, Augmented and Mixed

Immersive technology exists as a continuum of modalities ranging from fully virtual environments that transport the learner in time, space, and scale to holographic overlays on our real environment, enabling users to view digital content in immersive, real world contexts. Milgram and Kishino (1994) established a taxonomy for immersive technologies, defining the "virtuality continuum" as an array of immersive simulation modalities as shown in Fig. 1.

As shown in the diagram, one end of the virtuality continuum exists the real environment with the opposite end represented as a fully virtual environment. Within the real environment, AR simulation can bring anything to you in the form of simulated digital content, typically overlaid via a camera and digital display. In contrast, VR—referred to in continuum diagram as augmented virtuality (AV)—brings the users anywhere through immersion in a fully simulated reality that is entirely separate from the real environment. In the center of the virtuality continuum is MR, which blends virtual content with the real environment. Each of these modalities within the virtuality continuum relies on external hardware in the form of monitor-based displays, transparent head-mounted displays (HMDs), and fully immersive HMDs.

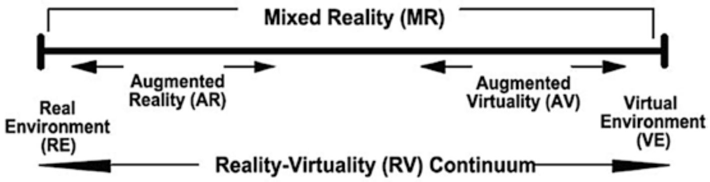

Fig. 1 The virtuality continuum. (Milgram and Kishino 1994, p. 3)

Table 2 Immersive technology modalities

Modality	Cost	Definition	Example
Virtual reality	\$5–\$800	A fully rendered representation of a virtual environment	Oculus Go
Augmented reality	\$100–\$1400	An overlay of virtual content onto the real environment	Apple iPhone
Mixed reality	\$1000–\$3000	A blend of a virtual environment with the real environment, in which virtual objects interact with the physical environment	Microsoft HoloLens

2.4 Recent Advances in Affordable Immersive Simulation

Innovation in the field of immersive technology has increased both the affordability and fidelity of commercially available devices. Recently released headsets include the Oculus Go, Lenovo Mirage Solo, Magic Leap One, and Microsoft HoloLens. Each of these devices enables realistic simulation in one or more of the following modalities, compared in Table 2.

3 Immersive Technology Modalities

Immersive technologies can be categorized into VR, AR, and MR depending on the degree to which the simulation environment is real versus digital. While VR is widely considered the generic term for all immersive technologies, there are many important and distinct functionalities that that differentiate each modality.

Virtual Reality The modality of VR transports the user into an entirely virtual environment outside of physical reality through a digitally constructed rendering (Barsom et al. 2016). The HMDs used for VR fully immerse users in the virtual environment. The leading VR HMDs are HTC Vive and Oculus Rift, both of which were released in the spring of 2016. Both HTC Vive and Oculus Rift require the processing power of a computer equipped with advanced graphics functionality and the Windows 10 operating system. Additionally, external infrared tracking systems devices are required to physically move within the virtual space. Since the release of Oculus Rift and HTC Vive, several standalone VR HMDs were made available at a fraction of the cost. Oculus Go and Lenovo Mirage Solo were released in the spring of 2018 for \$199 and \$399 respectively. Both the Oculus Go and Lenovo Mirage Solo operate without the need for external computing or tracking hardware. Other VR hardware includes smartphone auxiliary HMD devices, including Google Cardboard and Samsung Gear, that utilize existing computing power and display of smartphones.

The VR modality enables users to interact with simulations within a location or scale appropriate to the content. For example, The Body VR application enables the learner to travel virtually through a three-dimensional representation of the human body at the micro scale. Through the VR hardware functionality, the software enables the learner to navigate within the simulated human body to explore human biological systems.

Augmented Reality The AR modality overlays digital objects within the context of the learner's physical environment. This overlay of virtual content within the physical environment allows learners to visualize relationships between physical and virtual content, as well as simulate low-frequency, high-risk events (Akçayır and Akçayır 2016). AR software utilizes the location tracking, accelerometer, and camera hardware standard in smartphone and tablet devices to deliver immersive simulation through hardware many students already own.

One example of the use of AR simulation is the SkyView mobile application, which utilizes the user's location combined with the accelerometer and front-facing camera built into modern mobile devices to overlay planets, stars, and constellations over the night sky. SkyView provides graphical representations of celestial bodies, along with descriptive annotations.

Mixed Reality The MR modality combines the ability to use physical interactions to control and interact with virtual components (Chiu et al. 2015). As the term *mixed reality* implies, MR combines physical and virtual manipulates resulting in a mixed digital and physical experience. Commercially available MR HMDs include Microsoft HoloLens, Meta 2, and Magic Leap One, each of which enables the user to integrate holographic content within the physical components of the real environment through hand gestures. The hand gestures, as well as objects in the physical space, are mapped and recognized through infrared sensors on the front of the HMD. Simulation delivered via the MR modality enables learners to interact with virtual content integrated into the physical environment. This combination of virtual and physical elements enables MR to be particularly effective for scenarios in which the physical environment is important to the learning task, such as a clinical setting in which nursing students practice.

4 Economic Projections for Immersive Technology

The innovation in immersive technology is projected to generate major economic activity, with *Business Insider* projecting the immersive technology market to reach $162 billion by the end of 2019 (Blodget 2016). International educational content publishers recognize immersive technology is poised to become a dominant mode of information and knowledge transfer and are therefore investing in the development of educational content. Pearson and other publishers are currently investing heavily in these new technologies, with the potential to impact millions of students globally (Meyer 2016). The technological innovation in hardware, combined with the investment in educational immersive simulation software development, creates the potential for immersive simulation to transform education. There is therefore a strong need to empirically assess the efficacy of immersive technology through the scholarship of teaching and learning.

4.1 The NLN Simulation Framework

The National League for Nursing/Jeffries Simulation Theory (Jeffries 2005, 2012) is widely used as the theoretical foundation for implementation and evaluation of nursing simulation use and efficiency within the United States and beyond (Jeffries and Rogers 2007; Young and Shellenbarger 2012). The model blends experiential learning and technology as a method to enhance learning and skill performance for students. The framework helps articulate the unique experiences that exist within clinical simulation and offers a way to disseminate best practices. The framework builds upon perspectives of expert simulation researchers and is the foundation for future discoveries.

NLN Jeffries Simulation Theory identifies multiple variables that exist to produce desirable outcomes for the system, patient, and participant (Jeffries and Rogers 2007; National League for Nursing 2015). The framework identifies the importance of a process that begins with background and design leading to the simulation experience. The success of the simulation experience depends upon an environment of trust, leading to a learner centered experience that is collaborative, interactive, and experiential (National League for Nursing 2015). The dynamic interaction between the facilitator and student must be directed by strong educational strategies (National League for Nursing 2015).

4.2 Student Motivation and the ARCS Model

Several recent studies of augmented reality devices, such as Google Glass, showed positive effects on student confidence, satisfaction, and motivation (Akçayır and Akçayır 2016; Vaughn et al. 2016). One of the educational frameworks most used to evaluate student motivation to learn is John Keller's ARCS model (Keller 1987, 1999, 2010). The ARCS model asserts that motivation to learn is comprised of the degree to which the learner becomes engaged in the learning experience through elements of attention, relevance, confidence, and satisfaction. To measure the four constructs of the ARCS model, Keller (1993) developed the Instructional Materials Motivation Survey (IMMS). This instrument was created to measure and identify issues related to student motivation to learn with the use of self-directed learning materials, therefore the IMMS is an appropriate research instrument to measure nursing motivational attitudes toward the use a self-directed immersive simulation.

4.3 Educational Potential of Immersive Simulation

Immersive technologies offer a new simulation modality with the potential to transform education across the medical field. Several recent studies have explored the use of immersive simulation in medical education, particularly in the anatomy curriculum. Anatomy education presents challenges due to financial, ethical, and supervisory restraints with using human cadavers. Immersive technology provides an alternative through simulation of interactive, photorealistic anatomical representations of human anatomical systems. Immersive simulation also provides safe, realistic, and meaningful practice complex scenarios such as disaster relief, medication administration, and psychiatric care (Smith and Hamilton 2015; Ulrich et al. 2014; Vottero 2014).

The use cases for immersive simulation in education extend beyond the field of medicine. Studies across astronomy, chemistry, mathematics, and social sciences indicate immersive technology promotes both affective and cognitive student gains. This research includes the use of immersive simulation to promote science learning through hands-on interaction, virtual introduction to chemistry concepts, and increased astronomical knowledge retention (Cai et al. 2014; Chiu et al. 2015; Salmi et al. 2016; Zhang et al. 2014). As previously discussed, immersive technology is also shown to be effective in increasing student motivation (Vaughn et al. 2016; Akçayır and Akçayır 2016).

4.4 Use Cases Within Nursing Education

There are many opportunities for the use of virtual standardized patient simulations within undergraduate nursing education. According to Skiba (2016), the classroom lecture of today is waning as the primary teaching method in undergraduate nursing education. Interactive technologies provide more project-based, inquiry-driven learning experiences. Virtual simulation shows great promise when used in cases that deal with high-risk to patients involved (Skiba 2016). According to Decker et al. (2008), learning with simulation requires gaining knowledge, making sense of the knowledge, and then making use of the knowledge. Ultimately, the goal is for the assimilated learning to transfer into clinical readiness skills in a real-world setting. Best practices in simulation have been identified when it is integrated throughout the entire undergraduate nursing curriculum, increases in difficulty, aligns with student learning outcomes, and uses the appropriate tools for both teaching and measurement (Decker et al. 2008; National League for Nursing 2015).

The New Media Consortium (NMC) (2017), identified ten big picture themes that are positioned to impact teaching, learning, and innovation in higher education. The themes are a result of seventy-eight experts partnering with the EDUCAUSE Learning Initiative (ELI) to outline the 5-year impact of higher education innovation across the globe. The NMC Horizon Project is seen as education's longest-running exploration of new technology practices. The following ten themes outline what institutions should know about the use of technology to improve, support or extend teaching, learning, and creative inquiry: (1) Student success should be at the center of institutional learning approaches, (2) real-world skills are needed to ensure students are prepared for the workplace, (3) collaboration is key for scaling effective solutions, (4) inequity regarding student access to technology in education must be addressed, (5) educators must develop new ways to evaluate acquisition of individualized vocational skill, competencies, creativity, and critical thinking, (6) digital fluency is critical, (7) multiple strategies for integrating blended learning must showcase enriched learning outcomes, (8) learning ecosystems must be flexible enough to embrace the future practices, (9) higher education must be a developer of intuitive technology that responds to human interaction, and (10) lifelong learning must be fostered by higher education (Becker et al. 2017).

Recent undergraduate nursing studies showcase concepts of the EDUCAUSE movement and lay the foundation for immersive technologies to be safe, realistic, and meaningful. Limited studies exist, but there is promise for situations where teaching complex assessments are difficult to simulate such as a disaster (Ulrich et al. 2014), for administering medication within a busy environment (Vottero 2014), and when encountering a patient with psychiatric signs and symptoms (Smith and Hamilton 2015). Additionally, virtual technologies have been shown to be effective for technical skill acquisition for invasive procedures such as urinary catheter insertion (Smith and Hamilton 2015), hazardous chemical decontamination (Ulrich et al. 2014), and communicating with mentally ill patients (Kidd et al. 2012).

Discussion from individual studies within undergraduate nursing have identified four positive concepts regarding use of virtual simulation: (1) Virtual simulation is promising for knowledge and skill acquisition, (2) the technology creates an opportunity for student centered learning experiences, (3) the technology can be a safe and realistic evaluation method, and (4) the technology is user friendly and able to help save vital academic space. The main concern articulated by the initial researchers surrounds early coordination in the planning phase with instructional designers to ensure that the simulation experience is related to student learning outcomes, realistic, and not a distraction to the particular scenario or skill that should be the focus of the experience (Berndt 2014; De Gagne et al. 2013; Fisher and King 2013).

Immersive simulation is a new theme that shows promise for low-frequency, high-stakes scenarios that are difficult to replicate with current nursing simulation modalities. These modalities are sparking interest among nurse educators because they are less expensive and able to provide a standardized patient within a more immersive environment. The use of virtual simulation is changing rapidly and there is a need for research to assess this evolution (Doolen et al. 2016).

5 The Virtual Standardized Patient

5.1 Meeting the Need for Affordable, Realistic Nursing Simulation

In October of 2016, SDSU's Instructional Technology Services and School of Nursing partnered with Texas Tech University, Microsoft, and

Pearson to develop the virtual standardized patient (VSP) simulation. Our research is focused on the use of the Microsoft HoloLens as a simulation tool for nursing students to deliberately practice addressing such low-frequency, high-risk scenarios. A nursing student rarely witnesses a patient exhibiting the full array of symptoms related to anaphylactic shock, thus this clinical experience is currently supplemented using written case studies. In order to simulate anaphylaxis, a holographic video for the VSP captured a standardized patient actor portraying symptoms of anaphylaxis. The holographic video was recorded using an array of 25 infrared cameras and 100 video cameras. The holographic video was then built into a Microsoft HoloLens application using the Unity game development engine.

The VSP interactive functionality allows a nursing student to view the holographic video of the standardized patient exhibiting symptoms of anaphylaxis overlaid onto a physical hospital bed in a clinical teaching facility. The student can walk around the patient and observe the symptoms as they advance the application through the three stages of anaphylaxis. The development of simulation similar to the VSP provides a much more affordable and transportable simulation modality compared with traditional nursing simulation, however research is needed to determine the outcomes on nursing student skills, knowledge, and motivation to learn.

5.2 Description of the Study in Progress

The study currently in progress included baccalaureate nursing students (n = 161) enrolled in three levels of nursing courses at San Diego State University, both at the main campus and at the Imperial Valley satellite campus located 115 miles east of San Diego in Calexico, California. The three levels are defined as level 1 (n = 65), consisting of students familiar with reading case studies with no formal clinical experience; level 2 (n = 60), consisting of students with basic clinical experience; and level 3 (n = 36), consisting of students with extensive clinical experience. The research questions guiding the study include:

1. Does baccalaureate nursing student motivation to learn differ as a result of the modality of instruction employed among (a) a written case study; (b) a written case study plus two-dimensional video; and, (c) a written case study plus three-dimensional, mixed reality anaphylaxis simulation delivered via the Microsoft HoloLens?
2. What factors predict nursing student motivation to learn through mixed reality anaphylaxis simulation delivered via the Microsoft HoloLens?
3. Does baccalaureate nursing student knowledge, of anaphylaxis, differ as a result of the modality of instruction employed among (a) a written case study; (b) a written case study plus two-dimensional video; and (c) a written case study plus three-dimensional, mixed reality anaphylaxis simulation delivered via the Microsoft HoloLens?
4. Does baccalaureate nursing student intervention, for anaphylaxis, differ as a result of the modality of instruction employed among (a) a written case study; (b) a written case study plus two-dimensional video; and (c) a written case study plus three-dimensional, mixed reality anaphylaxis simulation delivered via the Microsoft HoloLens?
5. What variables predict nursing student knowledge and/or skill when the modality of instruction employed is mixed reality anaphylaxis simulation delivered via the Microsoft HoloLens?

All students enrolled in the three levels of courses during the Fall 2017 semester were invited to participate. Participating students were stratified and randomly assigned to one of the following groups: Research group 1, which provided students with an anaphylaxis written case study containing two-dimensional still images (n = 54); research group 2, which provided students with an two-dimensional video VSP anaphylaxis simulation via a computer monitor plus a written case study (n = 54); and research group 3, which provided students with a three-dimensional, MR VSP anaphylaxis simulation via the Microsoft HoloLens plus a written case study (n = 53).

All participants received written instructions accompanied by the anaphylaxis case study. Each student completed a pre-survey to collect data related to previous clinical and simulation experience. Upon finishing each anaphylaxis observation, participants completed a knowledge measure to determine understanding of the content conveyed in the corresponding observation. The data collection instruments are outlined below.

Pre-survey The pre-survey portion of the research instrument was used to determine demographic information (age and nursing level), previous clinical experience, previous immersive simulation experience, and previous nursing simulation experience.

Case Study The case study selected for the VSP was centered on anaphylaxis. Anaphylaxis is a severe, life-threatening allergic reaction. It can occur within seconds or minutes of exposure to an allergen. The VSP scenario for anaphylaxis involved three VSP observations. Each VSP observation showcased a scenario in which the patient demonstrated signs and symptoms of anaphylaxis and increased in severity rapidly. Students experienced the VSP observation through three different methods based upon their randomized research group assignment (video, Microsoft HoloLens, or written case study).

Observation Measures As the VSP scenario unfolded, there were three VSP observation periods that nursing students were prompted to respond to. Upon completion of each VSP observation period, students were asked to complete a set of questions to determine knowledge and skill regarding assessment and intervention in the low-frequency, high-stakes scenario. There was a total of three knowledge questions and two skill questions in observation period one. There was a total of three knowledge questions and two skill questions in observation period two. There was a total of three knowledge questions after observation period three and a total of four overall knowledge questions upon completion of the VSP scenario. Student responses were written on the research instrument scored dichotomously (1 = correct, 0 = incorrect) by the researchers. Knowledge and skill questions, with grading criteria created by the School of Nursing Director, Assistant Director, and the Medical-Surgical I and II Course Coordinator. Knowledge questions were added together to create a total knowledge score for observation period one, two, three, and overall. Skill questions were added together to create a total skill score for observation period one and two.

Post Survey Upon completion of the scenario and knowledge measure questions, each student completed a post-survey related to the simulation experience, focusing on their opinion of the simulation and the degree to which they felt it helped their confidence and motivation. The post-survey included the National League for Nursing (NLN) Student Satisfaction and Self-Confidence (SCLS) in Learning instrument and the Instructional Materials Motivation Survey (IMMS).

5.3 Planned Analysis

The planned quantitative analyses to address the research questions include comparisons of survey responses between the three research groups. Analysis of covariance (ANCOVA) will be used to determine if differences exist between research groups in terms of skills, knowledge, or student motivation to learn. Covariates will include age, digital quotient, clinical experience, simulation experience, and course in which the participant was enrolled at the time of data collection.

In addition to the ANCOVA, factor analysis, path analysis, and structural equation modeling will be used to determine which factors predicted increased skills, knowledge, and motivation to learn when the modality of instruction employed was mixed reality anaphylaxis simulation delivered via the Microsoft HoloLens. Confirmatory factor analysis will be used to determine which variables should be included within the factors.

5.4 Planned Discussion

Discussion of our future analysis will provide quantitative data not currently found in the literature regarding the effectiveness of using mixed reality simulation experience to address low-frequency, high-risk nursing clinical content. The results can be used by policymakers, educators, students, and clinical partners to make evidence-based decisions when contemplating use of simulation modalities to prepare student nurses and licensed nurses for the workforce. Additionally, the potential benefits of the study include determining if mixed reality is a viable means of providing simulation education to nursing students through devices much less expensive than using standardized patient human actors and/or high-fidelity manikin simulators.

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Potential Application of Virtual Reality for Interface Customisation (and Pre-training) of Amputee Patients as Preparation for Prosthetic Use

David W. Sime

Abstract

Virtual Reality has been used to great effect in the field of retraining and strengthening neural pathways in victims of serious brain injury and stroke.

Meanwhile, VR visualisation of missing limbs in amputees has been used to great effect not only in the treatment of "phantom limb syndrome" but in helping amputees restore muscle tone in remaining limb sections and torso prior to fitting these areas for prosthetics.

The natural next step, combining elements of both approaches, is the potential application of virtual reality to actively train the patient for using these prostheses prior to them being fitted, and furthermore adjusting and customising the prosthetic itself to the emergent needs of the patient whilst using the VR training.

This raises fascinating new applications not only for virtual reality itself, but for the numerous peripheral technologies which have risen around VR. These technologies include force feedback, "haptic" sensory simulation and monitoring of muscle strength, position and movement ranges.

This chapter aims to assess the capabilities of these technologies, both now and in the future.

By reviewing the work of two key studies in this area this chapter aims to bring together the necessary skills and establish the collaborative crossovers (and existing precedents) which would be required to develop this application of VR in the future.

Keywords

Prostheses · Amputee rehabilitation · Haptic feedback · Force feedback · Muscle conditioning · Neural retraining · DBI (Direct Brain Interfacing)

1 Virtual Reality and Serious Gaming

Serious Gaming is a phrase coined by Clark C Abt in 1970, describing the application of what might previously have been developed as interactive entertainment and its re-application to educational or other real world application (Ritterfeld et al. 2009).

Serious gaming has been applied to everything from academic education and practical workplace training to socio-psychological and physical rehabilitation (Wilkinson 2016).

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In the medical context we will be discussing here, social gaming is most aptly defined as *digital tasks and visualisations with "an explicit and carefully thought-out educational purpose* (which) *are not intended to be played primarily for amusement. This does not mean that serious game are not, or should not be, entertaining"* (Abbot 1987).

Serious Gaming, previously part of the comparatively less successful "*edutainment*" category (Ritterfeld et al. 2009) has enjoyed renewed success in recent years over a number of fields, particularly medicine, due to the application of Virtual Reality to the genre.

1.1 Virtual Reality in Serious Gaming

Much advanced in recent years, Virtual Reality has enjoyed considerable improvements in realism, comfort and affordability since its inception in the 1970s (Cruz-Neira et al. 2018). Moving from a primarily visual experience, where users were immersed in an apparently three dimensional virtual world by use of a binocular, motion responsive headset (Snyder 2016a, b), Virtual Reality or "VR" has broadened in its scope to encompass a number of other senses:

> Realistic auditory feedback, creating a sense of depth, distance and direction, known as Binaural Audio, has been shown to considerably enhance VR experiences and extend their applications to a number of real world training scenarios, including virtual military manoeuvres and traffic safety training for those with visual impairment (Loomis et al. 2005).

Physical sensation has also been added to the range of senses provided in VR by way of *Haptic Feedback Peripherals* (Hinchet et al. 2018). These devices allow for the sensations of touch, impact, motion and even variations of resistance when gripping virtual objects. This illusion is created by various devices from force feedback gloves and full body suits which use motors or micro pneumatics to mimic contact and physical resistance with virtual objects (Delazio et al. 2018) to ultrasonic speakers which create shaped sound fields mimicking the form and even texture of objects being encountered in the virtual environment, allowing many users to obtain a sense of physical sensation from a single device (Freeman et al. 2017).

In all cases, haptic devices like these open up opportunities for new use cases for virtual reality, including safe training in manual and physical tasks which may be difficult or hazardous to achieve in real life (Pocket Sized Hands 2017) such as electronic or mechanical engineering tasks, particularly maintenance in the oil and gas sector.

Finally, virtual reality and, by extension, serious gaming applications like those mentioned above have been considerably advanced by the advent of un-tethered devices (where the headsets require no wired connection to a static computer) allowing for "6D" movement.

6D refers to the various dimensions of movement which can be picked up and replicated by VR devices. Previously VR headsets were limited to three degrees: Pitch (forward/backward tilting motion); Yaw (turning horizontally clockwise or anticlockwise) and Roll (side to side tilting motion) (See Fig. 1).

However, with 6D we have seen the addition of tracking and replication or forwards and backwards movement (such as walking and running), upwards and downwards motion (standing, sitting and climbing) and sideways movement. These referred to as Surge, Heave and Sway respectively.

Olfactory haptics, simulating smell (Li and Bailenson 2017); thermal haptics, simulating temperature change (Pieris et al. 2017); and advanced tactile haptics, simulating textures (Freeman et al. 2017) are also in advanced development at labs all over the world, seeking to complete the sensory somatic spectrum and allowing for a panoply of serious gaming applications from hazard perception training to the treatment of eating disorders (Li and Bailenson 2017).

Together, these have been shown to deliver a far higher degree of freedom and realism, and

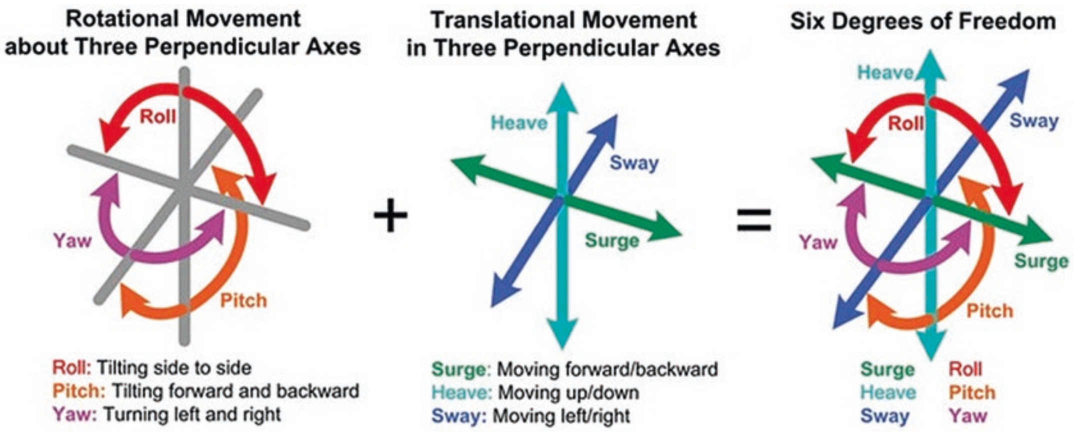


Fig. 1 6 Degrees of freedom in virtual reality

allow for many more real world training applications such as the ability to move around virtual surgical tables, large equipment, machinery and numerous workplace or domestic environments (Snyder 2016a, b).

2 Virtual Reality and Serious Gaming Applications to Disability

Until recently however, the majority of these applications and devices have assumed the user to be fully able-bodied. The obvious applications of, for example, compensation for physical mobility impairment due to physical (Calhane 2017) and mental (Sime 2019) restrictions are only now being fully explored (Chandrashekar 2018).

And, in the case of amputees, the use of haptic peripherals such as gloves and other tactile feedback devices face obvious barriers, where the limb or hand is simply not present.

However, the advent of myoelectric sensing devices – which pick up neural activity from electrical currents passing across the skin surface (Rouse 2005) means that not only can restrictions in VR control and feedback be addressed in amputees, but specific benefits can be created by applying VR serious gaming to training for responsive artificial limbs, known as MyoElectric Prostheses.

2.1 Myo-Electric Prosthetics

Myo-electric prosthetics are advanced artificial limbs with functioning powered functions such as grasping, clenching and extending of fingers, flexing and extending of knees and elbows and wider flexing and rotational movements of wrists and ankles (Ottobock 2017).

Picking up on and responding to the myoelectric signals being generated across the remaining muscles and skin of the user, the devices can replicate natural movement in response to similar neurophysiological commands the user would have used to control their original limb.

2.2 Limitations in Use of Myoelectric Prosthetics

2.2.1 Sensory Deficit

However, for the user this process is not as straightforward as attaching the implant and immediately being able to use it like a normal limb. Various limitations such as the **absence of sensory feedback** in most devices make using and controlling them more difficult. An apt analogy is where a healthy limb develops numbness due to anaesthesia or restricted blood-flow as encountered in “pins and needles” – use of this numbed limb can temporarily prove cumbersome and movements inaccurate.

2.2.2 Experiential Control Deficit

In addition, many amputees have been without the limb for long periods of time, meaning their “memory” of the method of manipulating that leg, arm or hand has been atrophied both at the mental, neural and muscular levels (Phelan 2015).

Finally, many patients missing limbs are as a result of Congenital Amputation – better described as “Upper and Lower Limb Reduction Defects” (Centers for Disease Control and Prevention 2018) where they have been born without the limb/s and therefore have no experience or memory whatsoever of how to operate them.

2.2.3 Training Interface

Given the extremely high cost of Myoelectric Prosthetics (Over £30,000 per artificial limb), (NHS 2018) publicly funded health services such as the NHS in the United Kingdom have strict vetting procedures to ensure potential recipients not only have a need for the device, but has the ability to use it (which, as mentioned, can be extremely difficult for the new user).

Restrictive to this process, however, is that due to the expense of the prostheses, the specialist clinics themselves have insufficient funds to provide the patient with a device to practice or prove this ability to them. (Phelan 2015).

Patients are made to undergo 2 weeks of training and assessment using a basic Electromyographic (EMG) system attached to a conventional computer and display with a simple, binary game like interface (See Fig. 2). The process of interacting with this game sought to re-stimulate and build up atrophied muscles and neural pathways while helping the patients’ to improve their control levels, all the while measuring their ability, improvement and overall suitability for a prosthetic.

Unfortunately, due to the binary and, reportedly, non-instinctive nature of the game, coupled with the difficult and cognitively exhausting nature of the exercise itself, many patients reported severe frustration and stopped engaging with the process quickly (Prahm et al. 2017). This meant that many, potentially viable subjects, do not end up qualifying or completing the training process for a myoelectric prosthetic, even when they might have had the ability to use and benefit from it.

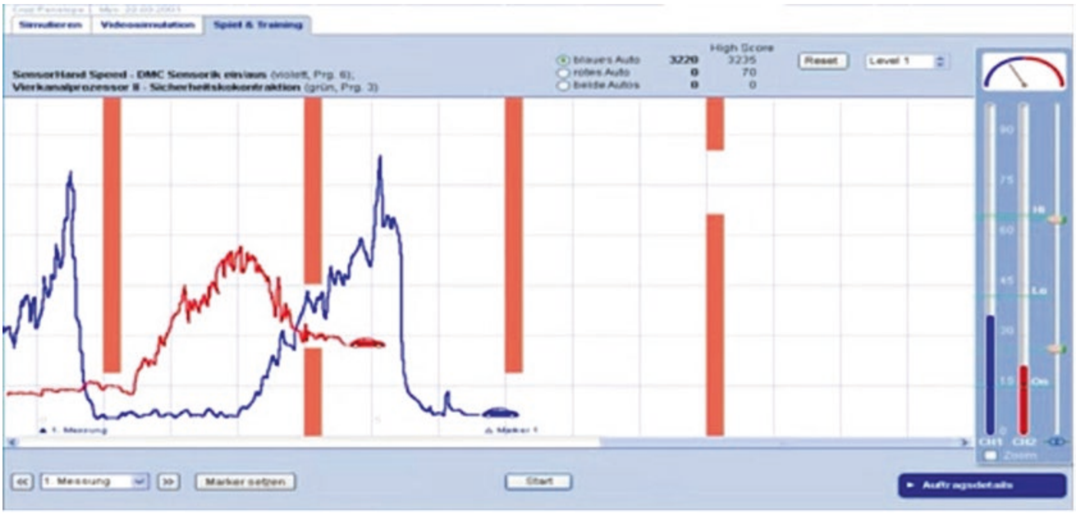


Fig. 2 Current EMG training “Game”

3 A Potential Solution in VR

There have however been a number of technological developments in both sensory reading, processing and playback.

3.1 Myo Armband

The first of these, progressing from the expensive and rudimentary EEGs in use previously was Atomic Labs' commercially available "Myo Armband" – in comparison to previous offerings utilised by the NHS, this consumer device was lower in cost and weight and was able to measure the signals for a fist, an open hand and a variety of more intricate gestures (Sathiyanarayanan and Rajan 2016) (Fig. 3).

The device was able to relay the strength and timing of the movement signals to a graph to measure the users' ability and progress.

3.2 Visual Tracking and Playback

Coupling this technology with an early Oculus Rift Virtual Reality headset (at the time the state of the art for visual VR playback) and the Kinect external motion sensor (both commercially available, and therefore low enough in cost to make the equipment available even in low funded clinics), researchers at the University of Sheffield were able to build a system which was capable of being used to create a responsive virtual arm which could be controlled by the user, matching their intended movements and body position (Phelan et al. 2015).

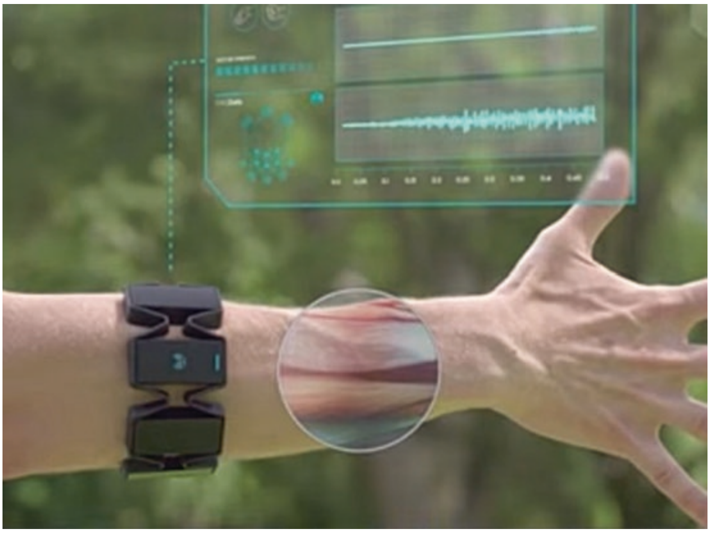
3.3 Limitations and Refinements

Initially the armband left something to be desired in terms of consistency of responses to the users' intended movements. In addition to this, the standard means of calibrating the device required making a complex hand gesture that inexperienced amputees were unable to recreate.

Fortunately programmers were able to directly adapt the code in the Unity 3D engine they were using (Unity 2018) to bypass this calibration phase.

Initial experiments, however, still resulted in "jittery" movement due to failings in the Kinect's motion sensors, and the Myo Armband at this point was only capable of allowing binary "grabbing" motions; simply "connecting" the virtual arm with

Fig. 3 Myo Armband



the item being grasped, rendering the two virtual representations temporarily one solid object.

4 Initial Subject Testing

Having tested this system on themselves, the (able bodied) developers at the University of Sheffield then tried the system with actual patients, including those whose limb absence was congenital and those who had lost a limb during their lives ("traumatic" amputees). Subjects covered both with and without experience of myoelectric prostheses. Seven patients were tested in total, both male and female and covering an age range of 20–60 years old (Fig. 4).

4.1 Effects of VR Interface

Their first patient attempted to use the arm band without the VR helmet – the arm band didn't register any signal at all. However, when they donned the VR headset they were immediately able to interact with the virtual objects within the model – they stated that it just seemed instinctive to want to pick up the apples in the model and move them around. Although this patient had lost a limb as a result of an industrial injury some seven years earlier, the dramatic difference in results with and without the virtual reality raises genuine questions on the role of vision in instinctive versus deliberate movement where no other sensory cues are present (Pélisson et al. 1986).

4.2 Exaggerated Signal Strength

Interestingly the initial patient (and, in fact all subsequent subjects tested) were actually generating 5 times the myoelectric signals as those with present limbs. It was surmised that this was due to the absence of sensory and mechanical resistance factors which, in a biological/physical hand, would be limited to a fully clenched fist. So much stronger, in fact, were the myoelectrical impulses from these patients that that subsequent sensors had to be equipped with a neural signal limiter, referred to as a "lightning rod" to avoid overloading and shorting out the system (Phelan et al. 2015).

4.3 Patient Outcomes

Another positive result from the same initial test subject (who, after conventional ECG training and assessment had stated that he couldn't use a prosthetic and didn't want to be fitted for one) immediately afterward the VR experience stated he was now fully confident now that he would be able to operate a myoelectric prosthetic and asked his occupational therapist if he could be fitted for one (Fig. 5).

Fig. 4 Initial patient testing

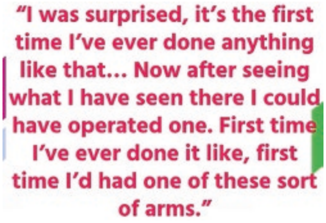

"I was surprised, it's the first time I've ever done anything like that… Now after seeing what I have seen there I could have operated one. First time I've ever done it like, first time I'd had one of these sort of arms."

Fig. 5 Initial Test Subject Quote

4.4 Hardware Upgrades

Upon upgrading from the Oculus Rift Headset to a newer HTC Vive, the researchers noticed a significant improvement to user experience, both visually and in terms of accuracy of virtual arm position.

4.5 Software Upgrades

In addition, using the "Steam" online VR platform's "Lab Renderer" the team were able to take and improve upon a highly realistic home interior and kitchen environments, allowing the subjects to operate in a believable environment and practice meaningful household tasks such as food preparation.

With continuous advances in the physical hardware and software being used by the Sheffield team, the strength of results they have obtained have only increased, and they are now looking to have the project funded to make their approach a fully approved means of testing and assessment for myoelectric prosthetics in the UK national health service.

5 Training the Prosthetic

The approach mentioned above has great implications for the future of training patients minds and bodies to operate prosthetics of this nature, but it has been observed that neural pathways and signals for the same movements can differ from patient to patient. Indeed, a related study in Toronto (Saposnik and Levin 2011) explored the issues of neural pathway "re-programming" after stroke or serious traumatic brain injuries, which could mean that the same movement intention in a stroke patient could result in entirely different myoelectic signal patterns than that in an otherwise unaffected subject.

To this end, the adoption of the "one size fits all" approach to myoelectric prostheses might be unhelpful. It was with this in mind that a team at the EPFL in France sought to adopt an approach that turned this approach, both literally and figuratively, on its head.

5.1 Brain Interfacing

Using a Brain Machine Interface (BMI) or Direct Brain interface (DBI) this EU funded group had a prosthetic arm carrying out a series of goal related tasks and recording the users' reactions as to whether these were correct or not. The cognitive activity patterns created as the user interpreted the actions of the prosthetic allowed the system to learn the appropriate signals from them to achieve that task, movement or goal in future (Iturrate et al. 2015).

Although this approach was successful enough to be able to replicate goal achievement across several different prosthetic devices with no need to the user to re-learn or adapt their cognitive commands, it was noticed that the signal patterns from each patient differed in all cases.

This indicated that it was incumbent upon the system, at least partially, to learn the intentions of the user, rather than the user to learn the machine.

5.2 Limitations

5.2.1 Convenience/Appearance

This study had three notable limitations – the first being the requirement for a DBI headset to be worn (as shown in Fig. 6) in order to pick up the complex signal patterns in the brain of the subject, rather than merely the myoelectric signals emanating from the nerves and muscles nearest and most pertinent to the users prosthetic.

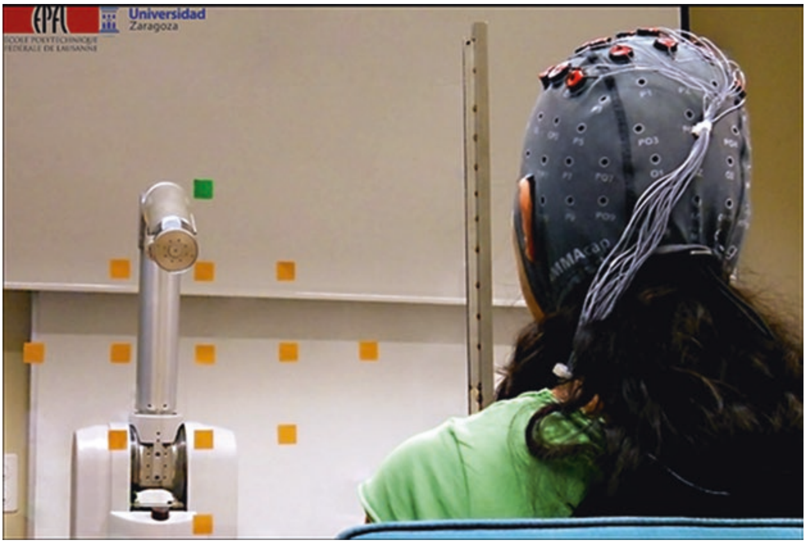


Fig. 6 Direct brain interface prosthetic learning

Although this is likely to be a requirement for the initial "device training" component of the calibration, it may be possible to match this with simultaneous myoelectric observations of the limb connection area. This would ideally create a pattern which can be detected in this area and thus avoiding the need for the subject to wear a DBI equipped cap every time they wish to operate their prosthetic (Johnson 2015).

5.2.2 Limited Complexity of Tasks

Another limitation is that the prosthetic in question is limited in terms of complexity for what is, in effect, a single digit. Although the team have stated that complex movements and kinetic goals can be achieved, there is so far no evidence that this extends to the full range and variety of movements that, for example, a human hand is capable of.

5.2.3 Cost

Finally, the prosthetics used in the (well-funded) studies are all physical, mechanical devices, which does not address the issue of prosthetic cost being a prohibitive factor in the testing and training of many patients in publically or even privately funded clinical environments (Iturrate et al. 2015).

6 A Combined Solution

It could therefore be postulated that combining the clinical approaches, findings and even equipment of both of the studies examined in this chapter, it could generate a number of potential advantages:

6.1 Speed

Given the noted speed at which both studies accelerated the subjects being able to fully control their prosthetics, is can be suggested with relative confidence that combining both approaches may generate results that are more than the sum of their parts in terms of learning time reduction, as the device and user both learn from, and adapt to each other.

6.2 Accuracy

Given the intricate direct brain interface used in the latter study, and the surprisingly effective combination of electrical and visual sensors in the former, it seems worthy of further investigation. Indeed with less laboratory based user experience of the virtual reality home environment and tasks, the results could improve variety, accuracy and real world relevance of movements which could be increased beyond what was achieved in either study alone.

6.3 Intrusiveness

Although, as mentioned, the enhanced sophistication and granularity of data which can be achieved by a cognitive reading from a DBI cap will likely considerably outstrip that of a localised myoelectric band or sensor. Through a combination of these at the training/assessment phase, and the mutual learning potentially generated between the two, it would be worth examining whether consistent, cohesive localised and cranial signals could be identified to allow the user to simulate more complex movements though the local myoelectric interface alone.

6.4 Cost

By utilising a virtual prosthetic, tasks, objects and environment, the associated costs over the European study could be significantly reduced, and the number of people tested in these environments potentially increased (as numbers would not be limited to the volume of available prosthetics).

Also enhanced speed of testing could increase throughput over shorter timeframes, reducing fixed costs per patient trained/assessed, such as premises, staff etc.

6.5 Results

Once again, both studies have achieved ground breaking results, but neither have yet reached what their team members have considered to be their desired end goal.

The approaches used, however different from each other, are to all appearances entirely complementary, and the potential results together therefore are considerably greater than either study or approach could achieve alone.

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Visualising Medical Heritage: New Approaches to Digitisation and Interpretation of Medical Heritage Collections

Kirsty Earley and Ross McGregor

Abstract

New approaches to digitisation and interpretation of the heritage collections at the Royal College of Physicians and Surgeons of Glasgow (RCPSG) have been developed in partnership with the Anatomy Facility at the University of Glasgow. Drawing upon the work of the Medical Visualisation and Human Anatomy MSc programme at the University and The Glasgow School of Art, the approach of RCPSG has been to utilise innovative medical visualisation methods to provide an enhanced level of access to their museum collections. This chapter will discuss how this approach has opened up a wide range of possibilities for how these challenging objects can be interpreted and engaged with. It will outline how visualisation methods such as 3D digital modelling, photogrammetry, augmented reality, and animation can unlock the stories of scientific innovation, of the evolution of medical and surgical care, and of the wider social and cultural context of medical heritage.

Keywords

Digitisation · Digital visualisation · Medical visualisation · Museums · Heritage

1 Introduction

This chapter will outline how new approaches to digitisation and interpretation of the heritage collections at the Royal College of Physicians and Surgeons of Glasgow (RCPSG) have been developed in partnership with the Anatomy Facility at the University of Glasgow. Drawing upon the work of the Medical Visualisation and Human Anatomy MSc programme at the University and The Glasgow School of Art, the approach of RCPSG has been to utilise innovative medical visualisation methods to provide an enhanced level of access to their museum collections. We will discuss how this approach has opened up a wide range of possibilities for how these challenging objects can be interpreted and engaged with. We will outline how visualisation methods such as 3D digital modelling, photogrammetry, augmented reality, and animation can unlock the stories of scientific innovation, of the evolution of medical and surgical care, and of the wider social and cultural context of medical heritage.

The chapter will also discuss how participatory engagement has been a key part of this new approach to digitisation. We will outline how digitisation combined with participatory engagement can enhance understanding of historic medical and surgical procedures and innovations, across a wide range of audiences. In conclusion we will consider how this approach can be embedded within medical heritage practice.

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2 Background

RCPSG's heritage collections include over 3000 medical instruments and pieces of equipment dating from eighteenth to the twenty-first century, in addition to an extensive medical library and archive. The organisation's museum collection began in the seventeenth century, when specimens and objects were collected, stored and used for teaching purposes (Geyer-Kordesch and Macdonald 1999). In these early years the museum collections, along with the library collections, were seen as essential teaching resources to help RCPSG achieve its aims of teaching, examining and licencing physicians and surgeons. By the mid-nineteenth century the museum collection, mainly of pathological specimens, was transferred to Glasgow Royal Infirmary's Pathological Museum, to be used for teaching purposes there. Thus began the development of a different kind of museum – not as a teaching aid to improve the clinical and pathological skills of doctors, but as a repository of historically interesting objects that helped tell the story of the history of medicine.

In October 2015 RCPSG became an Accredited Museum. This is the quality standard in the United Kingdom set by the museum governing bodies, in Scotland's case Museums Galleries Scotland (MGS). Accreditation requires that a museum's collections are cared for and accessed according to the national guidelines of best practice. RCPSG's Accredited status allowed it to re-evaluate its status as a museum, what the museum collection was for, and how it could be better utilised. Accreditation also allowed RCPSG to access funding from MGS to develop its museum practice.

The first step in this process was to secure a small grant for an initial-stage digitisation project in 2016. The project 'Uncovering our medical instruments' employed a Digitisation Project Intern over a 6 month period, to photograph approximately 200 medical instruments, creating digital content for a redeveloped collections website (https://heritage.rcpsg.ac.uk). This project was conceived as the initial stage of a longer-term digital heritage plan, building on a successful MSc placement and dissertation from the University of Glasgow and The Glasgow School of Art's Medical Visualisation and Human Anatomy postgraduate taught programme (Earley et al. 2017).

With the successful completion of this project RCPSG was able to cement digital heritage as a core component of its work. It was then able to propose a more ambitious digitisation project, 'Visualising medical heritage: new approaches to digitisation and interpretation of medical instrument collections', with the aim of enhancing access to its museum collections beyond two-dimensional images. With the support of the Museum Development Fund from MGS, RCPSG was able to begin the two-year project in September 2017, appointing a part-time Visualisation Project Officer.

3 Our Approach

The aim of the 'Visualising medical heritage' project is to research, develop and share participatory approaches to visualisation and digitisation of RCPSG's heritage collections, via a public engagement programme. This section sets out the project's approach and its context, both nationally and locally at the institutional level.

It is important to set out the project's approach in the context of MGS's National Strategy objectives and priorities. Aligning with these national objectives and priorities has allowed RCPSG to develop and improve its museum practice. In the case of this project, RCPSG has been supported in integrating innovative digital technologies and experimental public engagement into its practice. The project demonstrated alignment to all three of MGS's priorities – Enterprise, Skills Development and Advocacy.

The project also contributed to a significant number of the objectives of the National Strategy (Museums Galleries Scotland 2015). Two of these are particularly relevant to this chapter. Firstly, the project contributes to the objective to develop and share collections knowledge by the additional level of research required to provide enhanced access to these collections. Many of RCPSG's museum catalogue records do not contain enough information to provide enhanced access or to offer detailed interpretation of the objects. Collections research was required to explore the instruments' practical uses and impact in their clinical field. Importantly, collections research was needed to find the human stories attached to these objects. Secondly, the project successfully harnessed a number of collaborative and cross-sector opportunities. Most significantly, the partnership with the University of Glasgow's Anatomy Facility provided expertise and support, increasing the project's capacity and impact.

Having established the project's alignment with museum priorities nationally, we can now look at the approach at the institutional level. The project's approach identified three main barriers to accessing RCPSG's museum collections, and the ways in which digital visualisation can be used to overcome these barriers. Firstly, physical access and lack of public display space. This was chiefly addressed by a parallel capital project to improve the display space in RCPSG's building. Part of the capital project included plans to incorporate enhanced digital content into the new display space, for example screen-based animations of historical surgical procedures using 3D digital models of instruments. Secondly, subject matter and perceived barriers to specialist medical collections. As objects, medical instruments can often be perceived as tools for unpleasant procedures, with little potential for engagement with human stories and their wider historical context. However, a strong focus of the project was to explore not only the technology of how the instruments worked, but also the stories invariably attached to them, and the potential interpretation possibilities of these stories. Both the technical and the human elements are key parts of enhancing access. Thirdly, two-dimensional, static digital access. While photography is an essential part of the RCPSG's digital heritage activity (outlined below), the project fundamentally seeks to utilise the full potential of digital images, moving beyond two dimensions. Digital photographs of objects have similar access limitations as the cased display of objects, in that they can't demonstrate how the instruments work. This approach is particularly important when the focus is on increasing knowledge of advances in medical care, how medical care has evolved, and the technological innovations behind these improvements. To provide this kind of enhanced access to the objects, they have to be shown as working instruments, for example as 3D models within animations.

This section has outlined the project's approach – to provide access to how medical instruments work, and to the stories attached to them. The next section will look at the methods used to achieve this.

4 Method

4.1 Photography

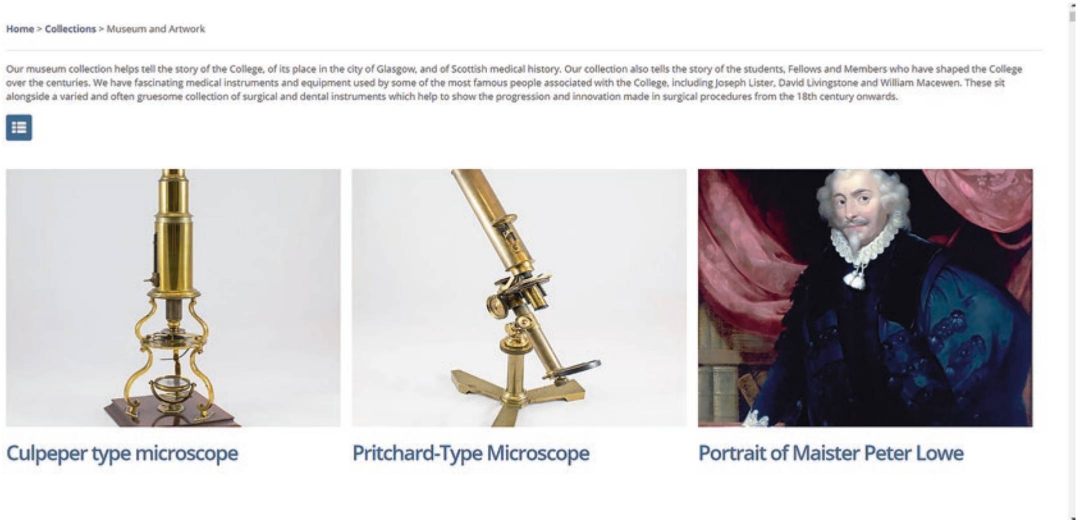
Behind all high-tech visualisation technology lies the basic principles of image capture. While visualisation products are in development, access to museum collections can be provided via web-based catalogues of images. That is why as well as developing visualisation products, providing high quality static digital photographs for web-based display continues to be an essential part of RCPSG's digital heritage activity.

Due to the high levels of specular and glossy materials within RCPSG instrument collections, photography set up is vital for the acquisition of high-quality images. Exposure is controlled using a photography light tent of 90×90×90 cm with two LED lamps on either side and different backdrops for aesthetic variation (Fig. 1). Images are captured using a Nikon DSLR D3300 camera and are then further processed and edited in Adobe Lightroom and Photoshop.

For particularly reflective surfaces prone to glare, a polarising filter is placed in front of the camera lens.

Before the initial-stage digitisation project in 2016 around 60–70 digital images were accessible on the heritage pages of RCPSG's website. These images included items from the museum collection, art collection, and digitised volumes from the library and archive collections. By September 2018, 710 digitised items were acces-

Fig. 1 Photography set up



Home > Collections > Museum and Artwork

Our museum collection helps tell the story of the College, of its place in the city of Glasgow, and of Scottish medical history. Our collection also tells the story of the students, Fellows and Members who have shaped the College over the centuries. We have fascinating medical instruments and equipment used by some of the most famous people associated with the College, including Joseph Lister, David Livingstone and William Macewen. These sit alongside a varied and often gruesome collection of surgical and dental instruments which help to show the progression and innovation made in surgical procedures from the 18th century onwards.

Culpeper type microscope

Pritchard-Type Microscope

Portrait of Maister Peter Lowe

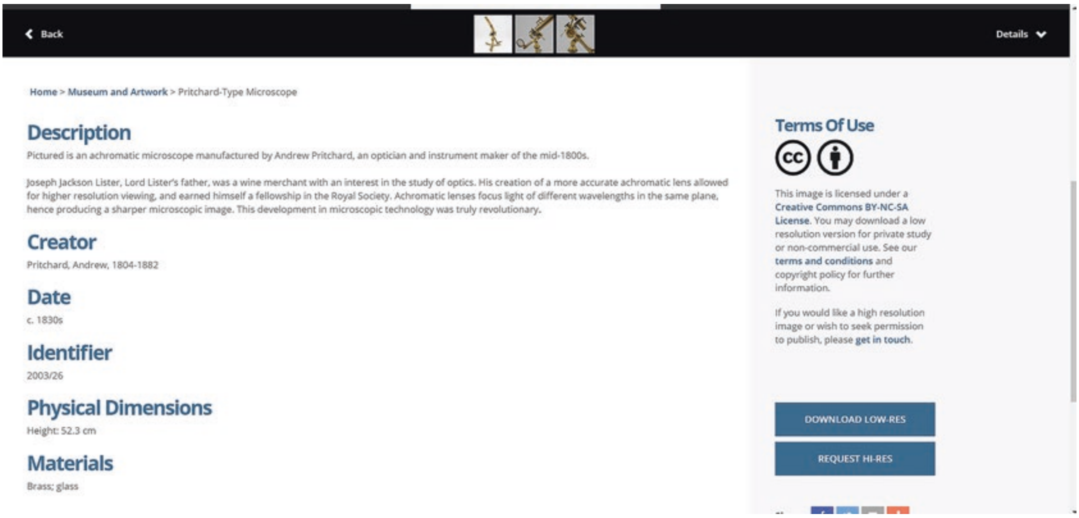
Fig. 2 Updated collections on heritage website

sible on a new collection-focused site for RCPSG's heritage collections (Royal College of Physicians and Surgeons of Glasgow 2018) (Fig. 2).

Each entry contains at least one digital image of the item, accompanied by catalogue information, e.g. description, creator, date, and format (Fig. 3). This initial-stage digitisation project significantly increased the accessibility and visibility of RCPSG's museum collection, while increasing collections knowledge and improving catalogue records.

4.2 Photogrammetry

Since the origins of photogrammetry in the middle of the nineteenth century, it has mainly been



Home > Museum and Artwork > Pritchard-Type Microscope

Description

Pictured is an achromatic microscope manufactured by Andrew Pritchard, an optician and instrument maker of the mid-1800s.

Joseph Jackson Lister, Lord Lister's father, was a wine merchant with an interest in the study of optics. His creation of a more accurate achromatic lens allowed for higher resolution viewing, and earned himself a fellowship in the Royal Society. Achromatic lenses focus light of different wavelengths in the same plane, hence producing a sharper microscopic image. This development in microscopic technology was truly revolutionary.

Creator

Pritchard, Andrew, 1804-1882

Date

c. 1830s

Identifier

2003/26

Physical Dimensions

Height: 52.3 cm

Materials

Brass; glass

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Fig. 3 Supporting data for each item

used for the measurement of geographical areas. Only in recent decades has this method been applied to the reproduction of cultural artefacts.

Photogrammetry itself involves the collation of several overlapping images of a target in order to digitally reconstruct said target in three dimensions. There are clear reasons as to why utilising photogrammetry would benefit a cultural institution. Firstly, the creation of digital copies of collection items adds a level to preservation techniques and can be used to restore lost and/or damaged collections. Secondly, digital collections can overcome the limitations of available space in the physical museum itself. And finally, photogrammetry provides a level of access and immersion to the visitor that is not possible in a physical exhibition.

RCPSG has been using photogrammetry as part of its digital heritage activity since 2016. Initial experimentation began in 2015 with the scanning of six items from the museum collection, each representing a significant advancement in medicine and surgery (Earley et al. 2017). Objects are either placed on a turntable that can be rotated between images, or the object remains stationary and the camera itself circuits around the object in a 360-degree manner.

In the initial study, each item was composed of highly specular and glossy materials, such as glass or metal. In fact, the majority of items held in the museum collections are made of specular materials. This posed an issue when attempting to match overlapping points between photographs – the presence of reflection and glare distorts camera alignment when processing images (Figs. 4 and 5).

Final models were distorted and incomplete, despite the fact that extra steps were taken to increase the likelihood of successful camera alignment. For example, extra markers were placed around the object to act as references for the camera alignment, as well as the application of a polarising filter to reduce glare, and manual masking of images in Agisoft Photoscan. However, the final models were not of high enough quality to be used in public-facing display. Instead, a series of 2D VR models were created to provide an alternative to a static 2D image of the object.

Since that initial study, several advancements have been made in RCPSG's photogrammetry process. Illumination of the scanning environment became more controlled with the application of a light tent and LED lamps, whereas previously lighting was limited to that available in the building. Whereas the level of exposure appears to be an obvious factor affecting scan quality, it is a difficult factor to manage within a

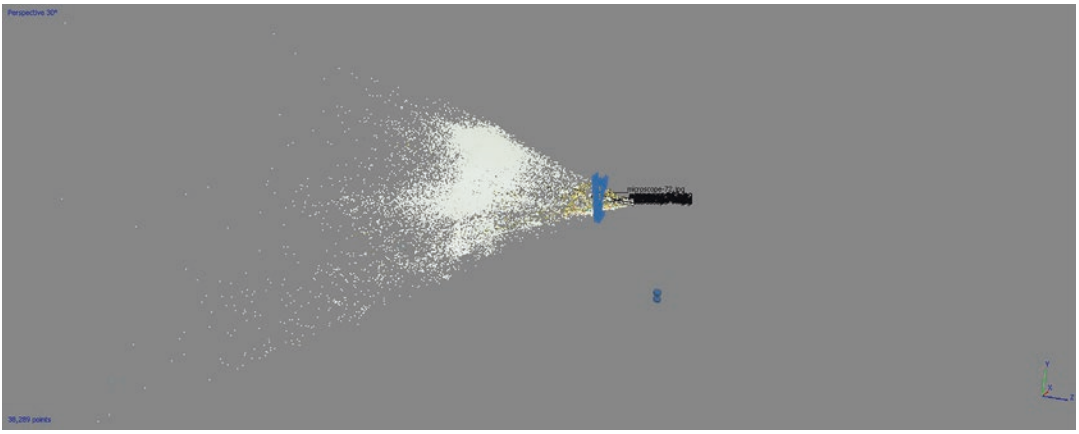


Fig. 4 Poor camera alignment due to specularity

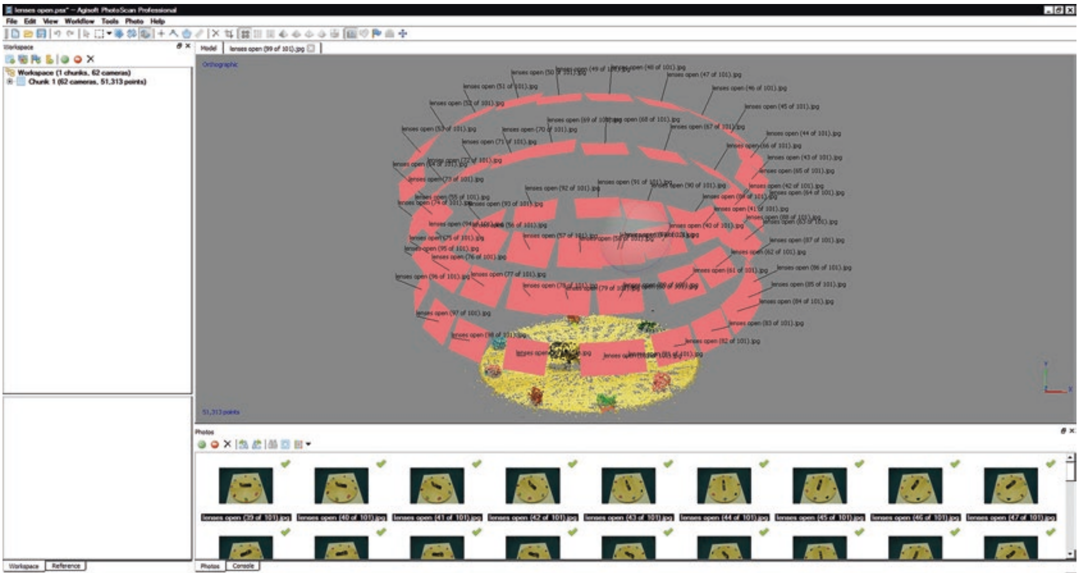


Fig. 5 Successful camera alignment

multi-function building, especially in relation to object size (Menna et al. 2016). The photogrammetry process carried out by RCPSG became much more time-efficient, however it is still highly variable depending on the materials of the collection items.

Although the ability to scan specular objects remains a challenge, meshes can be salvaged and edited in a variety of software programmes, such as Autodesk Meshmixer These tools were not used in the initial study.

Overcoming problems that arise due to the presence of reflections on instrument surfaces continues to be a challenge. It has been shown by several researchers in the field that coating the object with a fine powder decreases the level of specularity in glossy samples (James et al. 2015). In a museum context this level of interference with the surface of the objects is problematic, not least from a preservation perspective. Instead of this, RCPSG chose to model the museum items from scratch in 3D modelling programmes, for example using 3DS Max or Mudbox. Although this method required more time and expertise, it was far preferable to the potential damage to an item as a result of using a powder coating.

It is uncertain as to whether there will ever be a solution to scanning specular items. Although some research into the use of Infrared-based scanners suggests that the scanning of specular objects may soon be possible, more samples are required to determine the likelihood (Aubreton et al. 2013). Until then, it is always good practice to have an alternative. The access to museum items in a 2D static form (photographic image) is better than no access whatsoever. That is why RCPSG continues to update collections online with high-quality digital images accompanied by the relevant catalogue information.

The ability to showcase 3D digital objects online is far easier now than 2 years prior with the increasing popularity of online platforms like Sketchfab. These models can be embedded onto websites or viewed on the Sketchfab mobile application (Fig. 6).

Sketchfab also has a built-in virtual reality (VR) headset setting, allowing the scanned object to be viewed up close in a virtual world (Fig. 7).

3D scanning is becoming an ever-popular method of digitisation for museums and cultural institutions around the world. As of this year, the Uffizi in Italy has published over 300 3D digital models online of their collection, with more to come in the future (Bridge 2018). Another example is the Kremer Museum, a completely virtual museum based on the artwork of the Kremer Collections (The Kremer Collection 2018). What is less common within the cultural sphere is the regular scanning of museum collections in-house, without the aid of external visualisation companies. There is yet to be a staple procedure that can be applied to every type of collection, regardless of size or financial cost (the majority of museums that are utilising high-end interactive technology are those with larger collections and more financial resources).

Another benefit of the use of 3D scanning in the museum sector is the generation of digital

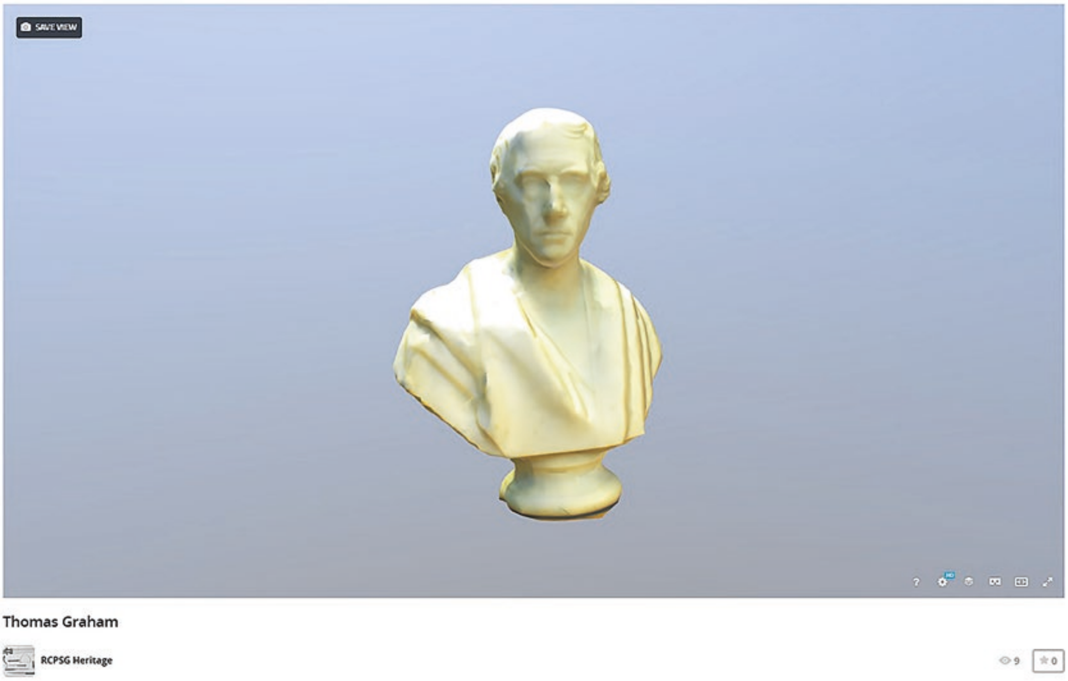
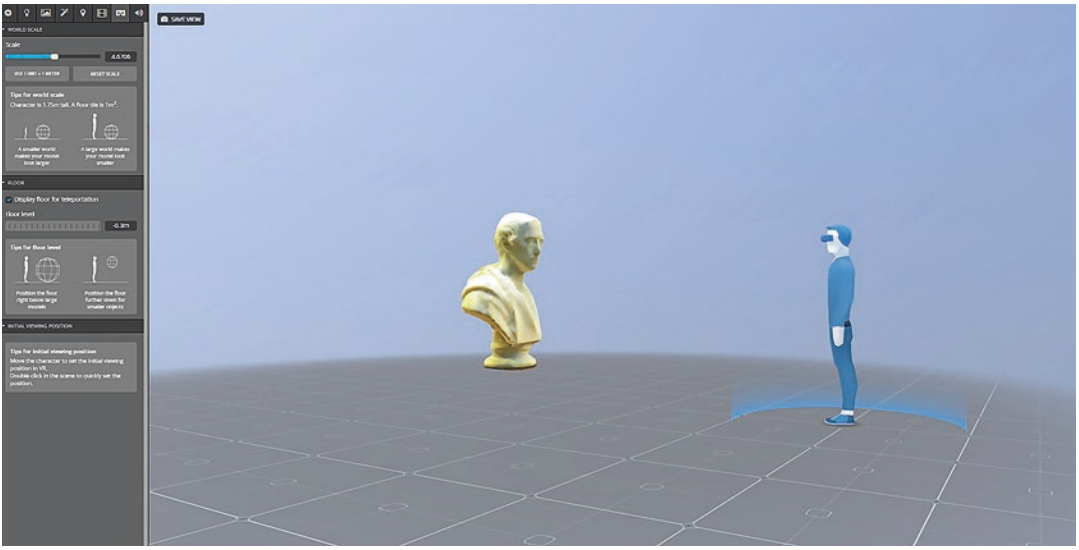


Fig. 6 Example of 3D digital model on Sketchfab



Scale 4.6706

Tips for world scale
Character is 1.75m tall. A floor tile is 1m².
A smaller world makes your model look larger
A large world makes your model look smaller

☑ Display floor for teleportation
Floor level -0.3m

Tips for floor level
Position the floor right below large models
Position the floor further down for smaller objects

Tips for initial viewing position
Move the character to set the initial viewing position in VR.
Double click in the scene to quickly set the position.

Fig. 7 VR headset option in Sketchfab

models that can be 3D printed. 3D printing involves the creation of physical models, usually out of some form of plastic, by building them up layer by layer (Ultimaker 2018). The basis for the 3D print is a 3D digital model that has been developed in a computer-aided design programme (CAD). In a museum context, 3D plastic replicas of items can be printed, which can prove to be valuable additions to collections. Not only do 3D prints act as a mode of preservation for museums, but they also allow visitors to safely interact with items in a manner that provides more access and control to the visitor. 3D prints can also replace items that are difficult to transport when undertaking outreach events, bringing the museum closer to the public (Ferro 2018).

Through photogrammetry and 3D printing, RCPSG was able to produce a physical replica of Victorian doctor, missionary and explorer David Livingstone's humerus cast. The cast shows the obscure fracture of Livingstone's left arm after he was attacked by a lion (Livingstone 1857). The print was created by the Glasgow Science Centre for a collaborative outreach event in 2018 (Fig. 8).

Not only has this 3D print given more access to visitors, but also to researchers. The anatomy of the fracture and subsequent clinical problems it may have caused can be analysed more closely using the 3D print without risking damage to the original cast.

4.3 3D Animations/3D Modelling

The core of the visualisation project at RCPSG, and the core of any product of visualisation, is to communicate information in a way that is easy to understand. To tell a story, of sorts, in an entertaining way. Increasing access to museum collections digitally is an important step, but without the accompanying stories all that is produced is a series of pixels. It remains the purpose of the museum to inform and engage visitors with the rich heritage within its collections.

Along with the number of digital heritage products that have been produced at RCPSG thus far, 3D animations have been a core part of digitising the collections. In a relatively short period of time, visitors can learn the background of an item or collection by watching a "mini-movie". Animations have the advantage of showing the function of the item through 3D visuals – providing access to how the object works and potentially, the stories attached to it (Fig. 9).

However, the production of a 3D animation is time-consuming. Behind the final product are

Fig. 8 Humerus cast and 3D print of humerus cast

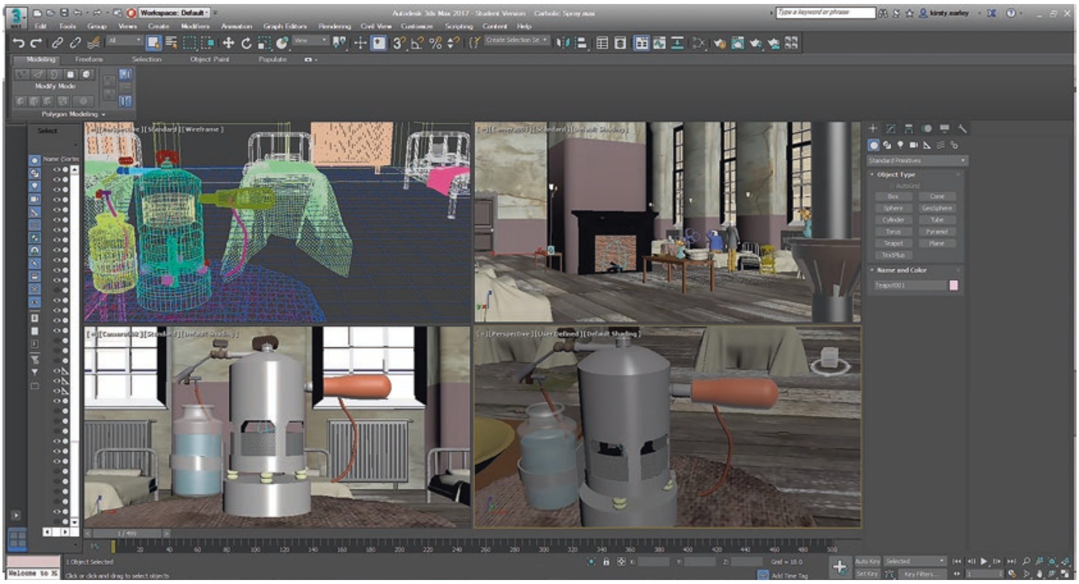


Fig. 9 Scene modelling for Lister Spray animation

lengthy periods of collection research, storyboarding, 3D modelling, animating, scene editing, and post-production rendering. Time can further be extended by the computer software used. Programmes such as Autodesk 3DS Max and Mudbox, along with Adobe After Effects and Media Encoder, encompass a lot of RAM and require a high spec computer to support. Animations can also be limited by the level of training required to learn these programmes.

RCPSG has found the use of 3D animations a valuable addition to its physical exhibitions and displays. During its 2017–2018 exhibition “Physicians and Surgeons of Glasgow”, a series of animations were created and displayed on a screen in the exhibition space. Each animation focused on a particular item or theme within the exhibition and provided enhanced levels of interpretation. For example, one such animation focused on the Laennec-type stethoscope in the museum collection, the first instrument used for indirect auscultation (Laennec 1819), which was simultaneously displayed in a case.

Not only can visitors view the animations within exhibition spaces, they can also view them online via RCPSG's website and YouTube channel. The project is enabling RCPSG to provide an engaging experience of its heritage online to those who cannot visit its building in Glasgow, for example an international audience. Enhancing the online experience for museum visitors is becoming a key role of institutions worldwide (Padilla-Meléndez and del Águila-Obra 2013).

Another benefit of using 3D modelling in a museum digital activity is the reproduction of items that are difficult to display. Within medical heritage, items are often composed of fragile materials, such as glass, and require custom mounts for display. Others can be particularly sharp and dangerous to handle, whilst others may not get displayed due to issues of sensitivity and taste. For example, the public display of anatomical specimens is a highly debated issue (Durbach 2014). Thus, recreating these items as 3D digital models can overcome these barriers and sometimes allow the display of "controversial" items in a more appropriate manner.

A key difference between the digitisation products is the flow of narrative. Though items presented on Sketchfab or via augmented reality can have accompanying annotations with relevant information, the connection of object and interpretation can seem separate. In an animation, catalogue information is used as part of the story narrative, linking scenes together, making the interpretation more integrated.

One thing that is lacking from 3D animations is user control. Although users have the ability to start, stop, and pause animations, they cannot interact with the objects within the animation. However, this can be overcome by presenting the animation online with an accompanying 3D digital model.

Creating a variety of digital products enables museums to communicate information to a wider array of learner types, a theory known as the multisensory learning principle (Shams and Seitz 2008). Physical museum visit experiences, incorporating viewing static objects, reading labels and interpretation, moving around spaces, and so on, are multisensory (Levent and Pascual-Leone 2014). This principle states that everyone absorbs information in different ways, some through visuals, some through audio, some through tactility, etc. Each individual has a more dominant mode of learning that will ultimately lead to a better retention of information. Hence, communicating heritage in such a way that several senses are activated should theoretically engage more people. Combining the visualisation products with different activities, such as storytelling, arts and crafts, and illustration ensures that a wide range of learner types can interact with and understand medical heritage. This informed RCPSG's approach to the project's engagement programme.

4.4 Augmented Reality

Since the mainstream release of virtual reality software in 2016, virtual and augmented realities have become integrated into the structure of museum spaces around the world (Murphy 2018). As people can now experience such technology in everyday life, i.e. at home, they naturally expect virtual interactive experiences at cultural institutions as well. Museums need to evolve and keep their mode of storytelling up-to-date.

Often clumped together, virtual reality (VR) and augmented reality (AR) are quite different. Whereas in VR an individual is transported to a virtual world or space, in AR that virtual world is superimposed onto reality. Everyday examples include photograph/video filters found on a variety of social media platforms.

AR works by attaching a 3D digital model to a tracker in the real world. For example, through AR technology it has been possible for RCPSG to bring woodcut illustrations from Andreas Vesalius's *De Humani Corporis Fabrica* (1543) into the 3D world (Fig. 10). Using an illustration as the template, it was possible to create a 3D digital version in 3DS Max.

By scripting the original woodcut illustration as a tracker, once the image is scanned through

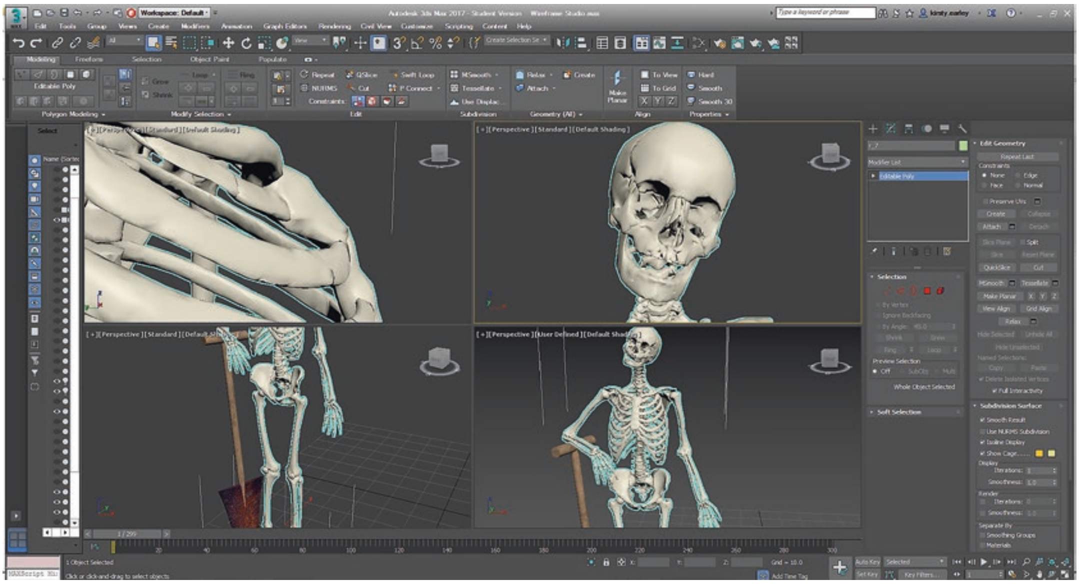


Fig. 10 3D modelling of Vesalius illustration

Fig. 11 AR model in the exhibition

the Augment app, the AR version appears on the screen (Fig. 11). The user can then zoom, translate, and rotate the model at their will.

The current limitation on AR is the ease of availability. At the time of writing there is no universal way for any media device to scan any tracker without the need to download an app. This is mainly due to competing companies developing their own AR software. However, a recent advancement has been made through the production of the first cross-platform AR app created by Google (Gil 2018). Society is not at the stage where every mobile device has AR technology built in, but it is certainly moving in this direction (Ciecko 2018). The majority of new mobile devices have the ability to support AR applications.

It is uncertain as to whether "download-free" AR will ever be possible. This may be problematic in the cultural sphere as not every visitor wants to download an app, in fact some come to museums and galleries to escape technology-driven society altogether (Krauss 2018). There is also the question of whether museum visitors would use mobile applications at all.

One of the benefits of AR in the museum context is the ability for visitors to interact with collection items that would usually be held in glass cabinets or cases. This makes the experience for the visitor educational and entertaining, a balance that museums can find difficult to achieve (Weil 2012). Through AR, fragile items remain protected, yet more accessible. Items that are harmful for visitors to physically hold can also be interacted with in a safe environment via AR. Exhibition content and engagement can therefore be enhanced by AR. However, the level of content should not be restricted to AR – visitors should have the ability to access content through several different modes.

All methods discussed have shown the steps that are being taken to not only help the museum remain relevant, but also be at the forefront of visualisation technology. In order to relate to their audiences, museums must embrace current and new technologies in a strategic manner, using them well and often (Padilla-Meléndez and del Águila-Obra 2013). These techniques are not to replace heritage objects, but to show them in a new light (Waterton 2010). They must develop with the new technology (Lehman and Roach 2011).

5 Engagement

The new approaches to digitisation and interpretation of medical heritage collections as outlined above have one core aim – of making RCPSG's heritage collections more accessible. This driver, of enhancing access, and of tackling the identified barriers to accessing these collections, invites engagement and participation, also at an enhanced level. The engagement programme devised by RCPSG for the project runs in parallel with the exploratory and experimental flow of the digitisation process. Testing, trial, error, showcasing success and investigating failure – sharing this process with an audience is a bold but essential process. If the core driver of the digitisation work is significantly enhancing access for the audience, the audience must be involved.

RCPSG's engagement programme encouraged collaboration, experimentation and reaching new audiences, with the heritage collections at the core. As the project progressed, RCPSG found that further collaborative opportunities were being harnessed, drawing on a wide range of inter-disciplinary expertise. In addition, the collaboration with the Anatomy Facility at University of Glasgow expanded into most of the engagement programme's activities. The intensification of the collaborative nature of the project helped develop new experiences for audiences with an interest in this subject-matter.

RCPSG's first engagement event was a collaboration with historical novelist E. S. Thomson, whose novels explore the period at the threshold of scientific medicine in the mid-nineteenth century (Thomson 2016). The event was a workshop that combined both creative writing and historical medical visualisation, and resulted in the creation of a fictional, virtual nineteenth century anatomy museum. Further events included a collaboration with the Anatomy Facility at the University of Glasgow and Glasgow Science Centre on the theme of Visualising Medical Heritage and Innovation. Combining screen-based visualisation products, 3D printed objects from RCPSG's collections, and pop-up displays of museum collections, the events aimed to unlock the stories of scientific innovation, the evolution of medical and surgical care, and the latest advances in anatomy teaching. The increasing level of collaboration between RCPSG, the Anatomy Facility and Glasgow Science Centre demonstrated the project's ambition to tackle the barriers to accessing medical heritage collections. Glasgow Science Centre attracts approximately 330,000 visitors per year, contributing a fantastic boost to the project's aim of increasing access to medical heritage collections (Glasgow Science Centre 2017).

6 Conclusions

This chapter has outlined how new approaches to digitisation and interpretation of the heritage collections at RCPSG has enabled enhanced access and engagement with these collections. Digital visualisation methods such as 3D digital modelling, photogrammetry, augmented reality, and animation have been shown to help unlock the stories of scientific innovation, and of the wider social and cultural context of medical heritage. The chapter also discussed how participatory engagement has been a key part of this new approach to digitisation. We outlined how digitisation combined with participatory engagement can enhance understanding of historic medical and surgical procedures and innovations, across a wide range of audiences.

How can this approach be embedded within medical heritage practice? RCPSG's heritage activity operates on a moderate budget, and has benefited from moderate levels of external funding. A digital visualisation approach can be embedded in medical heritage practice by approaching it as a normal part of collections access and interpretation, with a priority focused on enhancing access for a twenty-first century audience. Most museum objects on display would be subject to effective labelling and some form of interpretative text. If a digital visualisation approach is prioritised, the object should also be photographed or scanned. The method of visualisation would be adapted depending on the object, the appropriate style of interpretation, and the most effective way of telling its story.

Institutions with medical heritage collections require moderate resources to make this priority shift. However, equally important are the development of skills in digital visualisation techniques (and access to training), and harnessing collaborative opportunities.

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Integrating 3D Visualisation Technologies in Undergraduate Anatomy Education

Iain D. Keenan and Abdullah ben Awadh

Abstract

Anatomy forms the basis of clinical examination, surgery and radiology and it is therefore essential that a fundamental understanding of the key concepts, structures and their relationships is gained by medical and healthcare students during their undergraduate training. Anatomy involves the study of three dimensional entities relating to the human body itself and its constituent structures. In our experience, the appreciation of 3D concepts is one of the most demanding areas for medical student learning of anatomy (ben Awadh et al. 2018, unpublished observations). The ability to interpret 3D anatomical features in 2D cross-sectional clinical images can be troublesome, while the dynamic nature of embryological development is a further challenge.

The aim of introducing technology enhanced-learning (TEL) approaches into our practice is with a view to enhancing undergraduate medical student learning of clinically relevant anatomy. Here we will explore the importance of visualisation and visual learning in anatomy as a scholarly basis for the integration for TEL approaches. We will then describe examples of visualisation technologies that are currently being implemented within the School of Medical Education at Newcastle University based on a research informed understanding of how students learn anatomy. We will consider the available evidence that supports best practice, identify limitations where they arise, and discuss how these visual 3D learning technologies can be effectively utilised as adjuncts and self-directed resources to supplement more established approaches to undergraduate anatomy education.

Keywords

Anatomy education · Visual learning · Visualisation table · Autostereoscopy · 3D printing

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1 Visual Learning of Anatomy

1.1 Evidence-Informed Approaches

The study of anatomy relies upon visual and three-dimensional concepts and it logically follows that appropriate resources should therefore be utilised (Sugand et al. 2010). Modern digital and 3D modalities can serve to supplement more traditional cadaveric approaches and there is evidence that anatomical understanding can be enhanced through the use of imaging resources (de Barros et al. 2001; Erkonen et al. 1992; Pabst et al. 1986). There have been many recent technological developments for the study of anatomy including visualisation tables (Ward et al. 2018), virtual reality (VR) and augmented reality (AR) (de Faria et al. 2016; Hanna et al. 2018; Kugelmann et al. 2018; Ma et al. 2016), and 3D printing (3Dp) (Hu et al. 2018; Li et al. 2017).

That such innovative visualisation technologies are available is not a sufficient or robust basis to use these resources in teaching however, and it is important that a scholarly and evidence-informed approach is taken to the implementation of any educational intervention (Clunie et al. 2018; Pickering and Swinnerton 2018). For example, the concept of millennial students as *digital natives* contrasted with *digital immigrant* educators from earlier generations was a popular idea among some educators during the previous decade since its conception around the turn of the century (Prensky 2001). This concept has been used to support the implementation of technology into curricula (Dreon et al. 2011; Greenhow et al. 2009) but has been critically explored and effectively discredited, due to the finding that the use of certain technologies during their formative years does not necessarily influence a student's ability to learn using those technologies (Bennett et al. 2008; Selwyn 2009).

While the concept of *digital natives* and *digital immigrants* may be consigned to the realm of educational myths, it is important that educators do not fall into similar traps when implementing visualisation technologies. Simply because such technologies are innovative and appealing does not necessarily mean that they are more effective for learning than existing approaches. Furthermore, because such technologies have been implemented relatively recently, there is limited and occasionally conflicting evidence available to support their usage. Indeed, a recent systematic review has identified that much of the available research into technology-enhanced learning (TEL) in anatomy education are not sufficiently comprehensive (Clunie et al. 2018). Moreover, digital visualisation and TEL approaches can be stimulating when initially experienced, resulting in students reporting enjoyment when using these resources (Clunie et al. 2018). Enjoyment does not necessarily lead to effective and deep learning or understanding of 3D concepts in anatomy however. It is likely to be important that students are engaged behaviourally and cognitively as well as emotionally in the technology in order that they may achieve effective learning (Clunie et al. 2018; Pickering and Swinnerton 2018). How students engage should therefore be taken into account when utilising and implementing new TEL visualisation approaches.

1.2 Defining Visual Learning

When educational interventions that are focused upon a particular sensory stimulus are considered, the topic of learning styles is often raised (Pashler et al. 2008). Beliefs surrounding this idea concern the assertion that individual students fall into specific categories of learning and must therefore be encouraged to prioritise learning methods that are appropriate to their own learning style. One of the most pervasive and regularly cited learning styles concerns the categorising of students using the *VARK* (visual, auditory, read/write and kinaesthetic) model (Fleming and Mills 1992). If this model were accurate, then this idea could be extrapolated to suggest that only the proportion of undergraduate students with a visual learning style would benefit from the use of visual technologies when learning anatomy. While the seemingly reasonable and apparently intuitive idea of learning styles has been welcomed by many educators as an effective guide when practically implementing learning approaches, like digital natives, the concept has been effectively discredited (Coffield et al. 2004; Dekker et al. 2012; Hall 2016; Pashler et al. 2008; Rohrer and Pashler 2012). Learning styles should not therefore be used as legitimate justification for introducing visual learning technologies.

The *modality appropriateness* hypothesis (Lodge et al. 2016) however, may be able to effectively inform the use of visual learning methods in anatomy education where learning styles cannot. This model proposes that the approaches which are used to deliver learning are directly relevant to the activities being learnt and is independent of, or greater than, any impact of individual student learning preference (Hall 2016; Lodge et al. 2016). Anatomy learning requires an understanding of the structure and relative sizes and positions of objects in space, and requires the visual identification of structures in specimens and clinical images. Anatomy is also used and presented visually using microscopic and clinical imaging technologies in biomedical research and in medical and surgical practice. The use of visual approaches in undergraduate anatomy learning would therefore seem to be the most appropriate with respect to the modality appropriateness model. At the Newcastle University School of Medical Education (SME), UK, we use of a range of visual learning technologies to supplement anatomy learning for undergraduate medical, dental and biomedical sciences programmes, and postgraduate medical and medical sciences courses. Our rationale for doing so does not include consideration for our students as digital natives, nor is it influenced by the idea of learning styles. Our basis for implementing these technologies is however supported by the modality appropriateness hypothesis and is also underpinned by further concepts described below.

1.3 Integrating Technology with Cadavers

The functionality and utility of visualisation technologies in anatomy education are not limited to the presentation of anatomical images to students in a more detailed, interactive or accessible format, although some digital visualisation technologies can also provide these advantages (Bajka et al. 2004; Choudhury et al. 2010; Palombi et al. 2011; Webb and Choi 2014). Human cadaveric specimens tend to be the core resource utilised in anatomy education, with the view among anatomy educators and students that dissection and prosection are the most effective approaches, and that additional methods exist to support learning with cadaveric specimens (Chapman et al. 2013; Granger 2004). In opposition to this rationale, the logistical and ethical limitations of using cadaveric material have also been used as justification for introducing an anatomy curriculum based on the use of technology and living anatomy (McLachlan 2004). However, some educators have questioned the dichotomy which is occasionally presented as 'cadavers versus technology', based on the presumption that cadavers are the gold standard resource in anatomy education against which all other resources should be judged.

A variety of resources including both cadavers and technology can be complementary (Biasutto et al. 2006) and a recent meta-analysis has provided further support for this view through showing that cadaveric dissection is no more or less effective for learning than other pedagogies when compared to digital media (Wilson et al. 2018). That cadaveric material and digital technologies can provide their own respective advantages would suggest that using both types of resources within an integrated approach would be beneficial for student learning. Within SME, the use of human cadaveric material is considered to be extremely important and the contribution provided by donors is highly valued and respected. Prosected specimens are not used in isolation however, and are instead complemented by the usage of interactive and visual learning resources alongside the cadaveric material within dissecting room practicals. This approach is supported by findings that describe the educational value of variety and active learning (Eagleton 2015; Freeman et al. 2014; Hake 1998; Sugand et al. 2010; Ward and Walker 2008).

1.4 Visual Learning and Spatial Ability

While visualisation is usually defined as the representation of an object as either a physical or mental image, visualisation in the context of anatomy learning can be described in terms of student observational and spatial skills and abilities in the understanding of anatomical features (Pandey and Zimitat 2007). It has been shown that visual observation and visualisation are important processes utilised by students in anatomy learning and medical education (Bardes et al. 2001; Jasani and Saks 2013; Moore et al. 2011; Naghshineh et al. 2008; Pandey and Zimitat 2007; Pellico et al. 2009; Shapiro et al. 2006) Further to this, visually observing anatomical features in colour can also be effective in education as it can influence engagement, memory and therefore understanding (Dzulkifli and Mustafar 2013; Estevez et al. 2010; Finn et al. 2011).

A positive relationship between spatial ability and anatomy knowledge has been proposed (Fernandez et al. 2011; Garg et al. 2001; Guillot et al. 2007; Lufler et al. 2012; Nguyen et al. 2012, 2014; Rochford 1985; Sweeney et al. 2014) and in turn, it has been postulated that teaching methods which can enhance student spatial abilities are likely to be effective for anatomy learning (Fernandez et al. 2011; Vorstenbosch et al. 2013). Taken together with the established differences in spatial abilities and learning with respect to the gender of undergraduate students (Foster 2011; Kelly and Dennick 2009; Langlois et al. 2013, 2015; Linn and Petersen 1985; Masters and Sanders 1993; Schutte 2016), it can be suggested that both male and female students would benefit from anatomy learning approaches that support the development of their spatial abilities.

To explore these interesting findings in further detail however, it is important to establish what spatial abilities actually are. The term *spatial ability* is often used interchangeably with mental rotation ability in the literature, with many studies testing mental rotation as a measure of spatial ability (Garg et al. 2001; Guillot et al. 2007; Rochford 1985). However, spatial ability, which could be often considered as a fixed individual skill, actually may comprise multiple fluctuating attributes and therefore cannot necessarily be accurately measured through testing at a specific time point. A more comprehensive definition of spatial ability can comprise the understanding of spatial relationships, the speed at which objects are perceived, and the ability to visualise and mentally manipulate 2D and 3D objects (Carroll 1993).

All of the skills that constitute spatial ability are likely to be important and actively utilised when students use digital learning technologies, for example when using a visualisation table to view and interpret 3D anatomical structures in 2D clinical images. While the value of using 3D over 2D resources for learning anatomy may not yet have been comprehensively established experimentally (Jurgaitis et al. 2008; Keedy et al. 2011), there is some evidence that 3D resources can be more effective for learning than 2D clinical images (Li et al. 2015). It will be important to investigate all of these factors in future research when considering the impact of digital visualisation technologies on spatial ability and anatomy learning.

1.5 Integrating Clinical Imaging with Anatomy

Even though most practicing clinicians will commonly experience internal human anatomy through observing clinical images (Gunderman and Stephens 2009; Smith-Bindman et al. 2008), and that the identification of anatomical features in clinical images is a professional requirement (General Medical Council 2009; World Health Organization 2016; Royal College of Radiologists 2016), not all undergraduate medical students will go on to specialise in radiology. However, it can be proposed that the use of imaging technologies in medical school should not primarily be seen as preparing future clinicians to use these technologies in their future practice, but rather as an effective means for learning anatomy. Anatomical understanding, engagement, knowledge acquisition and clinical image interpretation can all be enhanced through integration of radiology and anatomy (de Barros et al. 2001; Dettmer et al. 2010; Erkonen et al. 1992; May et al. 2013; Pabst et al. 1986; Slon et al. 2014) and although strategies vary, many institutions currently integrate radiology into gross anatomy education (Al Qahtani and Abdelaziz 2014; McLachlan 2004; Miles 2005; Nyhsen et al. 2013). Based on these findings, it has been recommended that integrated radiology and gross anatomy training be delivered for all undergraduate medical students (Nyhsen et al. 2011, 2013). An effective approach for the integration of radiology teaching into anatomy learning can be supported by the use of digital visualisation technologies. However, caution is advised when considering the introduction of any new approach. For example, and as previously noted (Keenan and Jennings 2017), while ultrasound imaging is commonly used in undergraduate medical education, there is limited good evidence available to support the value of this technology for student anatomy learning, as identified in a recent systematic review (Feilchenfeld et al. 2017).

2 Visualisation Technologies in Anatomy Learning

Having identified some of the cognitive and educational factors surrounding the importance of visualisation in anatomy learning, the specific digital technologies that are currently available to facilitate these processes can be explored. We will describe some of the visualisation technologies used within SME below, how they are used in practice, and the available evidence to support their usage in anatomy education.

Fig. 1 Sectra visualisation table showing tilted screen position, CT stacks in axial, sagittal and coronal planes and 3D image render functionality. (Image courtesy of Sectra 2018a)

2.1 Visualisation Tables

Visualisation tables are now being increasingly used at medical schools to facilitate the integration of radiology and anatomy learning while also serving as interactive digital learning resources. Such devices include Anatomage (Ward et al. 2018) and Sectra (2018a) (Fig. 1) virtual dissection tables. Within SME, the Sectra table is used to supplement anatomy learning as part of wider practical sessions. The Sectra Table runs Microsoft Windows 10 as its operating system, which also allows other Windows-based software packages such as the Virtual Human Dissector (VHD) (Donnelly et al. 2009; Fogg 2007) and virtual anatomy atlases and to be installed and used, in addition to the primary usage with the

Sectra picture-archiving and communication system (PACS) imaging software (Sectra 2018a).

The Sectra table has a 55 inch touchscreen that can be tilted at different angles depending on user preference. The screen can be positioned as upright flat screen monitor that the educator can use to present, a virtual dissecting table that students can work around as a small group, or at other intervening angles. The Sectra table is mobile to the extent that it can be moved from one venue to another, for example between the dissection room, the clinical skills laboratory and a lecture theatre. In terms of functionality, the touchscreen monitor allows the interaction and the manipulation with images and the features by allowing the user to scroll up and down, zoom in and out, rotate images and manipulate the contrast, as well as swiping and navigating between images.

For typical usage in teaching, the Sectra PACS software can present a computed tomography (CT) stack of digital imaging and communications in medicine (DICOM) images in the axial plane. Patient cases are accessed via the Sectra Education Portal (Sectra 2018b), a secure and online library of anonymised anatomical and clinical content which allows educators to create, share and access cases between users across institutions around the world.

When using a specific patient case presented as a CT stack, once the CT images have been viewed and features have been presented and identified in cross section by students, the processing power of the Sectra table CPU is capable of achieving a 3D image render of the case in real time. Features such as the heart, lungs and thoracic cage will then be immediately displayed on the screen and represented as three-dimensional. The 3D render can be manipulated via the touchscreen in terms of movement, magnification, rotation, dissection, and 'preset' functions. Presets allow different tissue types and features, for example musculoskeletal structures, soft tissue, vasculature and the air within the lungs and gastrointestinal tract, to be viewed in isolation within the 3D render. Presets can also be combined so that different structures can be observed simultaneously. Users can dissect in any plane through the 3D render, for example to remove the sternum with a single cut to reveal the heart beneath using a virtual knife. This function also allows removal of superficial layers such as the skin and muscles, which can then also be easily replaced. The software provides functionality whereby bookmarks can be created from existing cases so that particular dissections and presets can be applied, in addition to a function that allows specific features of the 3D render to be labelled. The labelling function allows answers to be hidden so that students can attempt to identify structures before the answer is revealed.

We have developed our own protocols for usage of the Sectra within SME for usage in anatomy practical sessions. These protocols are used both by facilitators and students to access specific cases and bookmarks relevant to the session being taught. Typically, we use the Sectra to deliver learning outcomes relevant to clinical image interpretation and to support and enhance broader understanding of cross-sectional and three-dimensional anatomy. Clinically relevant content can be also be demonstrated to medical students by comparing normal anatomy with pathologies and common anatomical variations that are present in some patient cases. Sectra is normally included as part of a wider session in which a variety of traditional resources are used, focused around facilitated group learning activities with cadaveric prosections, and both commercially available and 3D printed anatomical models. In this way, small groups of students are able to view and use the Sectra in the context of the anatomy they are learning. In an SME cardiovascular anatomy practical, the first dissecting room session that new medical students experience at Newcastle, the Sectra table can be used to show a CT stack from a thorax case. Students are shown and asked to identify features of the cross-sectional anatomy of the heart such as the borders, chambers and vessels. The digital 3D render provided by the Sectra and physical 3D models of the heart and thoracic cage can be used in combination with the 3D render to emphasise the anatomical position of the heart versus the 'valentine' position made popular in contemporary culture, and also the orientation of the ribs as angled inferiorly rather than projected horizontally away from the vertebrae. An understanding of these concepts by students is essential when applying their knowledge in the context of palpation and auscultation positions within clinical cardiovascular examinations.

Furthermore, the VHD provides interactive dissection functionality and interactive viewing of cross-sectional anatomy in axial, coronal and sagittal planes, details of which have been described elsewhere (Donnelly et al. 2009; Fogg 2007). Within SME, the VHD is used in combination with the Sectra, cadaveric material and other resources to support learning of 3D anatomy and clinical image interpretation. The VHD is particularly effective when used for team-based activities in which students are asked to observe cadaveric specimens, visualise a specific axial cross-section and then to draw their understanding of the anatomy at that level. The VHD can then be used to check and support their drawings and therefore their understanding of cross-sectional anatomy.

2.2 Remote Anatomy Visualisation Resources

In addition to the learning technologies themselves, how these resources are practically implemented beyond the face-to-face teaching environment must also be considered in order to support modern approaches for the delivery of self-directed approaches. Encouraging students to take responsibility for their own learning, and the influence of content requirements and timetable pressures within medical programmes, can reduce the time available for contact teaching. One solution to this, which has been implemented at SME, involves increasing the availability of self-directed learning (SDL) resources for medical students. Recent studies of SDL in medical and health professions education support this approach by indicating that there can be value in encouraging and supporting undergraduate SDL activities (Murad et al. 2010; Murad and Varkey 2008; Slater and Cusick 2017). Integrating SDL into anatomy education has increased the requirement for access to the remote delivery of visualisation resources so that students have access to these potentially valuable resources outside of the dissecting room. While modern students may not possess any educational advantages from being *digital natives*, they do have wider access to their own smart devices and computers than their predecessors, (Gikas and Grant 2013; Khan et al. 2009; Ponce et al. 2014) and therefore the capacity to view and utilise remote digital visualisation learning resources.

The delivery of visual anatomy learning can be effective via e-learning resources such as interactive online tutorials (Backhouse et al. 2017; Choudhury et al. 2010; Feng et al. 2013; Van Nuland and Rogers 2015a, b) and massive open online courses (Pickering et al. 2017; Swinnerton et al. 2017). Within SME, an online tutorial system which students can access via their virtual learning environment allows access to anatomy resources and content from other medical disciplines, while the VHD can also be accessed outside of the dissecting room. The evaluation of certain SME online anatomy tutorials has demonstrated that they can be effective for learning (Backhouse et al. 2017). In addition to usage on the visualisation table during practical sessions, the available library of anatomical and clinical cases can also be accessed remotely via secure login to the Sectra Education Portal (Sectra 2018a). Cases and bookmarks can be personalised and customised by educators for student SDL activities.

2.3 Digital Autostereoscopic 3D Visualisation Technology

While anatomical features are regularly presented as three-dimensional objects on flat 2D screens, we have implemented an autostereoscopic (glasses-free) 3D screen approach in order that students can visualise digital anatomy presented in three-dimensions (Geng 2013). The Alioscopy 3D Display screen (Fig. 2) possesses Alioscopy's patented lenticular lens array, which is bonded to the front of the LCD panel to deliver volumetric and multi-view auto-stereoscopic

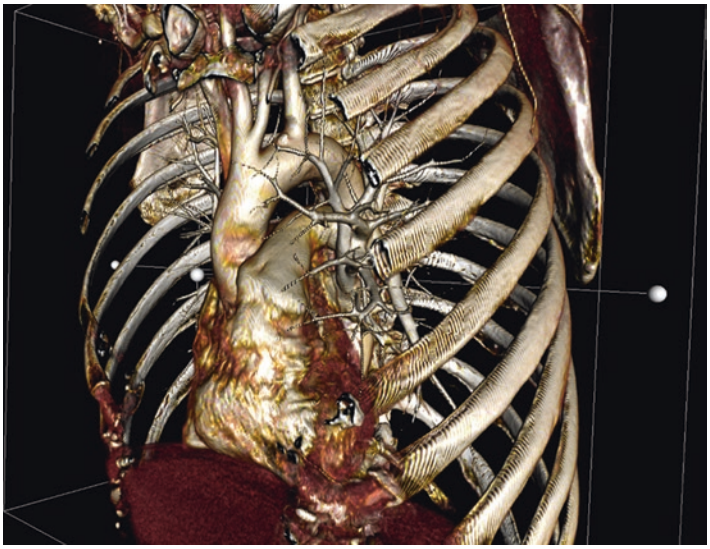

Fig. 2 Example image of the thoracic cage and heart within DICOM 3D software, that can be viewed autostereoscopically on the Alioscopy screen. (Image courtesy of Alioscopy 2018)

glasses-free 3D images using electronic displays (Alioscopy 2018). This enables groups of viewers to stand in front of an Alioscopy 3D Display (within a 100° viewing angle, 50° either side of the centre point) and view high resolution anatomical 3D images without the need for 3D glasses, which can be ideal for the dynamic nature of the practical anatomy learning and teaching environment. The Alioscopy DICOM 3D software supplied with the screen can convert DICOM images from CT or MRI datasets to render volumetric and multi-view autostereoscopic 3D images for presentation on the Alioscopy display in real-time. While 3D autostereoscopic technologies cannot currently be used for SDL purposes due the requirement of a specialised 3D screen, this approach can be effective within the dissecting room for presenting normal and pathological images in 3D that students may not otherwise have access to in terms of physical cadaveric specimens. While the use of this technology is in its infancy within SME, we consider that the Alioscopy screen will be valuable in the future for students to visualise the 3D arrangement, size, shape and position of important anatomical structures. We intend to develop and implement additional Alioscopy resources and to evaluate the impact of this technology on student learning and experience.

2.4 Visualisation of 3D Printed Anatomical Models

In contrast to the visualisation tables and 3D autostereoscopic technology described above, a number of research studies have generated evidence to support the use of 3Dp models in anatomy and medical education. 3Dp draws favourable comparisons with digital and physical anatomical models and resources (Chen et al. 2017; Lim et al. 2016; O'Reilly et al. 2016), and we have reviewed the advantages and limitations of 3Dp in anatomy education extensively elsewhere (Li et al. 2017). While 3Dp may not necessarily be considered as a visualisation technology, this approach does allow clinical images to be visualised and observed in three-dimensions. 3Dp also provides the additional advantage of students being able to handle and physically manipulate models and to potentially take them outside of the dissecting room for SDL purposes. 3Dp provides tactile learning (Jones et al. 2006; Reid et al. 2018) experience alongside visual 3D experience, and different materials can potentially be used to represent different structures within a single model. Some evidence indicates that there may even be an educational advantage of using physical over digital 3D models for learning anatomy (Preece et al. 2013).

An anatomy department with a 3D printer and access to DICOM images can produce bespoke models to suit different aspects of their course and focus on particular areas in which they may be lacking resources or that students find particularly troublesome. Having identified challenging topics and concepts (ben Awadh et al. 2018, unpublished observations), we have been able target our models towards these areas within SME. While different types of 3Dp models may be more effective for learning than others (Kong et al. 2016), the types of anatomical structures that can be produced by 3Dp are dependent on the type and specification of printer and materials used, and therefore are directly related to the costs of the equipment and consumables. In order to generate 3Dp models with anatomical details that can be compared to prosections or plastinated cadaveric specimens, a high specification, high cost printer is required (McMenamin et al. 2014). Complex arrangements of anatomical structures, for example membrane reflections, may be possible using a high specification printer, and different materials and colours are available to facilitate this (Maragiannis et al. 2015). However, simple but effective and educationally valuable models for use in taught and SDL contexts can be produced at a fraction of the cost (Smith et al. 2018). Using licensed software to convert DICOM files into 3D printer datasets can also incur large costs, but we have found that open source software can also be used effectively for this purpose.

Within SME, we have recently purchased a Prusa i3 3D printer for prototyping and training of staff and project students, and a Raise3D Pro2 3D printer (Fig. 3) for producing final educational models for use in teaching. We have developed our own protocol for the processing of DICOM datasets into 3D image stereolithography files (STL) via 3D Slicer (2018), Meshmixer (2018) and Blender (2018) open source software. Using DICOM images allows the production of models with anatomical variations and pathologies that are not always present in commercial physical and digital models (AbouHashem et al. 2015; Moore et al. 2017; Nieder et al. 2004; O'Reilly et al. 2016). STL files are then imported into Raise3D ideaMaker printer software for scaling, positioning and for the addition support structures that provide model stability during printing. The final file is then imported to the printer either by USB drive or SD card for printing.

While digitally painted 3Dp models can be produced for clinical and pedagogic purposes (Ejaz et al. 2014), the activity of physically drawing or painting labels and features on anatomical 3Dp models may also provide added educational benefits, on the basis that artistic approaches can be effective for anatomy learning (Backhouse

Fig. 3 Raise3D Pro 2 printer demonstrating Raise3D ideaMaker software and examples of 3D printed models. (Image courtesy of Raise3D 2018)

et al. 2017). 3Dp models can also be used to complement body painting, clay model and other activities when students are applying their understanding of the anatomical basis of clinical examination. For example, we have provided 3Dp kidney models printed to scale and asked students to place them into a model skeleton at the correct anatomical location based on their knowledge of abdominal anatomy, anatomical planes and the position of surface landmarks including the ribs and intercostal spaces. When working with the Sectra table and considering the cross-sectional and 3D anatomy of the kidney digitally presented onscreen, we can provide each student in the group with a 3Dp model kidney to support their understanding through observation and physical manipulation of the model in three dimensions. In the longer term, we hope to produce models to the extent that we can provide >300 students in each medical cohort with access to 3Dp models for SDL, to support use of the Sectra Education Portal and other remote resources.

3 Summary and Future Directions

Having recently introduced the Sectra Table and Education Portal, the Alioscopy screen and 3Dp anatomical models into our delivery of anatomy education within SME at Newcastle University, we are in a position to be able to provide some insights regarding the practical and logistical implementation of these new digital visualisation technologies into an integrated anatomy curriculum. While our current approach has been based on an understanding of the importance of visualisation, active learning and conceptualisation of 3D and cross-sectional anatomy, our future evaluations will shed further light on the potential value of these technologies. We aim to identify the extent of student performance and perceptions having used our Sectra, Alioscopy and 3Dp resources. In doing so, we aim to provide a greater understanding of the capacity of certain anatomy visualisation resources to facilitate learning through enhancing visual learning, interactivity, spatial ability and anatomical understanding.

The examples of visualisation technologies used for anatomy learning and teaching within SME are by no means exhaustive, and many other digital approaches are currently being employed in anatomy and medical education throughout the world. Historically, 3D techniques have been used to visualise anatomy in three-dimensions since the early stereoscopic atlases (Bassett 1954), which has more recently been achieved using stereoscopic software (Trelease 1998). Modern techniques for 3D visualisation include holographic imaging (Miller 2016) such as Microsoft HoloLens (Hanna et al. 2018; Microsoft 2018). These approaches are gaining attention for their capability in presenting virtual interactive 3D representations of anatomical structures within practical teaching, although initial set-up costs may deter some medical schools. Photogrammetry, an image-based modelling technique which produces digital 3D model and files suitable for application to 3Dp is becoming increasingly popular in anatomy education (Turchini et al. 2018), alongside a range of other 3D virtual modelling approaches (Beermann et al. 2010; Hoyek et al. 2014). Furthermore, VR (de Faria et al. 2016; Fang et al. 2014; Levinson et al. 2007; Nieder et al. 2004) and AR (Christ et al. 2018; Kucuk et al. 2016; Kugelmann et al. 2018; Ma et al. 2016) techniques are progressing in terms of their effectiveness and application to anatomy education. AR and VR can potentially be used as remotely accessible, if expensive, alternatives to autostereoscopic screens for the presentation of three-dimensional anatomy without the need for models or cadaveric specimens.

Further to the consideration of gross anatomy education, an understanding of human embryology is important for medical and biomedical students. Many clinical disorders arise due to alterations in normal development (Hamilton and Carachi 2014) and the dynamic and three-dimensional nature of development can be a troublesome concept for students to appreciate (ben Awadh et al. 2018, unpublished observations). Visualisation approaches to embryology include digital resources (de Bakker et al. 2012) and 3D-ultrasound (Werner et al. 2010). We aim to develop and evaluate visual digital embryology resources based on real human embryos (Keenan et al. 2016) that can be presented via our existing technologies, while providing complementary physical 3Dp embryos in order to demonstrate both normal development and common congenital abnormalities.

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Pedagogical Perspectives on the Use of Technology within Medical Curricula: Moving Away from Norm Driven Implementation

Gabrielle M. Finn and Joanna Matthan

Abstract

There is often an expectation that any educational institution worth its salt will be at the forefront of technological advances. An often unchallenged and somewhat romanticised viewpoint persists that, in all cases, technology is best. What is not always openly discussed is the evidence base and pedagogy behind the use of technology, visualisation and traditional approaches of teaching within the fields of medical and anatomy education curricula. There are many advantages to using technology within the learning environment but, often, it is possible to achieve the same outcomes through the use of many other non-technological instructional modalities. The frequent shortcoming when institutions use technology is that there is a lack of integration across the curriculum, a failure to map to the blueprint, little attempt to include technology in the feedback cycle and assessment, and insufficient time and resource allocation for educators developing resources. Without careful implementation and integration, it can appear that institutions are throwing the latest developments at students without due care and consideration to the evidence-base and without the necessary institutional support for staff and resource development. This is not the fault of educators; the competing demands on staff time and institutional drive to climb the ranking tables means that technology is often perceived as the quick fix.

Keywords

Technology · Curriculum · Medicine · Learning · Research · Visualisation · Pedagogy · Education · Students · Learners · Educator · TEL · Technology-enhanced learning

1 Technology Within Curricula

Technology, once an advance on the education landscape, is now mainstream and at the core of medical education – as well as education more broadly. Educators are bombarded with arguments as to why the latest technology must be implemented in order to optimise the learning experience for '*generation X*' or the '*digitally native*' student populus, with the widespread unchallenged assumption that 'millennials' require on-demand technology-enhanced

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learning resources (Roberts et al. 2012). Little contest is given to the idea that technology enhances learning, or indeed to the notion that programmes 'need' technology to ensure student acceptability. This chapter considers the frequently unattested viewpoint that technology always enhances learning.

1.1 What Does Technology Offer the Learner, and What Does It Not?

There are pros and cons to most things in life – technology being one such commodity. Technological advances are often lauded as revolutionary, cutting edge or at the forefront of innovation – this is likely true. A plethora of literature supports the idea that technological tools can foster students' abilities, revolutionise students' thinking, take their work to another level, provide them with new access to the world, support meaningful learning, facilitate collaborative learning, and enable the presentation of both dynamic and spatial images to portray relationships among complex concepts (Peck and Dorricott 1994; Dori and Belcher 2005; Resta and Laferrière, 2007).

2 Technology Within the Context of a Medical Curriculum

Technology is omnipresent and permeates every level of modern medical curricula. A typical undergraduate medical programme will include a host of technological enhancements, in addition to the traditional small and large group delivery methods. Virtual learning environments, such as Blackboard, provide learners with spaces for collating a range of course material utilising textual and visual learning material. Across institutions, lectures may be recapped to enable students to revisit tricky concepts at their leisure, some lectures are even relayed in real-time across sites, allowing students the option of either synchronous or asynchronous participation. Student response systems, such as TurningPoint and OMBEA, encourage students to engage more within large lectures, with the underlying assumption made that learner engagement equates with improved learning and retention. Learners may be encouraged to use their own devices in learning environment, or devices may be provided to enable engagement; these direct educators to gauging the pitch at which to deliver concepts. Educators may be encouraged to develop self-directed material for students using custom-made software or by utilising desktop capture technology, in a move to more self-directed learning and less face-to-face contact time.

Social media sites, such as YouTube, supply a constant stream of education channels, some institution endorsed, to target learning in specific specialisms, with resounding evidence that external digital learning resources are embedded into the learning toolkit available to medical students. Further, educators may utilise social media such as Twitter, Facebook, Instagram and Snapchat to provide a platform for discussion or dissemination of material related to their teaching or wider academic interests, despite the shelf-life of numerous platforms being unpredictable – hundreds have cropped up and disappeared into oblivion since the start of the millennium (Guckian and Spencer 2018; Dijck 2013). Feedback software systems allowing students to see comprehensive breakdowns of their exam performance may also be utilised to guide further learning. Simulation and video playback technology may further enhance learning in the latter years of the curriculum, utilising both expensive and resource-heavy technology to deliver teaching and learning in safe environments and provide the opportunity for expert feedback, or self assessment (Phillips et al. 2017). Although technology has been utilised very little in assessment, institutions increasingly utilise software such as Turnitin to prevent plagiarism and a surge in essay mills, with a recent surge in developmental projects seeking to incorporate more technology into the assessment process. Learners at all levels are encouraged to utilise well-established commercial exam banks with thousands of exam questions to improve their multiple choice response skills, leading to the establishment of free versions with questionable and unvalidated content that may inadvertently be detrimental to learners' knowledge base.

The widespread assumption prevalent in the education industry is that all learners have access to technology (not least, the financial means to pay for unlimited access to data and devices), want to use it and thrive in environments that endorse its use, with little institutional consideration for current and future stakeholders from widening access backgrounds (Delgaty et al. 2016). Beetham and White (2013) postulate that there is little understanding of how and why future university students will be using technology and, as institutions are encouraged to diversify their intake, themes around social equity and the digital divide (Lee 2017) must feature in universities' digital strategies to avoid inadvertently disadvantaging those stakeholders whose default is already one of disadvantage (Delgaty et al. 2016).

2.1 Freely Edited Content and a Call for Integration

Undoubtedly, technology makes information more readily available – whether it be at the click of a button or the swipe of a finger across a screen – an almost infinite number of resources are freely accessible. Of course, the counter to that, as Herring (2001) presents, is that the internet, unlike a physical library, does not have quality control. Herring also reminds readers that not everything is online, and that an online search may be analogous to searching for a needle in a haystack. The internet delivers information on the move, with unlimited access hours and no overdue book fines – it is not difficult to see why students love the internet as their primary source of information.

The internet has many excellent resources, and it thus becomes the duty of educators to upskill students in exercising criticality and caution when choosing sources and deciding on what is correct, but also in keeping themselves abreast of the constant barrage of new resources and applications, both freely available and commercial, and to potential dangers lurking in their lack of continued professional curiosity with regards to technological advancements in the field. Wikipedia is one such example – educators the world over will be sick of hearing, '*but it says on Wikipedia that…*', or reading a bibliography with Wikipedia as the most cited source.

A 'wiki' (noun) is a website or database developed collaboratively by a community of users, allowing any user to add and edit content. Wikipedia is the largest and most infamous wiki. What most users do not realise is that anyone can edit wikis. The editor of any given page could in fact by the world authority on a topic; however, it could also be someone with no credentials on the topic at all. Whether it is the duty of educators to ensure students are aware of limited rigour and quality control of freely available internet information, or whether it is the responsibility of the reader to consider the credibility of the sources they review is a contentious debate. Collaborative medical education learning resources, such as mediwikis, endorsed by medical organisations and colleges, do have verified content uploaded but this does not necessarily hold true for the majority of wikis. The point is that, while technology makes information easily accessible, it may not always present information that is correct or trusted. Naturally, the definition of a wiki for this chapter was looked up on Wikipedia, leaving the reader to decide on its veracity (Wikipedia 2018). In recent years, the reliability of Wikipedia has been challenged. A report published in *Nature* claimed that the information provided on Wikipedia was almost as reliable as that of the Encyclopedia Britannica (Giles 2005). Another study found that Wiki articles were on a par with professionally edited databases for health-care professionals. Readers were warned to err on the side of caution when turning to Wikipedia as a primary source of scientific information, the authors suggest that it is read critically and 'with the understanding that the content is dynamic and vulnerable to vandalism and other shenanigans' (Wilson and Likens 2015).

Wikis are a collaborative space – provided that they are not constructed in isolation. With careful, considered constructive alignment to the curriculum, they can be a tool for fostering peer relationships, for shared learning and, for integration of cognitive knowledge. They offer a tool for constructing new knowledge, sharing existing knowledge and linking technology to assessment as group efforts can be assessed for formative and summative purposes. Wikis are an example of the best and the worst that technology has to offer – a space to share but one that may be unregulated and therefore facilitate the sharing of fundamentally incorrect ideas, to the detriment of the learners. For online educational programmes, wikis can drive programme integration from the curriculum outline to the assessment blueprint and to the learning communities created – but they must be regulated, with authors held accountable for inaccuracies in their work.

A major limitation in the use of technology within education is that it is often limited to delivery and fails to feature in the feedback cycle or the assessment toolkit. Simple technological interventions, such as video playback, can be incorporated into the feedback cycle with good results (Phillips et al. 2017; Rammell et al. 2018) but the institutional commitment required to integrate it into the toolkit available to educators is somewhat lacking. When technology does feature in assessment, it is not integrated and its optimal functions utilised, but rather a basic tool for test administration. Simulation is one such example of the failure to integrate technology and assessment. Simulation within medical education has become extremely high fidelity, with enormous effort and resource invested in its use. The limitation is that simulation is most frequently restricted to use as a learning opportunity, rather than being integrated into the assessment structures and portfolios of institutions; this seems diametrically opposed to the rationale behind the implementation of simulation, real-world experiences for students, which should include assessments. A clear action point for technology enthused readers is to think carefully about how you map technology within your curriculum, ensuring its use is proportionate, representative and integrated.

3 Is Technology the Vehicle for Learning?

Within medical education, there is a long accepted view that learning anatomy from cadavers is the optimum method. Anything else, whether it be technology, plastic models, or an artistic approach such as body painting, is merely an adjunct. This viewpoint is often presented in the absence of evidence, prone to educators' biases based on their own educational experiences and preferences. Within the school based education literature, there is a philosophy of thought that teachers who readily integrate technology into their classroom are more likely to possess constructivist teaching styles (Judson 2006). Constructivism theories suggest that knowledge and meaning are constructed from the experiences of learners. It is important to note that constructivism is not a specific pedagogy. The implication from the link between the use of technology and constructivist approaches to pedagogy is that teachers who employ a constructivist-mindset maintain dynamic, student-centered classrooms, where technology is a powerful learning tool (Judson 2006). Through constructivism, the student transforms from a passive recipient of information or cognitive knowledge into an individual who is actively participating in the learning process. What drives this process – is it the technology or the teacher, or both?

3.1 What Does Technology Add That Other Modalities Do Not?

Only the most cynical educator will fail to appreciate the manifold opportunities afforded by technological advances. For the learner, numerous technological educational interventions have led to greater levels of engagement with key curricular material. Several widely utilised interventions offer learners incredible ease of access and the possibility to engage with the learning process in real-time or asynchronously across time and place. The lure of the screen to capture the attention of the learner is unparallelled, and the perception that learning is taking place while, sometimes, passively receiving information appeals to our sense of laziness and desire to learn with minimal effort. In fact, so common is the lure to utilise the internet and other readily available resources, it has led to a phenomenon known as digital amnesia (more commonly known as *Google effect*, Sparrow et al. 2011) or the tendency to forget information easily accessible utilising internet search engine such as Google due to the belief that the material is always at hand and available online. For the educator, technological advances offer limitless possibilities to enhance the learning experience for students and to present foundational knowledge in newer and more innovative ways. Institutionally, technology and the perception that it is widely utilised may impact on the all-important student satisfaction rates. So considerable and limitless are the digital opportunities for education that a national membership organisation is at the forefront providing digital solutions for education and research (JISC 2018). JISC recommends institutions and educators alike embrace technology, share discoveries, use time-saving technology, and sharing material across institutions. Their vision for technology usage in education is all about joined-up thinking, where for instance teaching and assessment are linked within an institution but also between institutions, and collaboration with others leads to seamless integration of technology into our everyday education.

4 Technology Is Not Always Better

One technology often found within the anatomists' toolkit is the portable ultrasound. Ultrasound machines have become cheaper and therefore more mainstream. Griksaitis et al. (2012) challenged the view that cadaveric anatomy was optimal when teaching gross anatomy of the heart by conducting a randomised control trial. The intervention was the use of portable ultrasound, the control was typical cadaveric anatomy teaching using prosections – the industry gold standard, so to speak. The study concluded that prosections and ultrasound are equally effective methods for teaching gross anatomy of the heart, as both of the teaching modalities used increased students' post-test scores by similar amounts but no significant difference was found between the two conditions. The authors advocated the inclusion of either cadaveric teaching or living anatomy using ultrasound within the undergraduate anatomy curriculum.

The aforementioned example perhaps highlights the notion that no teaching modality is ever truly superior. If one unpicks the learning experience surrounding the use of ultrasound, many advantages and disadvantages could be postulated. Firstly, students experience living anatomy as the scan is performed on a live volunteer. They get introduced to a technology that will be commonplace in the clinical environment that they will work within once qualified. They get introduced to ultrasound images and how to interpret them. Perhaps using the ultrasound machine helps reaffirm part of their current identity or helps in forming their future professional identity and exploring future career options within medicine. On the flipside, the ultrasound is limited to certain views due to the position of the probe and the depth of the scan. Students can struggle conceptually when working with such an advanced technology, and papers have highlighted a plethora of issues from greyscales images, probe orientation, and knobology to physics (Griksaitis et al. 2012, 2014; Finn et al. 2012).

There is sometimes, what could be described as, a romanticised viewpoint that merely the presence of technology within educational environments will enhance the learning of students and their levels of attainment (National Research Council 2000). It is possible that what technology actually offers is something that is different, out of the ordinary and thus perhaps more memorable and engaging. In the fields of medical education and biomedical visualisation, technology brings an entirely different, and otherwise impossible way to visualise or view the human body or, in fact, see multiple viewpoints of the body at every possible angle and orientation, readily accessible in laboratories, lecture theatres and on hand-held devices. There are a multitude of expensive, but highly sophisticated, technologies such as virtual autopsy tables and 3D dissection software that enable the user to rotate, dissect or project the human body in the blink of an eye. These available technologies within anatomical education offer many advantages: human tissue and the associated licences are not required (except during the initial creation of some software products), there are fewer emotional or sensitive issues related to death and dying associated with virtual anatomies, and multiple users can interact simultaneously with some select technologies. However, it is not just technology that presents such advantages, and modalities utilising art-based approaches may also possess such attributes – this will be explored subsequently.

4.1 A Comparison Between Technology and Art

As this book centres on visualisation, let us consider something of significant visual impact – anatomical body painting. The use of body painting within anatomy teaching is well documented (Finn and McLachlan 2010; Finn 2015; Cookson et al. 2018; Aka et al. 2018). A full critical appraisal of its effectiveness is not the remit of this chapter; however, a few ideas pertinent to the discussion will be shared.

Body painting enables learners to work collaboratively, both by painting anatomy onto a peer, and by allowing a peer to act as the painted canvas. Otherwise ‘invisible’ internal structures become visible on the canvas of the body without the need for cadaveric anatomy. There are many more advantages, and naturally disadvantages. Essentially, it all boils down to the fact that the learning experience is different, more hands-on and engaging than a traditional cadaver-based session, and the facilitators of such sessions are arguably more enthusiastic about delivering sessions that are not run-of-the-mill for them and during which their may be able to interact with their learners in novel ways, exactly the same selling points as the technology delivered visualisation in the former example.

The commonalities between the two examples are that both break the monotony of long practical sessions in the laboratory or lectures delivered in dulcet tones. The sessions are more lighthearted than is possible in the understandably highly governed dissecting room environment, present opportunities for near-peer teaching and promote accessibility to a broader audience of users. It is important to acknowledge that both are likely to have their own hidden curriculum associated with their use (Aka et al. 2018).

5 Simulated Learning and Gamification: Is High Fidelity Always Best?

Simulation has all the components of a game (goals, rules, challenge and interaction). Learners (its players) are tasked with achieving the preset educational learning outcomes. Simulation is used within medical education to enable interactive, and where possible, immersive activities that aim to recreate all or elements of a clinical experience without exposing patients or peers to any of the associated risks. As we know, there are a range of technologies used in simulation which fall on a spectrum from simple task training models to extremely sophisticated computer and technology driven models (Maran and Glavin 2003), all designed to represent clinical situations required to train, assess, and evaluate the knowledge of human systems and error (Reis et al. 2018). These approaches purport to develop participants’ cognitive abilities, and psychomotor and interpersonal skills, with high-fidelity simulations being the widely accepted gold standard within this simulation ecosystem.

In a study looking at the context dependent learning, Finn et al. (2010) found that using low fidelity simulation, clinical clothing to be specific, aided recall of knowledge in medical students. The study concluded that low fidelity, but authentic, simulation could have a significant impact on learning. Many other studies have looked at high fidelity simulations and the impact on learning but as Gordon et al. (2001) state, when considering implementing simulation, students' ability to practice without risk must be weighed against the cost of this new technology. Increasing popularity of simulation teaching methods has meant it is widely utilised in medical education but a downside is that it has been suggested that learners now know "how to play the simulation game", where they perform solely for the simulated setting with none of the skills learnt transferring into the workplace.

6 The Black Box of Educational Research: Is Technology-Enhanced Learning Problematic for Us?

Enhancement of learning and educational attainment – as well as innovation in education – is sometimes perceived to be solely possible in the presence of technological interventions (National Research Council 2000). This barely evidenced notion persists throughout the educational sector, although there is a growing body of less technology-enthused educators who argue that investments in technology are a financial and temporal drain, and a waste of students' valuable time (Lévy 1997) with no measurable learning gain. These polarised views remain prevalent through medical education, although educators persist in adopting new technologies into their learning and teaching practice indiscriminately, without scrutinising the available evidence on the efficacy of the new technology (or assessing it for efficacy and usefulness). E-learning serves as an example on this indiscriminate usage. It has been extensively researched but the evidence shows little improvement on traditional instruction and its uptake by academics (mainly in traditional institutions) is marginal (Cook 2009). Workloads on distance learning courses are often unsustainable for educators, and faculty workload assumptions from the past are inaccurate (Hovenga and Bricknell 2006; Delgaty 2014). Further, online learning represents discontinuity with previous practice, resulting in role crisis and ambiguity to academics (Briggs 2005) and the erosion of autonomy and academic freedom (Beaudoin 1990). The 'glorious revolution' of e-Learning appears to not be happening, clamouring for more clarity on when it is appropriate to incorporate this method of learning into educational interventions and highlighting the failure of e-learning research to inform educational practice.

When choosing to integrate technology into education, one may look to the literature for evidence to support such inclusion. Of course, this is good practice. What perhaps is given less consideration is the black box of educational literature. The black box metaphor is often used with reference to studies that report inputs and outputs but not the mechanism and inner workings of interventions (Pinch 1992), although the same metaphor is occasionally used for studies that are rejected or not submitted for publication due to negative results (Pinch 1992). A growing body of literature illuminates some of the manifold limitations of technology-enhanced learning, and the use of technology in medical education remains poorly understood (Wong et al. 2010). Academics are often socialised into only reporting positive results, negative findings are dismissed as not publishable and thus vanish into the black box of educational literature, never to see the light of day. Many of the published research papers are not rigorous in their research design and the information filtering out into the wider sphere of educational research may be selected to only report positive results with technological interventions, not those that fail to impress or show a marked difference to learners (Cook 2009; Clunie et al. 2017). Incorporation of technology into delivery of teaching is mistakenly perceived as synonymous with innovation (Delgaty et al. 2017) but indiscriminate use of technology may have unexpected downsides and prove hazardous, especially when it may come at the expense of a reduction in meaningful contact time and a range of other better-evaluated or tried and tested learning methods. The point is this, when considering implementing technology, using the literature to inform decision making is a must, but critical appraisal of the learning mechanisms behind the results must be given just as much consideration. Inputs do not necessarily equate to outputs, question cause and effect. Is it really the technology that is improving the learning experience? Of course, the answer may well be yes. The implementation of the any new instructional tool, whether technological in nature or not, should be based upon assimilation of evidence and best practice, rather than the desire to keep up with the status quo.

Some newer technology from the gaming industry offers learners with a fully immersive learning experience. Virtual reality (VR) and augmented virtual reality is a case in point. These environments are deemed safe and engaging educational settings where advanced learning can take place without patients coming to any harm and failure is not frowned upon. Yet, incorporation of VR into teaching requires investment on multiple levels and is riddled with obstacles. Issues with devices, compatibility, storage limitations and app and browser capabilities abound. Digital fluency and device types of the learners are rarely homogenous, and this diversity makes supporting learners an onerous undertaking. Not all learners are digitally savvy and mobile technology may also be challenging to some. Virtual reality sickness may also prevent learners from making full use of this technology in their learning. Not only are these environments and their educational impact poorly researched but they also highlight to educators the pitfalls of technology, where one size certainly does not fit all.

6.1 Digital Distraction and Cyber-Slacking

Part of the lure of widespread use of technology is the belief that it intuitively leads to better engagement and subject retention. Concerns have been raised on how technology is eroding an acceptable knowledge base. We know that students' attitudes tend to be influenced by numerous factors such as escapism, consumerism, inattention, and distraction by peers' cyber-slacking behavior. Inattention may be influenced by intrinsic and extrinsic apathy, lack of motivation, or wider classroom engagement. Sampson (2010) found that laptop usage improved students' levels of attentiveness and engagement in class. However, the flipside of this widespread usage is that access to technology provides an easy route to completely disengage from the learning environment. The same students who use technology to engage in learning will also engage in other activities that have little or no relation to what is being taught (Fried 2008; Ragan et al. 2014; Ravizza et al. 2014), and access to distracting social media sites is enabled by this ease of access through device usage in the classroom setting. A backlash against laptops surfaced but today laptop usage is widespread in education, although there is some evidence to suggest that use of laptops for note-taking in lectures is not as effective for retention of material learnt as handwritten notes (Mueller and Oppenheimer 2014).

7 Three-Dimensional Printing as an Example of Norm Driven Implementation

One new technologies that has emerged in recent years is three-dimensional (3D) printing. 3D printing has been used for multiple purposes, but is popular within anatomy education. 3D prints of bones are common, created from surface scans and medical images. Bones lend themselves to printing as they are a hard structure and monochromatic. These features make them easy to print, with accurate results that preserve the visual and haptic qualities of the real tissue (AbouHashem et al. 2015). This 3D printing technology clearly has many advantages: portability of the scans, artefacts are created that students can keep, colour can be used to promote learning, pathologies and variations can be printed. As with all technologies, there are issues with cost, ink jets clogging, etc. Interestingly, the 3D prints are used like any other anatomical model, whereby students examine and rotates the specimen in order to study the anatomies. Some institutions print white copies so that students can draw on neurovasculature. The 3D printing approach rapidly produces multiple, anatomically accurate reproductions of anatomies at any size and scale, use of which avoids some of the cultural and ethical issues associated with cadaver specimens (McMenamin et al. 2014).

3D printing is a fantastic technological advancement, it has many benefits for teaching and learning but it is another prime example, in some cases, of implementation without evidence. Many institutions chose to invest significant sums of money in 3D printers without consideration of how the technology is integrated into the programme of study, with little thought to assessment and the pedagogy involved in using printed artefacts and with consideration of a literature base primarily based upon student satisfaction. The 3D printing example highlights the gap in good quality, educational randomised control trials, whereby the effectiveness can truly be assessed. Of course, acceptability with students is of importance too but it should not be the driver for all change and innovation.

Educational research needs to continue building momentum, be better supported by funders and ensure rigour and quality. Buckingham (2005) state that 'educational research is often far from sound'. The reason she gives for this view is the current preference within education faculties for producing qualitative rather than, and at the expense of, quantitative research. The National Academy of Science evaluated educational research generically, and found "*methodologically weak research, trivial studies, an infatuation with jargon, and a tendency toward fads with a consequent fragmentation of effort*" (Atkinson and Jackson 1992). It is therefore the duty of those considering embedding anything enw into their curriculum, to make a judgement on the quality of the evidence base that they consult when making such decisions. Questions needs to be asked as to whether the implementation is norm or criterion driven? If it is a case of 'everyone does the same', there is a new realm of educational activity, whether that be a new technology being utilised or a change to an assessment structure, but no true progression. The use of our teaching modalities becomes norm driven, departments have the equipment so they must use it. It is this set of actions that devalues the research. It is a reflexive devaluation which then drives the devaluation further as the as it not used.

All hope is not lost, as Norman (2002) described in the British Medical Journal, and research in medical education has contributed substantially to understanding the learning process. The educational community is becoming aware of the importance of evidence in educational decision making. That being said, real improvement in education, just like real improvements in medical treatments, will only result when we combine better the understanding of basic science with the experimental interventions (Norman 2002).

8 Conclusion

New technologies bring with them radical opportunities but there are also significant often neglected and ill-considered challenges. This chapter has presented some of these challenges, or perhaps, better described as opportunities for growth and change. It is important to appreciate that technology-enhanced learning is not a magic bullet with which to plug the holes of programmes with pedagogical flaws or student satisfaction concerns. It cannot be a panacea for foundational curricular imperfections. Instead, it offers enhancement to already existing learning methods and, sometimes, can offer truly unique learning experiences that offer variation to the oftentimes mundane arsenal of learning tools available to the educator. Considered and targeted use of digital technologies can present new material in novel ways through a variety of learning tools with which to engage learners.

To truly embed technology within medical programmes in a meaningful manner, pedagogical interventions need to be continually assessed and revised, and coupled with a research-led approach to TEL. Significant institutional investments should support embedding selected evidence-based TEL interventions into programmes, with the necessary educator workload concerns and time constraints addressed, and with sufficient technology support at hand and institutional training and development opportunities readily available. Learners should be at the core of any interventions, and digital policies must be inclusive and consider the wider stakeholder capabilities and financial constraints.

What does the future hold for further technology-enhancement of medical education? The possibilities seem limitless and staggering. Already, there is talk about the enhancement of learning through artificial intelligence, truly immersive virtual reality and telepresence robots. Big data is bringing with it the possibility to build and target learning using analytics, and there is talk of next generation learning environments and intelligent campuses. To enable this level of change – if desired – "*technology leaders need to work together with educators, not as missionaries bearing magical gifts, but as collaborators in creating new opportunities to learn. It will take a concerted effort to bring about such a radical change in thinking.*" (Collins and Halverson 2010) Practice and pedagogy must walk hand in hand with technology innovation and higher-level institutional commitments to realise some of these enhancement measures in a manner that is valuable for learners but also meaningful for educators.

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Towards a More User-Friendly Medication Information Delivery to People Living with Multiple Sclerosis: A Case Study with Alemtuzumab

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Abstract

Multiple Sclerosis (MS) is an autoimmune disease of the central nervous system which leads to demyelination and neurodegeneration. The T and B cells, the body's immune cells, start attacking the brain and spinal cord, leading to a variety of symptoms. Alemtuzumab is a recently approved disease-modifying therapy that has been shown to have a very high impact on MS. However, it has many potentially life-threatening side effects which patients are often not aware of. For treatments as effective and risky as Alemtuzumab, patients who are considering it must be well-informed on the process and the potential side effects. Patient education is vital to equip patients with knowledge on their disease and treatment, and has shown to be successful in improving the management of chronic diseases and increasing medication adherence. Unfortunately, the language used is often too complex and at a higher reading level than average patients can comprehend, and available resources such as pamphlets and websites are often disorganized. This research proposes a radically different approach to patient education, using less formal channels such as a mobile application to improve health literacy, using LEMTRADA® (Alemtuzumab) as an example. MS patients were involved in a co-design process to produce a series of user-friendly, intuitive and interactive graphical interfaces which propose plain language, illustrations, animations, audio and Augmented Reality components that aim to enhance patients' knowledge retention and recall. Finally, nine MS patients along with a senior MS nurse tested the mobile application and answered a usability questionnaire that aimed to compare the delivery of information with typical websites and pamphlets. Results suggested this approach to be highly user-friendly and engaging, improving patients' understanding of medical information considerably. This research illustrates more engaging channels to communicate

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with MS patients in order to enhance health literacy.

Keywords

Multiple sclerosis · Alemtuzumab · Patient education · Mobile application · Health literacy · Co-design · Communication illustration

1 Introduction

Multiple Sclerosis (MS) is an autoimmune chronic condition where T and B immune cells attack the brain and spinal cord. This leads to demyelination and neurodegeneration (Dolati et al. 2017). This condition manifests in a variety of symptoms in patients that include motor, sensory and visual disturbances (Compston and Coles 2008). MS treatment can be classified into two kinds; disease-modifying therapies (DMTs), therapies that prevent the immune cells from crossing the blood brain barrier that leads to decreased inflammation, and symptomatic therapies, therapies that address MS symptoms (Dolati et al. 2017). A multitude of treatments are available that have demonstrated to have an impact on MS (Brownlee et al. 2017). However, these treatments have also shown to have potentially serious side effects. People living with MS considering a certain type of treatment must be well-informed to make the best possible decisions for themselves. Treatment benefits must exceed the risks of the side effects (Thompson et al. 2018).

For chronic conditions such as MS, patient education has become a crucial tool in treatment. Patient education materials are resources for patients to equip themselves with the necessary information on their disease and treatment. It has shown to improve disease management and medication adherence, which are two major factors in chronic disease (Suhling et al. 2014).

Alemtuzumab is a DMT that has a very high impact on MS while also having a high risk for dangerous side effects. There are a lot of infusion reactions when taking Alemtuzumab. The importance of patient education on the benefits and potential risks of this treatment can be illustrated by how patient education is being incorporated into the management of these reactions (Caon et al. 2015). This is to ensure that the patients will know what to expect and how to deal with the side effects (McEwan et al. 2016).

In this research, we demonstrate a patient education mobile application on Alemtuzumab that incorporates animations, illustrations, plain language and augmented reality (AR) for people living with MS. The application intends to be a friendlier resource compared to current methods of patient education such as pamphlets and websites. A patient education mobile application on Alemtuzumab was developed, and this research aimed to answer the following questions;

- Is a mobile application a feasible platform for patient education?
- Can plain language, illustrations, animations and AR improve the patient education experience?
- Will this application be a better alternative to existing patient education methods (i.e. brochures and websites)?

2 Patient Education

2.1 Patient Education and MS Treatment

In MS, there have been studies showing the effectiveness of patient education. Educational interventions can increase pain management awareness, leading to a decrease in potential difficulties in MS (Daniali et al. 2016). It has also been shown to successfully decrease stress and promote healthy coping mechanisms in women living with MS (Sanaeinasab et al. 2017). When patients are informed of the potential side effects of treatment, this can lead to early detection and better patient outcomes (Rath et al. 2017). Equipped with the appropriate education, patients are more likely to handle their conditions and treatment better in general (Zimmer et al. 2015).

2.2 Patient Education and Technology

E-learning, which is technology-based education, has been studied and shown to be a beneficial instrument in a medical context (Suhling et al. 2014; Morgan et al. 2015). Morgan et al.'s study (2015) found that technology-based methods that incorporated images, video, text and audio increased patient understanding and knowledge retention. Patients have found patient education mobile applications to be beneficial (Pecorelli et al. 2018) and encourage medication adherence (Zanetti-Yabur et al. 2017). When compared to print-based education, several studies have shown that technology-based methods frequently outperform printed material (Trinh et al. 2014; Alsaffar et al. 2016).

2.3 Current State of Patient Education

In 2016, Eloranta et al. wrote that over the past decade, no positive changes in patient education have occurred and improvements are needed. Educational material can be difficult to understand even amongst people who possess sufficient literacy skills, as medical jargon is often used to explain concepts to individuals unfamiliar with them (Hadden et al. 2017). Low health literacy is a major problem (Quesenberry 2017). Health literacy can be defined as one's "ability to access, understand and act on information for health" (Sium et al. 2017). Low health literacy has been correlated with more hospitalisations and decreased preventative care (Quesenberry 2017), emphasizing the need for improved patient education resources.

2.4 Our Approach

When producing an educational resource, patient understanding and accessibility should be the main priority. People are constantly being diagnosed with medical conditions they might not be familiar with and need resources with the appropriate amount of information that will be informative enough yet not overwhelming. To cater to all audiences, plain and straightforward language should be used in patient education (Hadden et al. 2017). The information should be well-organised and accessible to patients, easing the information-seeking process. Patient education should assist the patient instead of overwhelm them.

A mobile application was chosen to be the platform of this resource as technology-based methods have been shown to be effective as previously mentioned. In addition to that, mobile applications are very accessible, seeing as the mobile phone is one of the main mediums of information communication technology (Lopez-Fernandez et al. 2017). As of 2016, 62.9% of people worldwide owned mobile phones (Statista 2016) and that number is expected to increase to 90% by 2020 (Carroll et al. 2017).

There are not many patient education resources with plain language and organised information available for people living with MS. This research approaches this issue and fills this gap by developing a patient education application that integrates what has shown to be effective for users, such as illustrations and straightforward explanations. This aims to assist patients' learning and decision-making. Since Alemtuzumab does not have many available patient education resources, the development of this mobile application seems to be appropriate.

3 Our Work

3.1 Development Outcome

Prior to the development of the application, a co-design process was carried out, whereby potential users were able to give their input and perspective on what the final product should include. The users' needs get to be acknowledged via this collaborative method (Blackwell et al. 2017). Six people living with MS were consulted for this process. The following images show the outcome of the mobile application, called "AlemtuzumApp."

DISCLAIMER

This application does not contain health advice. The health information on this application is purely for general informational and educational purposes and is NOT a substitute for professional advice.

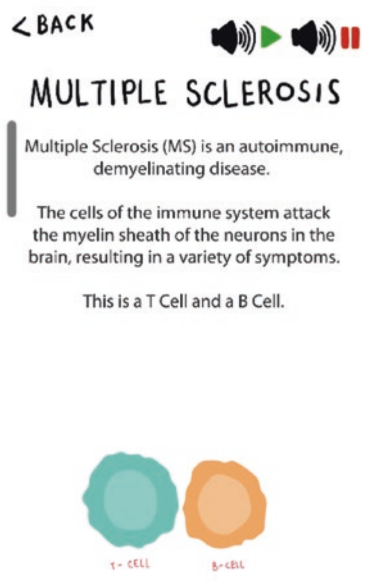
Under no circumstance does the creator of this application take responsibility for any consequence due to the use of this application. Your use of this application is solely at your own risk.

Please consult a medical professional if you require to do so.

AGREE

Fig. 1 Disclaimer scene

Fig. 2 Main menu scene



< BACK

MULTIPLE SCLEROSIS

Multiple Sclerosis (MS) is an autoimmune, demyelinating disease.

The cells of the immune system attack the myelin sheath of the neurons in the brain, resulting in a variety of symptoms.

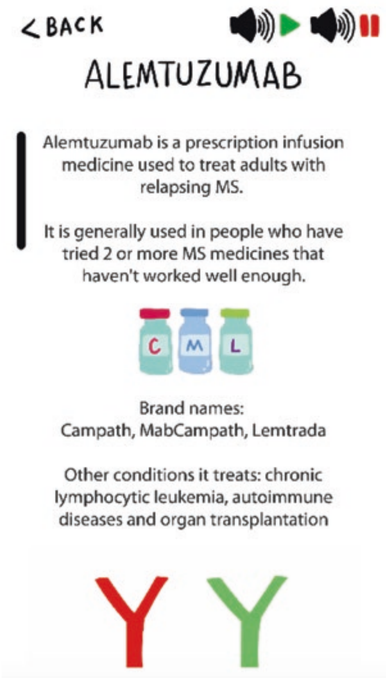
This is a T Cell and a B Cell.

Fig. 3 Multiple sclerosis scene

The first scene that appears when the application is opened is the Disclaimer scene (Fig. 1) that states that this application is purely an informational source, and not a substitute for medical advice. The Main Menu (Fig. 2) has six buttons which leads to the six main scenes that were decided on after the co-design session with the participants living with MS.

The explanations of MS and Alemtuzumab (Figs. 3 and 4) incorporate animations that aim to help users visualise the concepts better. The animations also act as breaks between the text, to ease the user's experience in absorbing the information. There is an audio option that will read out the text for users who prefer this modality. The audio can be played by tapping on the audio symbol at the top right of the screen for these two scenes. The content in the MS scene was obtained from a YouTube video called “The Immune Attack – Multiple Sclerosis” (DrBarrySinger 2010). The content in the Alemtuzumab scene was taken from several journal articles on Alemtuzumab (Fig. 5).

For the AR scene (Fig. 6), the device must be pointed at the trigger, which is a Lemtrada box. Lemtrada is one of the brands of Alemtuzumab. A 3D animation will appear, overlaying the trigger on the screen (Fig. 7), explaining how Alemtuzumab functions in a very simple way.



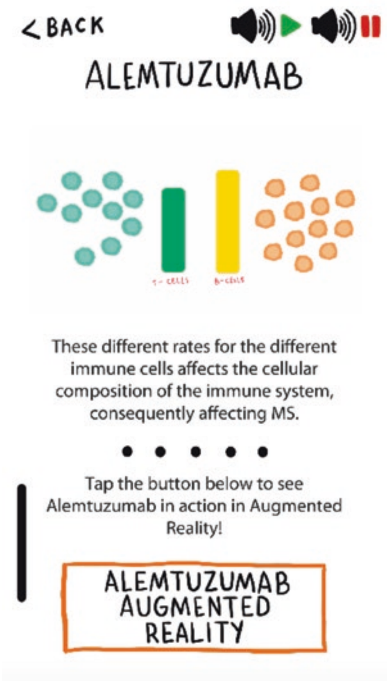
Alemtuzumab is a prescription infusion medicine used to treat adults with relapsing MS.

It is generally used in people who have tried 2 or more MS medicines that haven't worked well enough.

Brand names:
Campath, MabCampath, Lemtrada

Other conditions it treats: chronic lymphocytic leukemia, autoimmune diseases and organ transplantation

Fig. 4 Alemtuzumab scene



These different rates for the different immune cells affects the cellular composition of the immune system, consequently affecting MS.

Tap the button below to see Alemtuzumab in action in Augmented Reality!

Fig. 5 Button on Alemtuzumab scene to open AR scene

This scene was meant to capture the interest of the user and consolidate the information on Alemtuzumab.

The side effects scenes (Figs. 8 and 9) show a list of side effects accompanied by illustrations. Due to the gravity of the subject of treatment, the illustrations were meant to be colourful and humorous to ensure this application to be as nonclinical as possible. Illustrations have been found to increase patient understanding and information recall in a clinical setting (Hill et al. 2016). Illustrations seem to be an appropriate communication tool in medicine to reach all audiences, as they improve knowledge recollection in people who are not medically proficient (Bui et al. 2012).

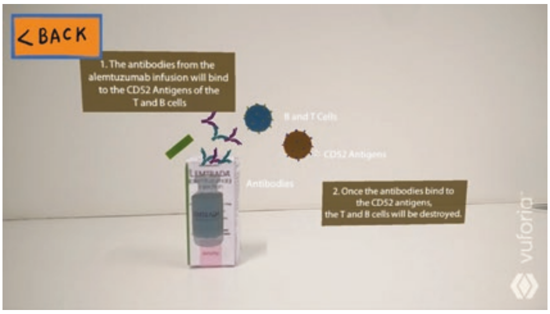
For the serious side effects, the icons can be tapped on and more information on the side effect will appear (Fig. 10), including symptoms and the likelihood of the side effect occurring. This gives the users a quick overview of how severe the side effect can be. The common side effects are just listed with no additional information. The content from these scenes were obtained from the Lemtrada website (Lemtrada 2018) and Medscape.com (Medscape).

The drug comparison scene (Fig. 11) was specifically requested by one of the people living with MS that were consulted during the co-design process. It shows a brief overview of the different DMTs available, using symbols and colours to indicate how big of an impact they have on MS, and the severity of the risk of the side effects. This way, users are able to have an idea of how well these DMTs work at a glance. If the users would like to read more on the DMT, the DMT name can be tapped on and more information will appear. The content from this scene was obtained from the MS Society website (MS Society).

The Treatment Scene (Fig. 12) has five buttons leading to five different scenes that describe the treatment process (Figs. 13, 14, 15, 16 and 17), broken down into specific time periods throughout the treatment. The content in these scenes were all obtained from the Lemtrada website (Lemtrada 2018). Illustrations are placed in between the text to act as breaks, with the intention of helping users

POINT THE CAMERA AT THE LEMTRADA TARGET.

Fig. 6 AR scene instructional dialog box



1. The antibodies from the alemtuzumab infusion will bind to the CD52 Antigens of the T and B cells

2. Once the antibodies bind to the CD52 antigens, the T and B cells will be destroyed.

Fig. 7 AR 3D animation

absorb the content more easily and to avoid overwhelming them with too much information. This aimed to lessen the possibility of important information being overlooked.

There is a list in the resources scene (Fig. 18) of links where the information on the application was obtained from. There are also additional links for users who would like to carry out any further reading on MS and Alemtuzumab.

3.2 Pilot Test: Research Methods

A pilot test was carried out to assess the application's usability, usefulness and enjoyment. It also intended to answer the research questions.

3.2.1 Participants

Ten participants volunteered to test the application at the Revive MS Support Centre. Nine participants were individuals living with MS, and the tenth participant was a MS specialist nurse from the centre. The ages of the participants ranged from 25 to 60. Overall, participants reported to feel very comfortable using applications on tablets and smartphones. Similarly, they reported to use computer systems frequently, although not for gaming.

3.2.2 Procedure

The testing was carried out in a meeting room at the Revive MS Support Centre. The participants were gathered around a table. They were given consent forms to sign and were informed about their right to withdraw at any point throughout the study. Participants were also given information sheets describing the task they were expected to perform and were provided with instructions on how to effectively use the AR component. The AR was to be triggered by a Lemtrada box, which was placed in front of them. The participants were required to go through every scene of the application.

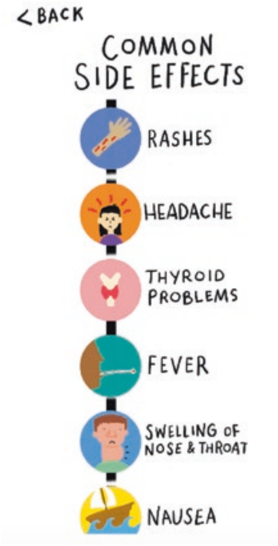


Fig. 8 Common side effects scene

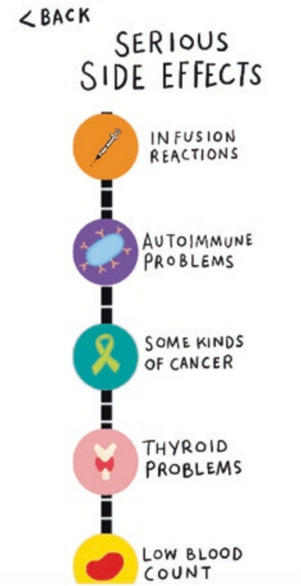


Fig. 9 Serious side effects scene

There were two android phones and one tablet. Since there were only three devices, the participants took turns to use the application. Once a participant completed the application testing, they were given a questionnaire to fill out and the device was given to another participant. Throughout the duration of the session, once participants had completed the questionnaire, they would leave while others would join the room.

3.3 Data Analysis

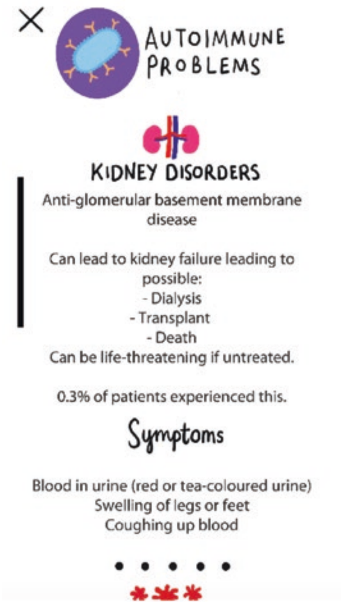
The questionnaire given to the participants contained statements that participants had to rate using a five-point Likert scale. The statements were regarding the application's usability, usefulness and enjoyment (1 = Strongly Disagree, 2 = Disagree, 3 = Neutral, 4 = Agree, 5 = Strongly Agree). There were also three open-ended questions, asking what the participants liked and disliked about the application and if they had any further comments.

All 10 participants were given the questionnaire but one could not be included in the final results as it was left incomplete. Since the nurse did not fall under "people living with MS", her questionnaire was evaluated separately.

4 Results

The following graphs depict the mean scores and standard deviations of the results. The statements are listed on the x-axis of the graph (Graphs 1, 2, 3, 4, 5, 6, 7, and 8).

Overall, participants' responses towards the AlemtuzumApp application were very encouraging. As they used it, they were giving verbal comments, saying how the layout was straightforward and the information was accessible. They enjoyed the illustrations, animations and AR. The results from the questionnaires were mainly positive. The statements regarding the application's usability, usefulness and enjoyment all had mean scores above 4, except for one statement regarding the AR component, which had a mean of 3.88. Two participants did not rate the statement about the audio, as they were not aware that the application had an audio component. The audio was added to the application as an afterthought, therefore it was not listed as one of the tasks in the instruction sheet



AUTOIMMUNE PROBLEMS

KIDNEY DISORDERS

Anti-glomerular basement membrane disease

Can lead to kidney failure leading to possible:
- Dialysis
- Transplant
- Death

Can be life-threatening if untreated.

0.3% of patients experienced this.

Symptoms

Blood in urine (red or tea-coloured urine)
Swelling of legs or feet
Coughing up blood

Fig. 10 Serious side effect additional information

as an oversight. However, the participants who were aware of the audio were satisfied with the component and felt it was beneficial for potential users. Many of the participants agreed with the statement regarding how this application is better than existing patient education methods. This was an extremely encouraging result, as it was one of the aims of the research to make this application a better resource relative to existing mediums.

Regarding the open-ended questions; most of the comments were positive, including how the application was easy to use and engaging, and how the information was well-explained, well-structured and easily accessible. A participant even described the content as being not too technical while also not being condescending, and another stated that learning about Alemtuzumab from this application was “less scary” than from the brochures they had been given previously. There were only four negative comments; two of them stated that the scenes took some time to load, one was regarding how the AR was unnecessary, and one said how there were too many unknown words used in the explanations.

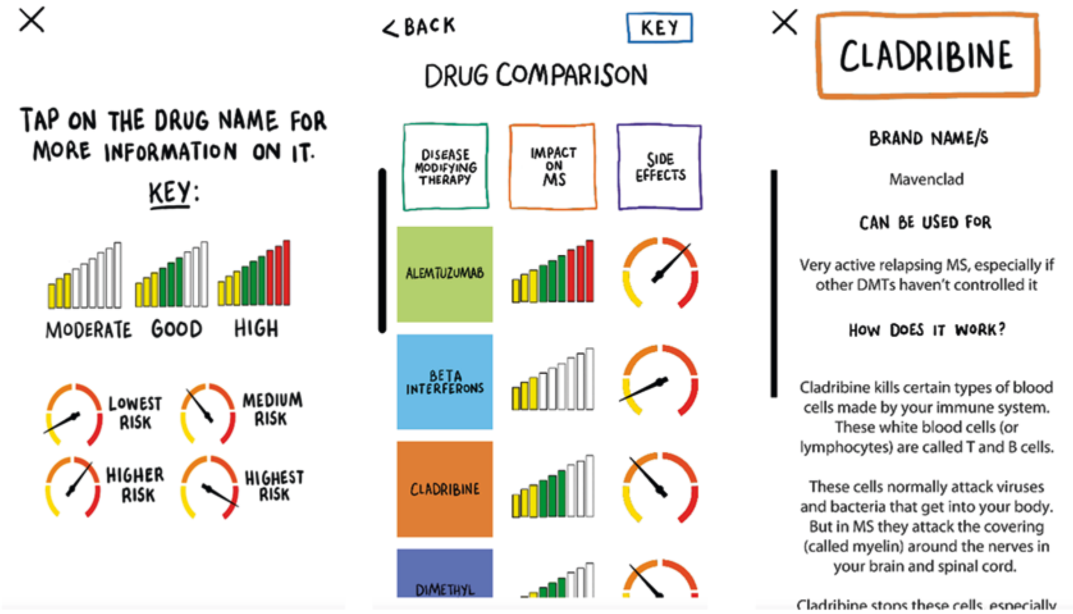
Overall, with the exception of one participant, the application was well-received. All the participants living with MS are regular recipients of patient education and some of them verbally mentioned how they are dissatisfied with these current methods. Five of the participants requested that the design of this application be extended to other MS treatments.

5 Discussion and Future Work

Many health mobile applications that are currently available function as trackers for diet, fitness, heart rate and so on. Not many health applications are designed to act solely as an education application. Furthermore, to the author’s knowledge, not many resources exist for Alemtuzumab. These factors inspired the creation of this application to fill this gap.

All the information on this application was obtained from resources found online. This is important to note as it illustrates how information is readily available on the internet, and yet it is not organized and presented in an efficient way. The literature regarding patient education reviews the issues that exist with its current state, such as the lack of plain language and accessibility, and how there could be an improvement. The objective of this research was to create a resource that addresses all these issues and improves the patient experience when seeking information on their medical conditions and treatment. This mobile application aimed to be an alternative to the current methods of information delivery that uses plain language, well-organised information, AR and illustrations to make the information more accessible and interesting to the users. The final product met all these requirements.

The participants of this study reported to be familiar with using applications on tablets and smartphones and are generally technology-proficient. Many of them reported the application to be intuitive, and they had minimal difficulty navigating around the different scenes. These results support the concept of a well-designed mobile application being a convenient and practical platform for patient education. Mobile phones and technology literacy are becoming wide-



TAP ON THE DRUG NAME FOR MORE INFORMATION ON IT.

Mavenclad

Very active relapsing MS, especially if other DMTs haven't controlled it

Cladribine kills certain types of blood cells made by your immune system. These white blood cells (or lymphocytes) are called T and B cells.

These cells normally attack viruses and bacteria that get into your body. But in MS they attack the covering (called myelin) around the nerves in your brain and spinal cord.

Cladribine stops these cells especially

Fig. 11 Drug comparison scene

Fig. 12 Treatment scene

spread, and applications are easily accessible as they can be downloaded for free.

Developing more applications similar to this has the potential to be useful to both patient and practitioner. Practitioners would be able to have an alternative when prescribing their patients with resources to refer to for more information. If there were to be a collection of treatment-specific applications for all the different treatments available, practitioners would be able to direct their patients to straightforward, simple information sources that would tell them everything they need to know about the treatments. Patients would be able to educate themselves without getting as overwhelmed as when they are told to do their own internet searches for information. This would be due to how these applications would have only the appropriate information that they are required to know, presented in a simple way.

Nevertheless, this research has a long way to go. The results obtained are extremely encouraging, however, more research should be carried out to support the efficacy of the application. Future research should implement more co-design sessions to obtain more input from potential users to improve the design. There should also be larger testing groups to make the results more representative of a bigger population, and the negative feedback should be addressed. In future, the design of this application could be replicated to expand to other treatments for MS, and even be developed further for other medical conditions.

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THE PROCESS

PREMEDICATIONS

To lower the chances of getting a serious infusion reaction

Corticosteroids – before your first 3 infusions
Antihistamines/fever reducers
Antivirals

1ST I.V. INFUSION

5 days in a row

Fig. 13 Process scene

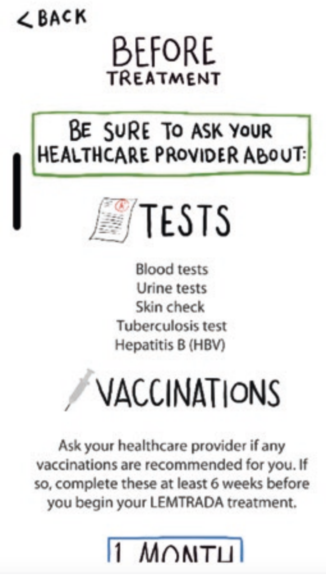
< BACK

MONTHLY MONITORING

Even after treatment is complete, it is important to establish a regular monitoring routine.

You will need to complete certain tests until 4 years, or longer, after your last treatment course, even if you are feeling well.

Fig. 14 Monthly monitoring scene



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BEFORE TREATMENT

BE SURE TO ASK YOUR HEALTHCARE PROVIDER ABOUT:

TESTS

Blood tests
Urine tests
Skin check
Tuberculosis test
Hepatitis B (HBV)

VACCINATIONS

Ask your healthcare provider if any vaccinations are recommended for you. If so, complete these at least 6 weeks before you begin your LEMTRADA treatment.

1 MONTH

Fig. 15 Before treatment scene

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DURING TREATMENT

Bring the bag you packed

Take any pretreatment medications before you arrive at your infusion appointments, as prescribed by your healthcare provider

Fig. 16 During treatment scene

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AFTER TREATMENT

Your risk of infection is greater following treatment. However, there are things you can do to help prevent infections. Here are some things you can do to take care of yourself:

Alert your healthcare provider immediately if anything feels out of the ordinary.

Rest and don't overexert yourself.

Fig. 17 After treatment scene

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RESOURCES

(TAP ON THE FOLLOWING TO OPEN THEIR LINKS)

ALL THE INFORMATION ON THIS APP HAS BEEN OBTAINED FROM:

lemtrada.com

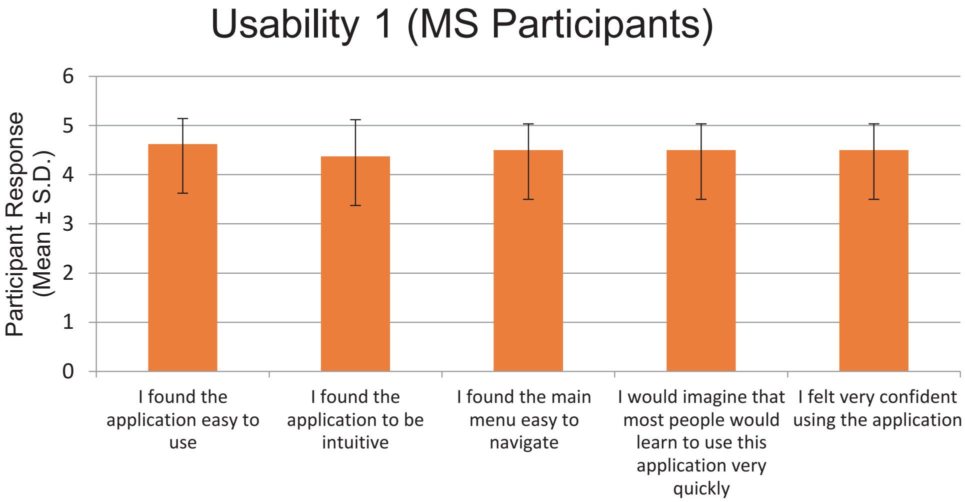
mssociety.org.uk

youtube.com

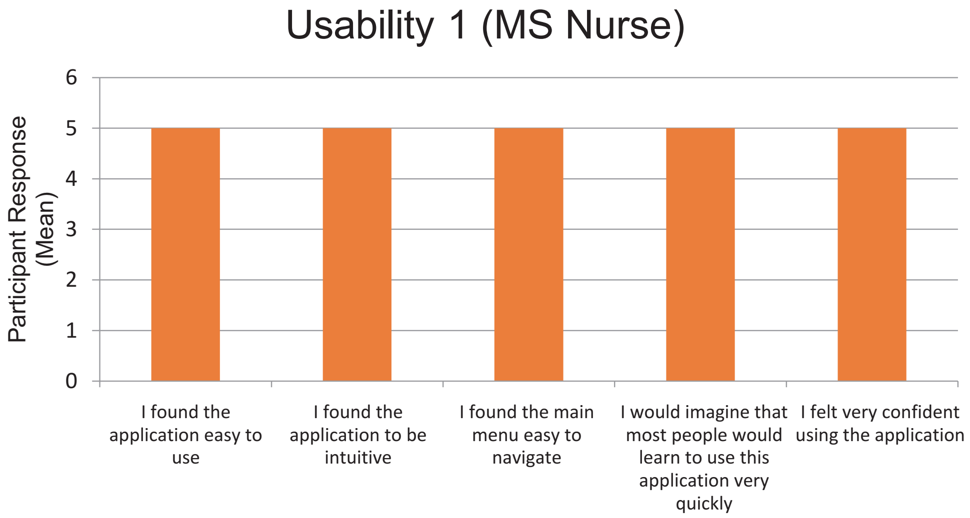
medscape.com

FOR MORE INFO ON MS & ALEMTUZUMAB:

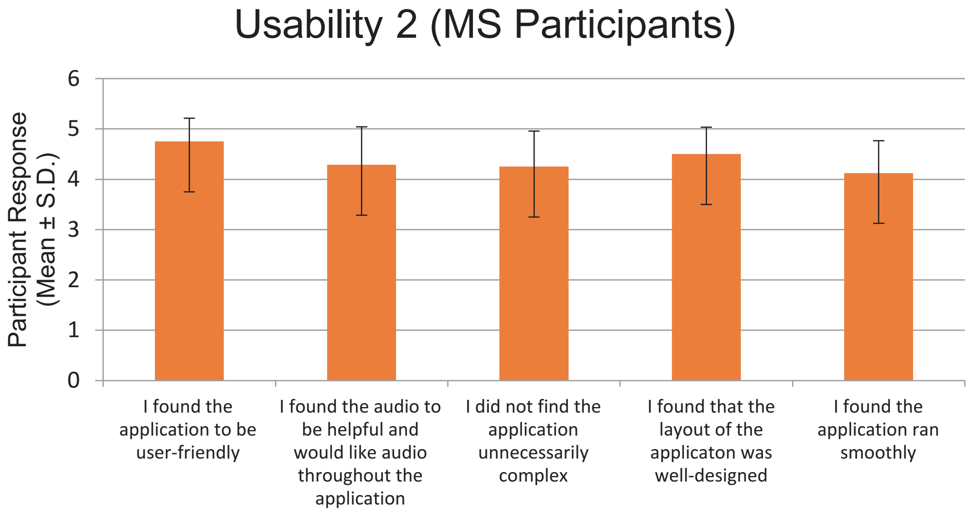
Fig. 18 Resources scene



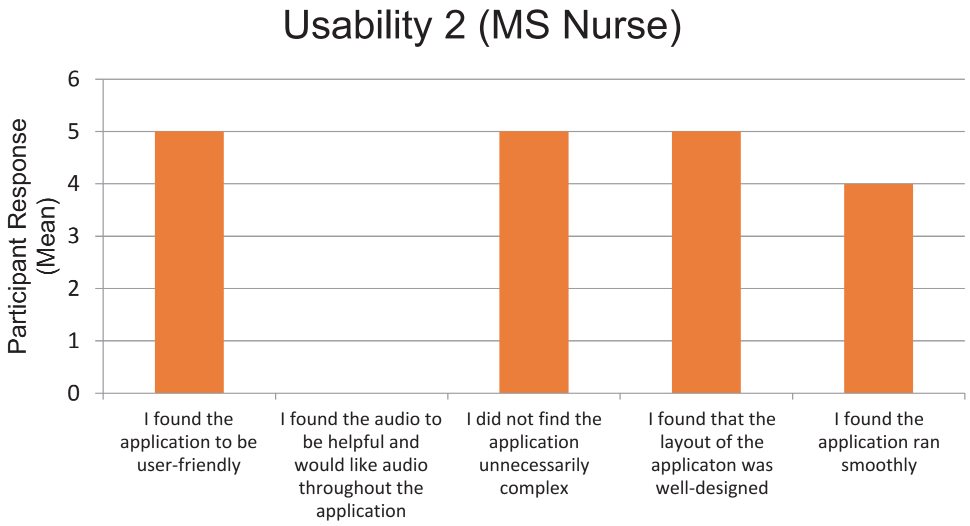
Graph 1 Responses from the participants with MS for the first five usability questions



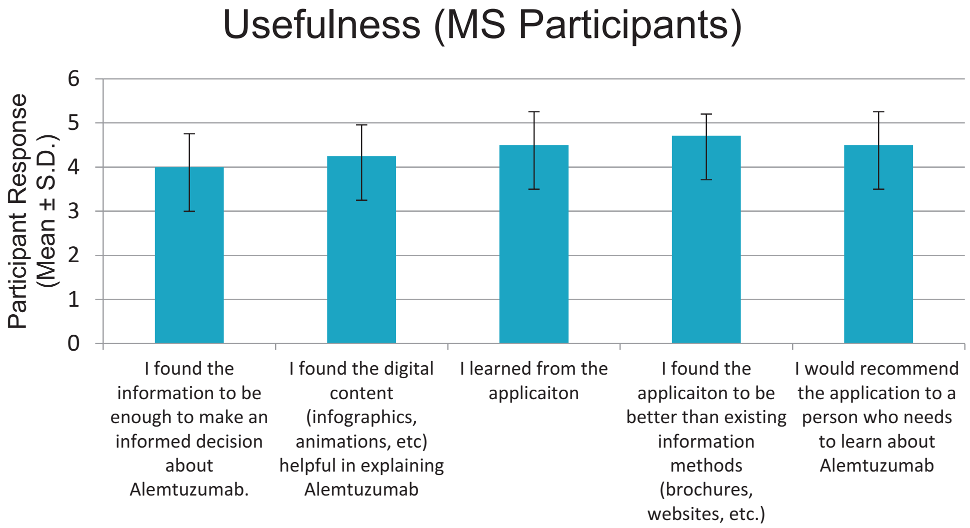
Graph 2 Responses from the MS nurse for the first five usability questions



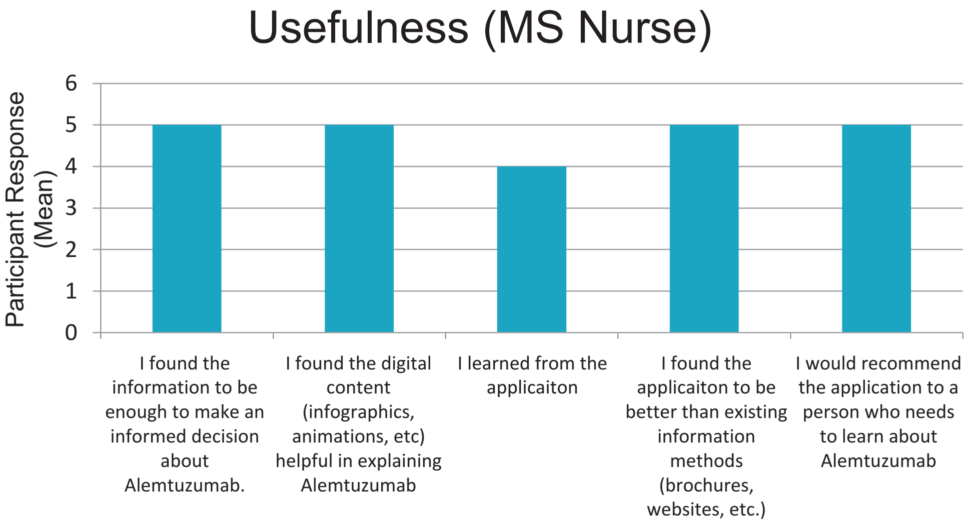
Graph 3 Responses from the participants with MS for the last five usability questions



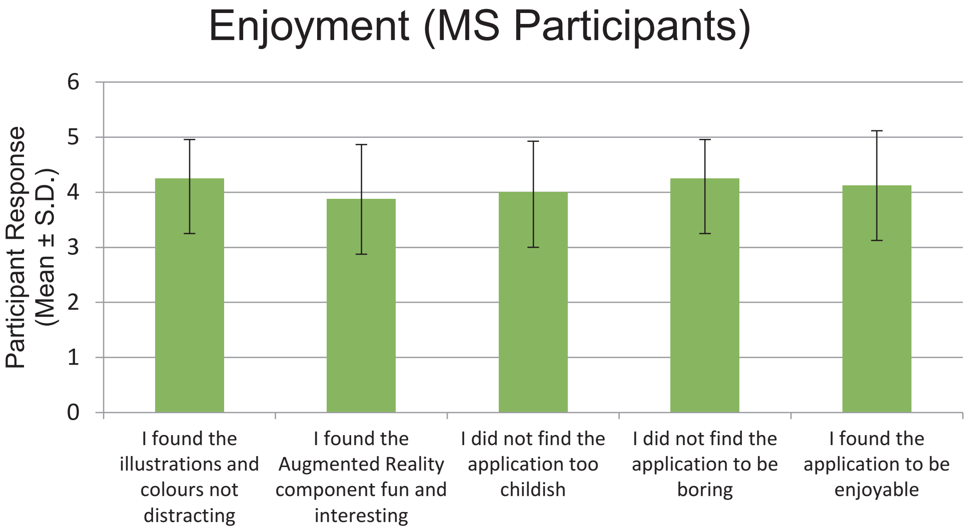
Graph 4 Responses from the MS nurse for the last five usability questions



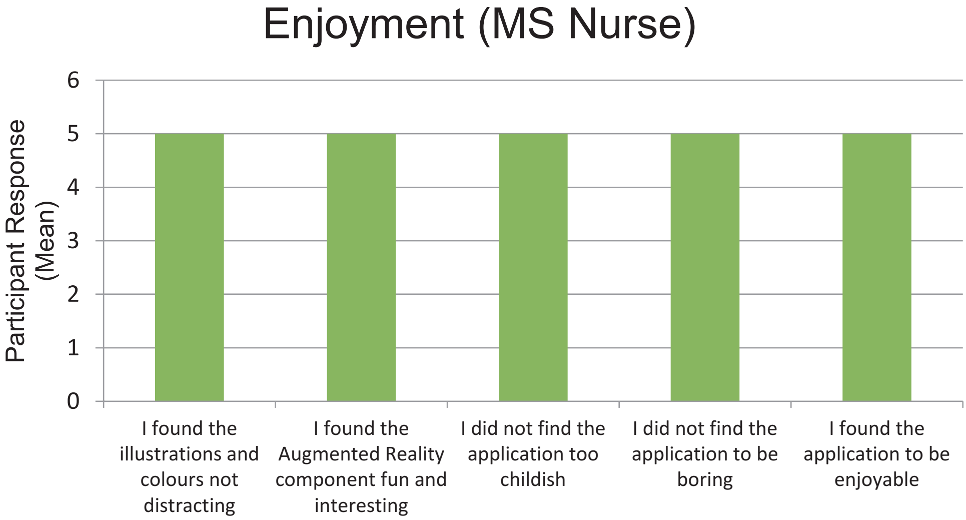
Graph 5 Responses from the participants with MS for the questions on the application’s usefulness



Graph 6 Responses from the MS nurse for the questions on the application's usefulness



Graph 7 Responses from the participants with MS for the questions on the enjoyment of the application



Graph 8 Responses from the MS nurse for the questions on the enjoyment of the application

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The Co-design of Hand Rehabilitation Exercises for Multiple Sclerosis Using Hand Tracking System

Amy Webster, Matthieu Poyade, Paul Rea,
and Lorna Paul

Abstract

Multiple sclerosis (MS) often affects motor function, leading to an adverse effect on daily living. Rehabilitation is important in terms of improving mobility and activities of daily living. Virtual environments (VE) are increasing in popularity within this research area, but research in terms of VE is still rare, for both the upper and lower limb, in people with MS. Leap Motion (LM), a hand motion tracking system, has demonstrated success in stroke research but has yet to be investigated within MS. Following a co-design approach, five participants with MS discussed in a focus group (FG) their hand mobility issues, their thoughts about this technology-based rehabilitation and motivational factors. Findings were incorporated into the design of a series of gamified upper limb rehabilitation exercises, using LM, on Unity Game Engine. Three participants returned and engaged in user testing session and a FG in order to evaluate and discuss their experience. Overall participants found the proposed technology-based exercises to be engaging, immersive and a desirable approach to rehabilitation. Participant feedback underlined the usefulness of co-creation, especially in accommodating the range of motivators and user preferences. However, the study highlighted the loss of tracking of hand movements with LM as one of the limitations. Participants stated they would be likely to use this approach at home if there was a definite rehabilitation benefit and related more to visualising which muscle groups or actions they were aiming to improve.

Keywords

Multiple sclerosis rehabilitation · Hand motion tracking rehabilitation · Co-design · Virtual environments · Leap motion

Abbreviations

FG	Focus Group
LM	Leap Motion
MS	Multiple Sclerosis
UI	User Interface
VE	Virtual Environments

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1 Introduction

Multiple Sclerosis (MS) is an inflammatory, debilitating, demyelinating disorder of the central nervous system which has a particularly high prevalence in Scotland (Mackenzie et al. 2014). The disease severity and symptoms are highly variable between individuals, but typically fatigue, loss of bladder control, and sensory and motor dysfunction are the most common (Kister et al. 2013). Motor deficits can specifically include loss of balance, spasticity, difficulties with gait and coordination, muscle weakness and loss of fine motor skills. Overall, these symptoms have a significant damaging effect on the individual's quality of life due to becoming increasingly more dependent on others, and patients often develop depression as a result (Fernández-Jiménez and Arnett 2015). Rehabilitation is one of the main forms of treatment to improve motor deficits and activities of daily living.

Novel approaches are becoming increasingly popular within rehabilitation and now often include the use of gamification strategies along with enhanced interaction into their approaches. There is the desire for balanced rehabilitation approaches that are accessible and affordable, but also effective and motivational. Despite being an ongoing healthcare issue, research into upper limb involvement and management MS is sparse. Research in recent years has highlighted the potential role of robotics of MS upper limb rehabilitation. Whilst studies have demonstrated its success (Gijbels et al. 2011; Carpinella et al. 2012), there have been issues with accuracy and some argue it may not be more effective than traditional methods (Maciejasz et al. 2014). Furthermore, these robotic systems require specific facilities, specialised apparatus and therefore are not as easily accessible to patients compared with other approaches. They are more expensive than alternative techniques and it has been disputed if the reported successful results are sufficiently cost effective to cause a substantial shift in using robotics (Van der Loos et al. 2008). This is where computer-generated environments often referred to as Virtual Environments (VE) are believed to tackle this issue. As well as being easily accessible, the advantages over conventional methods can include higher motivation, the provision of real-time user feedback and versatility (Lange et al. 2012). Commercially available gaming platforms in particular have been extensively studied, such as the Nintendo Wii system. However, their suitability for motor impaired individuals, such as MS, was argued not be sufficient due to participants reportedly feeling discouraged with negative feedback (Plow and Finlayson 2014) as these gaming systems target healthy individuals and with no consideration of differing ability levels. This highlights the importance of the creation of approaches based on games specifically targeted at improving functionality within disability-related conditions.

Literature has debated the effectiveness of virtual approaches in comparison to other low costing rehabilitation techniques (Saposnik et al. 2010). Whilst it is unclear if virtual rehabilitation is significantly more effective, it is argued that it offers benefits to the user including an immersive but safe environment; positive reinforcements using feedback; engaging and enjoyable experience; and these are believed to be important for patient compliance and thus recovery within MS (Massetti et al. 2016).

Motion capture systems are a more recent development in this research area. For instance, the potential of Leap Motion (LM), a powerful cost-effective hand tracking system, has recently been investigated for virtual rehabilitation research. Despite the technology not being extremely accurate with tracking, there are other multiple benefits to using it from a patient and healthcare standpoint. It is more accurate than e.g. Microsoft Kinect for hand tracking and cheaper than the robotics system; is compatible with most computers and is portable – making it ideal for use at home (Taylor and Curran 2015). It has been primarily researched with regards to stroke but has not yet been fully explored with MS patients. Studies have found it to be successful in terms of improving mobility, allowing excellent feedback to the user with no noted adverse effects in stroke patients (Khademi et al. 2014; Iosa et al. 2015). Therefore, it is possible these benefits could transfer to MS patients and has the potential to become a technique for MS upper limb motor rehabilitation.

To date, there is no published study on the usability or creation of serious games using LM technology for upper limb improvements in MS rehabilitation. This could be due to difficulties in game design in accommodating the wide range of symptoms and varying disability levels within patients. Therefore, this study used a co-creation approach to develop a series of its rehabilitation exercises using the LM technology. This involvement of participants from the early stages would potentially highlight common themes within this target audience and input these into the game design.

1.1 Aims and Objectives

The main aim of this project was to create a user-friendly collection of rehabilitation exercises to facilitate the improvement of hand dexterity in MS patients. Another aim was to determine the common hand problems people with MS experience and investigate if the rehabilitation of these movements could be incorporated into these exercises using LM. In addition, this project aimed to determine the opinion of MS patients on the developed exercises, the benefits of using LM in a rehabilitation context and of potentially using it at home. Adopting a co-design approach with early and continuous user input aimed to make the overall product more desirable and successful for use. Achieving these aims involved collecting qualitative data using focus groups (FG), to highlight common hand issues or their user preferences and input this into the game design and evaluate the developed game to strengthen it further. The evaluation will also highlight the suitability of this technology for this specific target group. Theme-Based Content Analysis (Neale and Nichols 2001) was used as an inspiration to determine user opinion and common themes amongst their comments.

2 Materials and Methods

2.1 Materials

A demonstration set up of the LM controller connected to a PC was used for the co-design FG. “Playground” was the demonstration game used to stimulate discussion among members of the FG (https://gallery.leapmotion.com/v2-playground/). The additional materials required for the evaluation stage was a videorecorder to record the hand movements of participants during use of the exercises and a digital audio-recorder to record the focus group interaction.

In terms of the rehabilitation gamified exercises, the graphical models of various objects were created using Autodesk 3ds Max, a powerful 3D computer modelling platform. The game engine Unity was used to construct the actual rehabilitation exercises. The device used to motion track the user’s hand was a LM controller connected to a desktop PC with a conventional 2D monitor.

2.2 Methods

This study used a co-creation approach in the development of the rehabilitation exercises. This involved the user input from the beginning of the development and evaluation after the first stage of development. This technique has increased in popularity within product development due to the advantages of early intended user input and can potentially create a more successful product (Kristensson et al. 2008). This collaborative approach, with early user input, before the production of the game design, is beneficial in establishing user needs and create a more successful design.

2.2.1 Predevelopment Focus Group

The participants for this study were recruited through a local MS social group in Glasgow. There were no exclusion criteria for recruiting theses participants, however to be included participants had to self-report some degree of upper limb dysfunction. Five participants, four females one male, all gave written consent to participate. A FG methodology was selected to gain information due to its benefits in acquiring a wide range of detailed information and evaluating group opinion (Rabiee 2004). The aim of this focus group was to gather information regarding the participants' MS symptoms such as what upper limb dysfunction participants experienced, their comfortability with this hand tracking technology and what would be motivating to use LM. This session lasted approximately 2 h and a transcript of the focus group taken from the audio-recording was produced. The participants were asked the following questions:

1. How does multiple sclerosis affect your daily function in life?
2. What do you struggle with your hands – particularly around your home?
3. Are there any actions which are impossible to do?
4. Do you do any hand exercises at the moment, if so what?
5. What do you like about this LM technology?
6. What concerns do you have about potentially using this technology?
7. What would motivate you to use it?

2.2.2 Development of Rehabilitation Exercises

Using the results from the FG, a functional and non-functional analysis of requirements was conducted to define relevant functions or system characteristics to be implemented. Certain functions and actions were chosen to be incorporated into the exercises based on mutual problems highlighted by the FG. A total of four exercises were created, with each incorporating a different hand movement, referred to as "Practice", "Pinch", "Type" and "Two Hand Interaction".

Practice The "Practice" exercise's purpose was to allow the user to become comfortable with using the LM device as well as interacting with a virtual environment. The assets used within the practice scene reflected what would be used within the other rehabilitation exercises and household items the participants expressed difficulty with using. The objects modelled were a wine glass, coffee mug, door key and ball as these were objects discussed as difficult to hold in the initial FG. A "Restart" user interface (UI) button was added for the user to set the models back into their default position.

Pinch The "Pinch" rehabilitation game was designed for the user to grasp bubbles in the virtual environment. It was scripted such that if the user successfully made the correct movement at the bubble model, the user would score a point. Consequently, a new bubble model would appear in a different positional transform after each successful movement. Audio feedback was added, with a popping sound after each successful hand movement. The scoring system was displayed on the UI along with a count down timer of 120 s for the user to track their progress. A "Restart" UI button was added to this scene to allow the option for the user to try again at this exercise.

Type The "Type" exercise included a model of a piano keyboard for the user to train their individual finger movement. This was created to replicate the typing action some participants struggled with. Audio feedback of a piano key note was implemented to convey to the user they had performed a successful movement. The piano keys were numbered corresponding to the finger the user was to use for a specific key.

Two-Hand Interaction The final rehabilitation exercise "Two-Hand Interaction" was developed due to the lack of LM studies incorporating the movement of both hands into therapeutic gaming. This scene included a tennis ball model and a net model which had an added animation to move up and down. The goal of this exercise was to throw the ball between the hands, with the added challenge of avoiding the net.

The application included a start scene, a main menu, an 'about application' page so the user could navigate easily through the exercises. Calming music was added to each exercise which was downloaded from the Unity store. The series of exercises were gathered as a game entitled "Handy Rehab".

The realistic hand model was chosen due to the disconnection a participant had with the mechanical one. The intractable elements of the scene were all ensured to be within the LM controller's range, as the user would use their hand to navigate through the application and interact with the virtual environment.

2.2.3 Evaluation and Post-development Focus Group

The participants were from the same group that took part in the predevelopment FG. However, due to scheduling difficulties, only three of the five participants, two females and one male, could attend the date for the post-development FG. Each participant individually tried out the exercises and were invited to go through each one and give an initial response as they participated. During this, their hand movements were video recorded to observe their own hand actions and compare to the game play. Participants were also informed that they could stop at any time and were offered arm support if required, because fatigue of the hand/forearm had been identified as a possible concern earlier. After each participant had taken part, the FG was conducted to gather qualitative data on their opinion was of the exercises.

The aim was to attain participant opinion and feedback of the developed exercises. As before the session was audio recorded and a transcript was produced. This FG lasted 35 min and the questions asked were:

1. What was the difficultly level when tasked with picking up objects?
2. Which objects were the most challenging to pick up?
3. What improvements or additions would you like to see in the exercises?
4. What was your favourite exercise? Why?
5. What was your least favourite aspect? Why?
6. Did you find the exercises engaging? Why?
7. Did you feel like that was your own hand displayed on the screen?
8. Would you use this at home? Explain.
9. What would further motivate you to use it?
10. What was your opinion on the layout, easy or difficult to understand?
11. Thoughts on the music?

3 Results

3.1 Predevelopment Focus Group

The data from the predevelopment FG were the transcript from the session. There were group discussions for each of the main seven questions, with participants often sharing similar problems with regards to their MS. There were differing opinions with regards to views of using the LM technology and motivational factors. Common thoughts or main opinions were highlighted for each question.

When the researched asked: "*How does multiple sclerosis affect your daily function in life?*": there was common agreement of symptoms experienced such as sensory discomfort, mobility issues, spasms, pain but also mention of how fatigue was a huge factor in their daily functioning and how it can alter their motor function rather than their own mobility levels. Furthermore, one participant stated that they needed to be in that mindset to do something mobility-wise and that readiness varied from day to day. One participant summarised what they felt the most common issues were to their daily living:

> *Bladder issues and fatigue are main aspects but also fine dexterity. But everyone is different.*

The participants also noted that they would have to "compensate" with their actions but also often depended on others in the home to assist. With regards to the question: *"What do you struggle with your hands – particularly around your home",* there were numerous actions and tasks the participants particularly struggled with, which are displayed in the Table 1 below.

Actions that the participants noted as impossible to do were very small finger movement

Table 1 List of difficult actions relating to everyday function

Dressing	Eating/Cooking	Grooming	Leisure
Fastening buttons	Using cutlery	Brushing hair	Typing
Using zips	Using scissors	Brushing teeth	Handwriting/signatures
Tying shoe laces	Opening packets or tins of food	Washing or bathing	Signing birthday cards
Putting on jewellery or watches	Picking up mugs, glasses or tumblers	Pushing up switches on appliances (e.g. hairdryer)	Turning pages in book
Fastening bras	Tying ribbon in apron	Toileting	Holding up newspaper to read
Putting on shoes	Chopping or preparing food	Pushing down on deodorant spray cans	Turning a key in lock
	Grabbing items	Squeezing bottles of shampoo/shower gel	Grabbing or retrieving items from handbags

such as: putting on jewellery, fastening buttons, using zips or tying laces. Participants expressed differences with hand mobility levels or which hand or fingers were more mobile. With regards to doing hand exercises at home, only one participant stated that they did an exercise such as hand stretching. Another stated:

> *You are meant to [do home exercises], but I don't.*

When asked *"What do you like about this technology?"* many participants stated that it was a "cool" and different views regarding gaming rehabilitation. They felt it could be good for muscle control and using the same muscles in the games as you could to do movements in a real environment. They reported enjoyment of the calm and relaxing music within the LM demo. Another positive response to LM demonstration was that *"you can see your own hand and you are the interaction"*. The demo LM game used a robotic hand, which received different opinions from participants. One participant argued that it was beneficial as you could visualise the joints of your hands, while another felt a "disconnect" with their hand:

> *I would like it [hand model] to look like a hand… My brain just wasn't connecting that it [robotic hand] was my hand on screen.*

Another concern about the LM technology was the potential to cause strain or discomfort with having the forearm raised for periods of time. Most participants additionally stated that they were not interested in gaming nor used gaming technology frequently. Only one participant mentioned previously using gaming technologies stating:

> *It reminds me of the Wii, but this would be good for dexterity.*

In terms of motivational factors, participants differed on what aspects would motivate them to use LM. They agreed there needed to be different games with instant gratification or feedback such as time or a score. Other motivators included progression such as unlocking new levels after completion or a multifunctional approach:

> *I would use it if I knew it was something I really had to do…Or I would need to do that to access my emails or something.*

3.2 The Developed Rehabilitation Exercises

The developed application was built in Unity specifically for Windows. The first display scene is the 'Introduction' page with three buttons to navigate through by using their hands instead of a mouse cursor. It gives the user the option to read the instructional rules to these exercises or to proceed straight to choosing a game to play if they are already familiar with what to do. Additionally, the user has the option to exit the application at this stage.

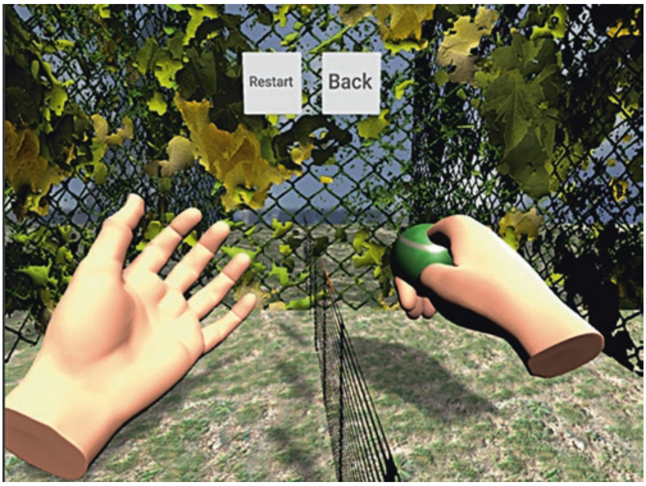
Four exercises were created in this game application: practising picking up household objects; pinching the bubbles; hitting the keys on the piano keyboard and throwing a ball between both hands. Actions were chosen based on FG data. Due to participants saying they struggled with grabbing or picking up household items, the "Practice" scene offered the user the opportunity to interact and grab these (Fig. 1). The "Pinch" game stimulates fine dexterity issues the participantss with fine finger actions they struggled with. The user can faciliate this action onto the bubbles and keep track of progress. The user can use either hand during this activity. The "Type" exericse simulates typing an activity participants reported they had difficulty with. This activity also faciliated independent finger movement. The user can use either hand during this activity. The "Two-Hand Interaction" exercise involved the overall coordination between both hands but also incorporated wirst action by throwing (Fig. 2).

3.3 Results from Evaluation and Post-development Focus Group

Each participant tried every developed rehabilitation exercise and gave their reactions and feedback. Whilst it was clear what do to in each game, the corresponding hand actions were not as obvious to the participants initially.

Fig. 1 The practice game play, along with image showing set up and user hand in correspondence with onscreen

Fig. 2 The two-hand interaction game play



Practice The participants initially struggled picking up objects in the scene but after being shown the specific hand action required for LM to recognise a successful grasp, it became easier for the participants. All participants experienced objects often dropping from their grasp or even disappearing from view. One participant stated they enjoyed the visuals of this scene and said it was a realistic representation of a home environment.

Pinch It was observed that participants found it difficult to successfully pinch the bubbles closer to the screen edge. This is not ideal as one participant expressed arm tiredness during this game and had to switch arms. Figure 3 shows a participant demonstrating the successful action within this exercise.

Type This exercise was received positively during testing by all participants, with comments including enjoyability of the overall task. All participants expressed difficulty in hitting individual keys with fingers other than the index finger (Fig. 4).

Two-Hand Interaction Participants liked the overall design and reported it was pleasant aesthetically. They enjoyed an outside element to

Fig. 3 Participant No. 3 user testing the “Pinch” exercise

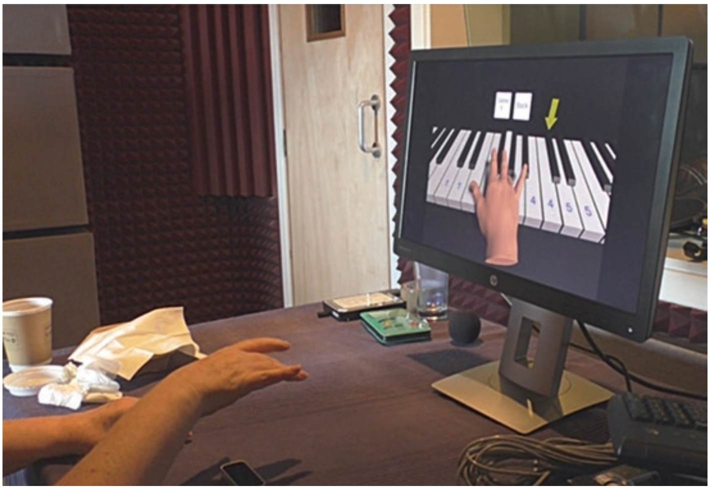


Fig. 4 Participant 2 user testing “Type” game

this exercise. During game play, the participants often struggled to control the rolling ball and would compensate their action by grabbing and placing the ball over the net. It was noted that the hand models would often distort when both hands were tracked.

Focus Group Data The transcript data were analysed by using an approach inspired by theme-based content analysis as described in Neale and Nichols (2001). This approach analysis for qualitative data regarding the user's opinion throughout evaluation and has proven useful within VE research contexts. Comments from the FG were assigned into common themes, which then related to a higher order theme category. The Table 2 below demonstrates common and higher order themes in the FG, along with a quantified number of responses by participants.

3.4 Participant Input into Game Design

Further minor developments were undertaken to the "Handy Rehab" exercises due to the feedback given by the participants as this was a co-creation process. These changes included the addition of count-up timers on all exercises in order to provide time feedback; changing the physical properties of the ball models to avoid rolling too much; and widening the piano keys making it easier to successfully strike the key. Other changes to the UI were made making the cursor easier to visualise and interact with the VE.

4 Discussion

This study aimed to develop VE rehabilitation exercises using a co-creation design with input of MS patients, to potentially improve hand motor skills and be used as part of their home-based rehabilitation. Overall, the participants found the developed exercises to be immersive, engaging and enjoyable. This study has therefore demonstrated a possible technique for upper limb rehabilitation in MS. Each participant had a different favourite exercise, suggesting co-creation was a successful approach, enabling the exercises to be enjoyable for all participants and also in highlighting concerns which could interfere with compliance in future use. The differing opinion in preferable exercise also demonstrates the need for choice and personalisation in rehabilitation game design. It was beneficial to have initial input as requirements in the game that reflected the needs as found in the predevelopment FG.

From the evaluation, participants were keen to use this approach at home if there was evidence for improving their dexterity and would treat it as part of a physiotherapy regime. Rehabilitation benefits was found to be a high order theme from the evaluation FG and was discussed to potentially be the greatest motivational factor in this group for rehabilitation exercises.

However, concerns with this LM technology were expressed by participants. Usability was another common theme in the post-development FG and there were noticeable problems during user testing. They expressed the movements they made during the exercises did not correspond exactly to the natural actions of the hand when picking up such objects – which they thought could be detrimental when trying to improve dexterity. In the Practice scene, even if they were making the appropriate action, grasping was not always successful. Though the difficulty aspect of this level made them "determined", they also commented that it was frustrating. This could be due to the tracking abilities of LM and should be addressed in future work.

Since this study is one of the first to investigate LM in MS patients, it is difficult to compare to other similar works. Literature is sparse in terms of upper limb motion capture-based technology for this branch of rehabilitation. Therefore, this study has provided first steps in developing rehabilitation gaming for this specific target audience. It has pinpointed the potential of an optional relaxing approach to serious gaming, as well as potential user discomfort and concerns – from feedback and input from MS users.

Realistic and interactive virtual environments have proven effective in improving upper limb

Table 2 Theme based content analysis of the evaluation FG data from MS participants

Responses from evaluation focus group	Common themes	Higher order themes
"It varied how difficult it was to pick up things"	Picking up objects difficulty (5)	Usability (13)
"Practice did not always mean perfect… bit irritating. Practice was a bit more challenging to pick up objects"		
"Could have instructions on the screen with what action it is you need to do"		
"Objects often became out of reach"		
"I think the problem is… when dexterity is being challenged but if it doesn't work and a big thud does happen [it drops or disappears] that could be a little infuriating and it is not really helping fine movement skills"		
"I liked that aspect that it felt like your own hand"	Immersive (3)	
"It did feel like it [that you were immersed]"		
"It did not feel like that the last time using the mechanical hand, this felt better"		
"With pushing the buttons maybe make that easier or instructions about what to do there"	Interacting with UI difficulty (2)	
"Have audio click more noticeable"		
"Yes, layout was easy to understand"	Layout (2)	
"It was easy and clear"		
"For practice…I would make it correspond to what it did… But doing it and it not doing what you want to do could be infuriating"	Natural action of hand movements (1)	
"Oh, I really liked it [music]… calming"	Music (2)	Enjoyability (8)
"Was there music?! I didn't notice... I must have been concentrating too hard"		
"Well for me it was the net one, and it was the background I felt as though I was in the Caribbean"	Favourite game (4)	
"The piano one was good…I also liked the net one"		
"The bursting bubbles was quite good fun"		
"I would agree with the bursting bubbles"		
"Some more engaging than others"	Engaging (2)	
"Piano was quite fun and bouncing the ball in the Caribbean was fun to do and nice to look at"		

(continued)

Table 2 (continued)

Responses from evaluation focus group	Common themes	Higher order themes
"What are they trying to achieve with each game in terms of which area or muscle"	Muscle usage (4)	Rehabilitation benefits (12)
"What would entice me it would be showing which muscles you are using"		
"Having different muscle groups for different stages"		
"I would need to know I'm doing a movement which corresponds to strengthening a certain muscle or action"		
"If there was a big benefit [to using this approach] I would be enticed"	Effectiveness (3)	
"If there was a benefit to it I would treat it like physiotherapy"		
"I would need to know… if this is what I'm trying to achieve and are the games doing that. Because it does not work precisely yet it is hard to gauge what you are developing in terms of dexterity"		
"May be good to have a time starting up and say it took me 20 seconds to that or to bring it down"	Feedback (4)	
"I know it's a bit stupid like a child getting a sticker but it's good to know I did as well or progress and compare with your last score"		
"Be nice to have some sort of conclusion [with the game objects in the Practice] and timing would help with that"		
"Timing is good [for feedback]"		
"Feedback to the physio would work if there are a set of exercise and fitted into certain goals"	Interaction with physiotherapist (1)	
"If it was prescribed exercise"	Potential Health Benefits (4)	Motivation (7)
"Good to have goals and objectives [to work towards]"		
"Know what movements it is trying to retain"		
"If it benefitted me"		
"Online competition would spur me on"	Competitive Factor (1)	
"It will [lose its novelty] but it's about what it can do that something else cannot do because if you were playing the Wii and you were doing the tennis you would only be doing only one type of movement"	Uniqueness (1)	
"Needs to be kept interesting"	Stimulating (1)	

dysfunction in stroke patients and are believed keep the patient engaged (Choi et al. 2014), but this is not as well documented in MS. Although this feedback came from a small sample of participants, it could be suggested that this group of individuals with MS would prefer engaging, realistic simulations in their virtual environment compared to abstract gamification.

The developed exercises aimed to offer a variety of different hand actions or movements which is reflected in the four separate exercises. However, the picking up objects and pinching bubbles within the different exercises involved the same movement detection within Unity. It involved fine opposition of all fingers at once which aimed to reflect the fine motor actions in Table 1, however, it was often difficult to grasp objects – even when facilitating this movement correctly. The participants often felt the interaction when picking up objects was not the same as in a normal setting. This highlights the restriction of the LM tracking in this rehabilitation approach. Contrastingly, a study by Gieser et al. (2015) found the LM controller to offer high accuracy using Unity for game development for cerebral palsy rehabilitation. However, this involved the detection of static gestures only and did not include interaction with virtual environments which the present study did. This suggests that LM could be restrictive when it comes to interacting with virtual objects and could be better suited to using gesture-based movements. Nevertheless, the challenge with this would be applying the engaging factor into this new approach that this present study offered.

4.1 Limitations

The main limitation of this study was using the LM technology itself. There is a lack of documentation with regards to this technology, Unity assets and involvement in rehabilitation studies. In terms of tracking, the user would often lose track of hand or object. Further disadvantages included frequent non-detection even with correct movements, and it was easily susceptible to occlusion interfering with tracking. Ebert et al. (2014) found similar weaknesses of LM, along with reported tracking time delays, in their study but suggests this could be short term with the increasing developments in refining tracking technology. Despite this there are advantages to LM over other more expensive tracking systems. This illustrates the idea of 'give and take' with technology. For usage by professionals in future, they must be aware there will be drawbacks that come with cheaper, more accessible technologies.

Whilst having input from individuals with MS was a positive aspect for this study, the number of participants was small - with a smaller number returning for the evaluation session. Opinions from a small, select group of individuals, from the same geographical location is not representative of all individuals with MS. It is hard to determine if these findings are representative of a wide field of patients and if the exercises' design would be as well received in a larger audience. Future applications should involve a larger number of participants to overcome this limitation.

4.2 Future Work

Although additions were made after the evaluation FG, these were limited due to time constraints. Therefore, future alterations could include the addition of different levels of difficulties and milestone achievements as these were found to be a potential motivator as well as adding more feedback values. Scoring and time feedback was difficult to implement into every game design and was not possible due to time constraints of the study. With regards to the Practice scene, this had the least positive response. The participants desired this to have an end result – rather than just picking up objects. This could include interaction between the objects themselves, such as placing them inside each other. This emphasised a clear purpose was needed for the exercises or for component parts of each exercise.

As highlighted by the evaluation FG, the participants would be keen to use this approach if this lead to improvements in their hand mobility. Therefore, future research could involve investigating, using a longitudinal study, if this method of LM would improve hand functionality long term. Additionally, this type of study would highlight potential adverse effects of using LM long term and the motivation the user possesses after continued use. To further investigate the benefits of LM over other methods, a comparative study could also be pursued. This would identify any advantages over other rehabilitation techniques and what LM can uniquely offer to patients.

5 Conclusion

This project achieved the main aim of making a collection of interactive and enjoyable rehabilitation exercises for MS patients made possible due to their early input in the design process. This study successfully inputted user opinion into the design to create a successful, promising product. The results from the evaluation highlight the limitations in hand tracking, thus LM may not be able to offer a wide range of movements that reflect the upper limb difficulties of people with MS. Although restoring hand mobility was incredibly important for these participants, they did not partake in any rehabilitation exercises at home. The positive responses to aspects of the created exercises, along with participants stating they would use this approach at home if there were reported benefits, suggests this approach possesses potential in rehabilitation. Therefore, more extensive research is necessary to determine the relevance and rehabilitation benefits of such approach in MS.

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Examining Vascular Structure and Function Using Confocal Microscopy and 3D Imaging Techniques

Craig J. Daly

Abstract

The structure of the blood vessel wall has historically been studied using thin cut sections using standard histological stains. In the mid-80s laser scanning confocal microscopes became available and offered investigators the chance to examine the 3D structure of thicker sections (i.e. ~60 μm depth penetration for a typical vascular wall). Unfortunately, desktop computers lagged far behind in their capacity to process and display large 3D (confocal) data sets. Even extremely highly priced graphics workstations of the early to mid-90s offered little in the way of flexible 3D viewing. Today's gaming PCs provide the kind of processing power that 3D confocal users have been waiting for. Coupled with high end animation software, virtual reality and game design software, we now have the capacity to exploit the huge data sets that modern microscopes can produce. In this chapter, the vascular wall will be used as an example of a biological tissue that can benefit from these developments in imaging hardware and software.

Keywords

Vascular · Imaging · Virtual reality · Artery · 3D imaging

1 Imaging

There exists a huge array of fluorescent biomarkers for Life Science research. Virtually every component of the cell can be stained, as can many of the components of the various signalling pathways. Confocal Laser Scanning Microscopy (CLSM) is a common technique that can be found in most well funded laboratories or research establishments. The CLSM produces sharply focussed serial images at incremental depths (typically 0.1–1 μm). The z-axis aligned xy (2D) images can then be combined to create a 3D image volume. The experienced CLSM user will have a sound knowledge of the available lasers and filters that will guide the appropriate choice of fluorophores for imaging.

Once a 3D image volume has been captured it is processed and visualised using a multitude of different methods and software packages. The most common of the freely available tools is ImageJ. It is relatively easy to use and has a broad range of plugins that can extend its capabilities. Whilst imageJ does have some 3D capabilities, other commercially available software packages (e.g. IMARIS & AMIRA) are more powerful and flexible. Both packages offer different 3D

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rendering modes including; volume rendering, iso-surface creation, simulated fluorescence projection, extended focus orthogonal sectioning, non-orthogonal sectioning and combined rendering with orthoslice projections. The list covers elements of both packages and each has its own specific advantages.

Whilst IMARIS & AMIRA are both excellent 3D microscopy packages they are limited in their animation capabilities. For this we need to use software that is not specifically designed for microscope-based data. Examples are Maya, 3DsMax & 4D Cinema. CLSM data can also be imported into game design software such as Unity3D. These packages offer unlimited capabilities for visualisation and rendering of microscope-based data. Animation and game design software is covered in the final section of this chapter.

2 Vascular Structure

The vascular wall at first glance, and as portrayed in many text books, looks like a relatively simple structure. There are three main tunics; intima, media and adventitia/externa. These are concentric layers of cells that are seemingly separated by a boundary sheet of external and internal elastic lamina (Fig. 1).

In reality the structure-function relationship is surprisingly complex and it would be a mistake to think of the tunics as independent functional units. Similarly, the structure of each elastic lamina is crucial to the function of the vessel wall as the precise architecture markedly affects the communication between the different tissue layers. As an example, the small holes (fenestrae) in the internal elastic lamina determine the number and efficiency of the myo-endothelial junctions between the endothelial cells and inner layers of smooth muscle cells. Furthermore, the fenestrae sizes change in cases of experimental hypertension (Briones et al. 2003). The following sections will examine each tunic of the vascular wall using CLSM-derived 3D image volumes as illustrations.

3 Perivascular Adipose Tissue (PVAT)

The fat cells surrounding most blood vessels has now been recognised as a source of many releasable vasoactive factors (adipokines) which can

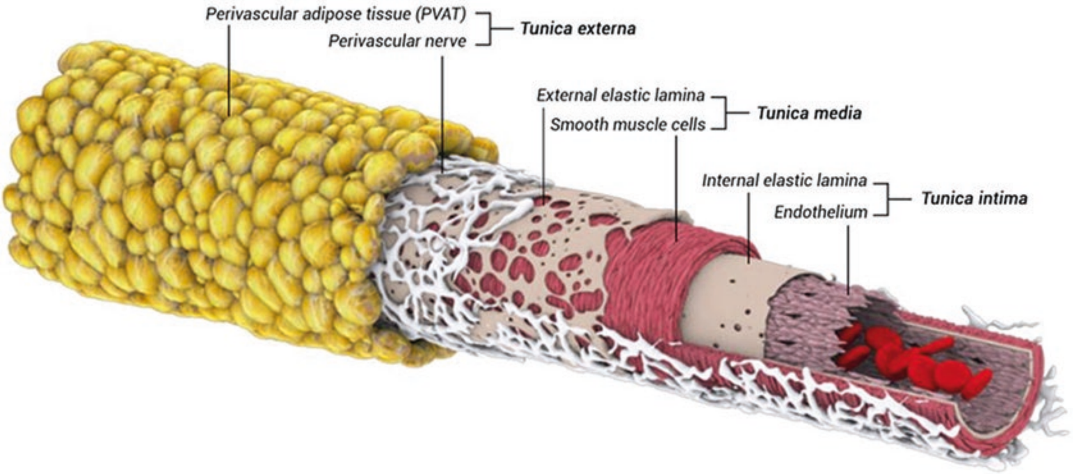

Fig. 1 Structure of a small 'resistance artery'. The 3D model shows the various layers of the vascular wall. The model was constructed using a combination of laser scanning confocal microscopy data and artistic impression. As such the model represents a very close approximation to the true structure of the vessel, unlike many textbook diagrams. The model was constructed by Uti Sari as part of a MSc in Medical Visualisation and Human Anatomy final project at the University of Glasgow under the supervision of the author. Note; whilst the perivascular fat is coloured yellow in this figure, the mesenteric arteries upon which it is based are normally covered in white adipocytes

have both pro- and anti-contractile effects (Cheng et al. 2018). The composition of the PVAT in different blood vessels varies markedly. The aorta is completely surrounded by a thick coat of beige adipocytes which are a mix of white and brown fat cells. These fat cells have different physiological roles and are reviewed elsewhere (Wang and Seale 2016). The rodent tail artery and cerebral arteries have very little PVAT. Renal arteries are buried in a deep mass of fat whilst the small mesenteric arteries are covered in mainly white PVAT (Figs. 1 and 2). It is surprising that the physiological relevance of PVAT has only been recognised for the past 20 years and has really only been studied in any great detail in the past 5–10 years (Bulloch and Daly 2014).

The lack of any substantial (if any) structural boundary between the PVAT and tunica adventitia (Fig. 2) could support the view that these two tissue layers act as one functional unit. That is the preferred view of the author and is substantiated by imaging-based evidence that both tissue types share the same nerve supply (Fig. 2; Bulloch and Daly 2014). The images presented in this chapter show the presence of nerves in the tunica adventitia giving rise to branches which associate with the adjacent PVAT. The dense nature of the innervation pattern in Fig. 2 is indicative of the adrenergic nerve plexus. Whilst the antibody that has been used (PGP9.5) does not distinguish between nerve types, it is highly unlikely that these are anything other than adrenergic. The sensory nerves in this particular vascular bed are of a much lower density (Bakar et al. 2017) and the author has no functional evidence for the presence of parasympathetic nerves. The purpose of this chapter is not to discuss the physiological detail of the autonomic neuroeffector responses but rather to focus on imaging of the vascular wall. In that respect, the figure clearly shows the utility of the PGP9.5 antibody. In a laboratory setting, the author has found this to be an extremely reliable marker for nerves in the vasculature. The image also clearly shows a relationship between innervation of the PVAT and the tunica media. The image in Fig. 2 is a 3D image volume which has been reconstructed using AMIRA.

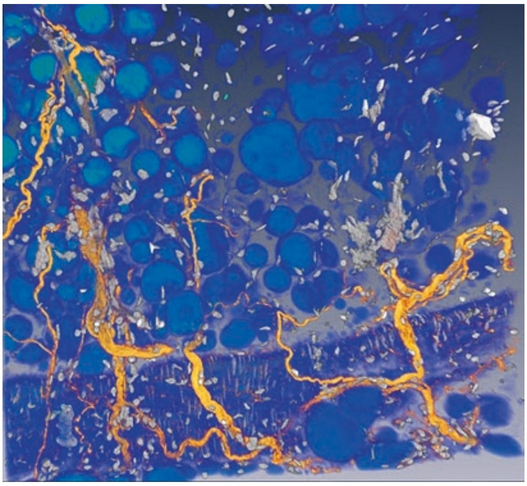

Fig. 2 The image shows the white PVAT (mouse mesenteric artery) in blue (pseudo-coloured and stained with BODIPY FL-prazosin). The yellow pseudo-coloured nerves indicate the presence of PGP9.5. The PGP is complexed with a secondary fluorescent antibody in the red fluorescent spectrum but is shown here in yellow. Nerves of the vascular wall can be clearly seen extending into the surrounding PVAT. The image is a 3D volumetric rendering of a confocal z-series

4 Tunica Adventitia

This is perhaps the least understood component of the vascular wall. It is also probably the most interesting. At the time of writing, Wikipedia refers to the adventitia as being ‘extraneous’ to the vessel. This view is not uncommon but is extremely misleading and probably disrespectful. The density of adventitial cells (macrophage, fibroblast and stem cells) is far less than might be imagined. However, the density of adventitia cells increases markedly in hypertension (Kantachuvesiri et al. 2001). Confocal scanning of the tunica adventitia reveals a complex network of elastin fibres upon which the adventitial cells can be found (Fig. 3). Labelling the adventitia with the fluorescent α_1-adrenoceptor ligand BOPIPY FL-prazosin reveals a population of cells that express these receptors but also a population which do not (Fig. 3). The presence of functional α_1-adrenoceptors in the adventitia raises the question of the source of the endoge-

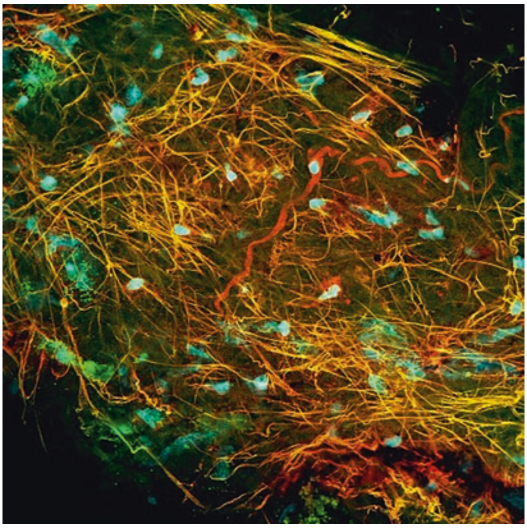

Fig. 3 Adventitial structure of mouse tail artery. The image is a z-projection (maximum intensity projection) view of the outer layers of the vascular wall. The thin yellow structural fibres are most likely to be elastin as they are weakly fluorescent. The green fluorescence marks the presence of the fluorescent α_1-adrenoceptor antagonist BODIPY FL-prazosin. Cell nuclei are bright cyan. Red fluorescent CGP-12177 is a β-adrenoceptor ligand and appears to bind to the perivascular nerve seen in the centre of the image

nous ligand. The most obvious source is the noradrenaline released from the sympathetic adrenergic nerves that are located adjacent to the adventitia and external elastic laminae. This raises the possibility that one population of adventitia cells can be activated by the vascular nerves. These would be the same nerves that innervate the PVAT and also the smooth muscle cells of the tunic media (Fig. 2). Thus, we have the possibility of sympathetic adrenergic nerves activating three different cell types within the vascular wall. This is an idea that has not been broadly considered and many textbooks continue to portray the idea that vascular nerves activate primarily smooth muscle. The presence of adrenoceptors on PVAT and adventitial cells demands that this overly simplistic view be revisited and studied further. To be clear, and in view of the current Wikipedia entry, the adventitia is an essential functional component of the vascular wall. The relatively low density of cells should not be misinterpreted as being proportional to importance. Consider instead the possibility that adventitial cells may be highly mobile, traversing the vessel surface in search of areas that require attention. Such a model would explain the apparently disorganised arrangement being due to single timepoint images (similar to an aerial snapshot of sheep in a field). It is possible the seemingly ‘extraneous’ tunica externa (adventitia) may be, by far, the most interesting and complex region of the vascular wall.

5 Nerves

The original method of visualising adrenergic nerves (Falk-Hillarp) involves drying the tissue and applying a chemical process that renders the catecholamine, noradrenaline, fluorescent. Fluorescence imaging of this type confirmed that the noradrenaline containing adrenergic nerves are largely confined to the adventitia-medial border. The process requires thin sections and is therefore 2D in nature.

3D imaging of the adventitial nerve network can be achieved through staining with the fluorescent ligands mentioned above (BODIPY FL-prazosin & fluo-CGP). Branches of rat and mouse mesenteric arteries are particularly well suited as they host a large adrenergic sympathetic innervation (Briones et al. 2005). Figure 4a shows the intricate nerve network that is directly adjacent to the adventitial cells and is sandwiched between the smooth muscle cells and the PVAT. This location gives access to neurotransmitter targets in three different cell types. The vessel in Fig. 4 has had the overlying PVAT removed to enable visualisation of the tunica adventitia. In this image volume the elastin matrix is not shown. The individual nerve fibres occupy different depths in the volume and therefore have the potential to influence muscle contraction more or less depending on their axial position. The smooth muscle lies directly below this nerve network separated by the loose weave of the external elastic lamina. The external lamina is not visible in Fig. 4 which enables visualisation of the long thin smooth muscle cells (tunica media) running

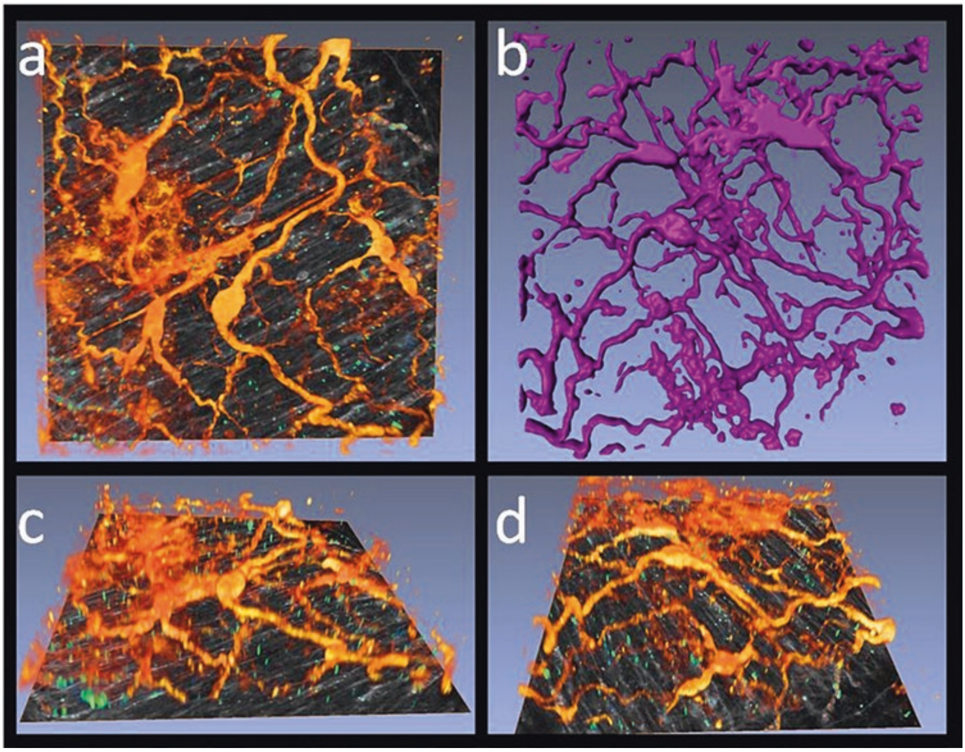

Fig. 4 The nerve network of a rat mesenteric artery tunica adventitia has been scanned using confocal laser scanning microscopy. (**a**) A volume rendering of the fluorescent-CGP stained adventitial nerves (yellow-orange) sits on a dark orthogonal image plane showing the underlying smooth muscle cell layer. (**b**) The nerve network has been segmented and converted into an iso-surface composed of triangular polygons. This data type is compatible with animation and games engine software. (**c** and **d**) Alternative views of the data shown in (**a**)

diagonally in the image. Some smooth muscle cells also bind fluo-CGP and this is discussed in a later section.

It should be noted that the vessel in Fig. 4 is an unfixed 'live' wet vessel. It is therefore under no circumferential or trans-mural pressure. The vessel would be longer if fixed under 40–80 mmHg intra-luminal pressure. Even within this shortened structure, the images suggest that live functional imaging of this site could be very informative. Membrane potential dyes, Ca++ indicators and other physiological markers could unravel part of the functional complexity that must exist in this region.

Nerve networks are difficult to fully illustrate using 2D images. Even viewing 3D volumes on a 2D screen can be limiting. A later section introduces virtual reality as a solution to the visualisation problems.

6 Smooth Muscle Organisation

Is it important to know the orientation and organisation of individual (or groups) of smooth muscle cells. The reason is that cells reorganise in hypertensive blood vessels. The form of this remodelling can be inward eutrophic or inward hypertrophic. In both cases the lumen diameter is reduced to normalise flow and pressure in the downstream tissues. The arterial wall increases in thickness to withstand the increased pressure. This thickening can occur as a result of increased cell size (hypertrophy) or through rearrangement of the existing cells (eutrophy). The adventitia also experiences an increase in cell density (Arribas et al. 1997; Kantachuvesiri et al. 2001). However, we can never hope to understand and repair a remodelled wall until we fully understand the normal distribution. Hypertensive medication is extremely efficient at lowering blood pressure through vasodilation. However, the drugs are less effective in reversing the remodelling. Therefore, we strive for a better understanding of normotensive cell arrangement.

Previous work has described the apparent helical arrangement of vascular smooth muscle using fluorescent nuclear stains (Daly et al. 1992; McGrath et al. 2005). A possible angle of alignment of cell groups was further identified using 2D and 3D image analysis techniques (Daly et al. 2002). Work is currently focusing on the possible existence of functional groupings of smooth muscle cells into vascular bands. This grouped banding pattern is most apparent when using cytoplasmic stains but is also detectable in the smooth muscle cell nuclei orientation and arrangement. Nuclear stains are effective in distinguishing smooth muscle from endothelium as each cell type has a nuclear shape and orientation that easily identifiable (Fig. 5).

The smooth muscle cells are long thin cells and their nuclei adopt that same shape. In cross-section (orthogonal viewing) the muscle cells can appear flat rather than round. This raises the interesting question of the orientation of the cell's flat surface; face down or edge down to the lumen? This and other questions can be examined using 3D reconstruction and viewing techniques. Figure 5a shows the nuclear arrangement in a mouse rat mesenteric artery that has been stained, inflated to 70 mmHg and fixed under pressure prior to confocal-based reconstruction. Careful examination reveals a clear diagonal pattern to the organisation. The underlying endothelial cell nuclei can be seen to largely associate with the muscle arrangement. This type of volumetric rendering enables several different mea-

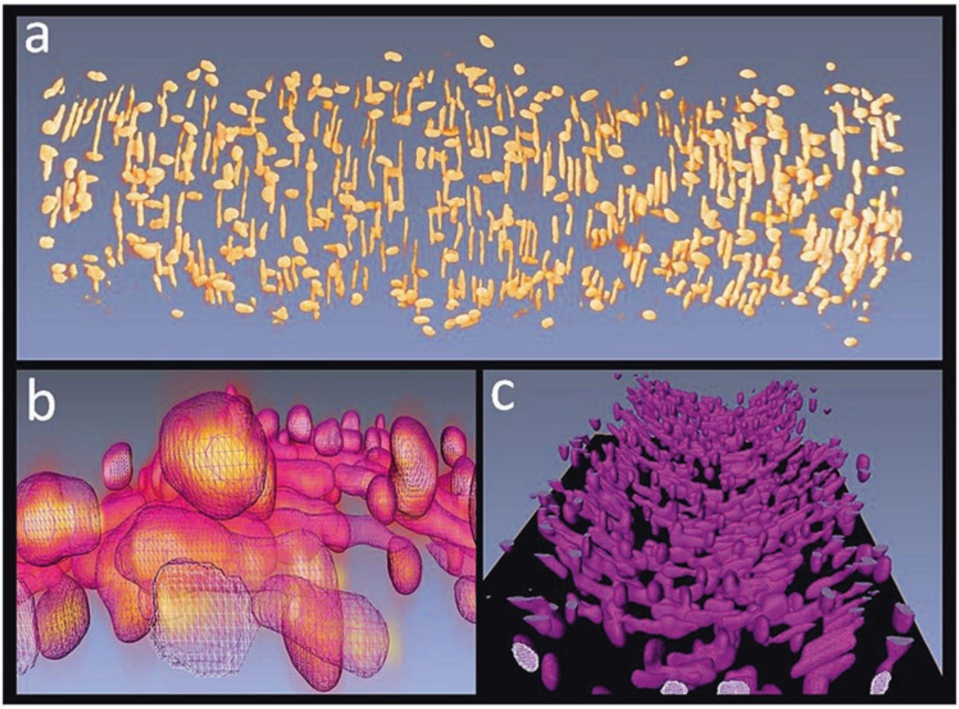

Fig. 5 A rat mesenteric artery has been pressure fixed at 70 mmHg and stained with the nuclear stain Syto 61. The artery was then scanned and the resulting image series used to construct a volumetric 3D image volume using AMIRA image analysis software. (**a**) The nuclear distribution and orientation within the vascular wall. Smooth muscle cell nuclei are long and thin and oriented vertically in the image. Endothelial cell nuclei run along the axis of blood flow and perpendicular to the smooth muscle cell nuclei. (**b**) A wireframe mesh of polygons (iso-surface) has been calculated for each object (nuclei). (**c**) The iso-surface is viewed looking along the inner axis of the vessel and in the direction the blood would be flowing

surements to be collected. A geometric polygon matrix (mesh or surface) can be automatically wrapped around each object (Fig. 5b). The polygon surface can then be given a solid colour, a desired transparency (Fig. 5c) and exported to animation software. High end animation software (e.g. Autodesk Maya) offers access to natural light and texture renderers that can be applied to meshed surfaces. This can create photorealistic 3D textures and materials. Much work lies ahead in this unexplored area of biological imaging of microscope-based data.

7 Receptor Distribution

Using fluorescent antibodies and peptides it is possible to examine the distribution of receptor proteins throughout the vascular wall (Daly and McGrath 2003). The first indication that the receptors driving vasoconstriction may be heterogeneously distributed in the wall came from the functional work of Graham and Keatinge (1972) using strips of sheep carotid artery. The experiments showed that inner layers of smooth muscle were more sensitive to noradrenaline than the outer layers. This raised the possibility that adrenergic receptors (adrenoceptors) in the inner layers of smooth muscle may be greater in number (or sensitivity) than those in the outer layers of muscle. It is precisely this question which led to our developments in the use of fluorescent drugs (ligands), CLSM and vascular tissue (McGrath and Daly 1995; McGrath et al. 1996).

Fluorescent ligands have been used for many years and offer several advantages over older methods (e.g. autoradiography) that use radioactive drugs (McGrath et al. 1996). The use of fluorescent drugs enabled image analysis techniques to be used in estimating drug affinity on a small patch of living cells. This technique provided quantitative measures that were very similar to traditional ligand binding and confirmed the selectivity and affinity of the (altered) fluorescent ligand (Daly et al. 1998). For the α_1-adrenoceptors the classic antagonist is prazosin. A fluorescent form of prazosin, BODIPY FL-prazosin became available around 1992 and was marketed by Molecular Probes. Following several takeovers that company now resides within the Invitrogen Thermo Fisher group who still sell BODIPY FL-prazosin. A note of caution though. This compound is not exactly prazosin due to the removal of a ring component to make way for the fluorescent BODIPY molecule. We have argued for a name change to reflect this and so often refer to the compound as QAPB (quinazoline piperazine BODIPY) which is more correct – but it is still a high affinity α_1-adrenoceptor antagonist. When applied to a mouse mesenteric artery, high concentrations of smooth muscle cellular α_1-adrenoceptors will show as green fluorescence. From a very early stage it was clear that some cells had a very high expression of α_1-adrenoceptors and others did not (Fig. 6a).

The mouse mesenteric artery contracts well to α_1-adrenoceptor agonists and when contracted can be relaxed using a β-adrenoceptor agonist such as isoprenaline. This is common for many arteries and suggests the presence of α- and β-adrenoceptors on the smooth muscle cells of the tunica media. The expectation may therefore be that each cell would have a compliment of both receptor types. However, to our surprise, we found, using a red fluorescent β-adrenoceptor ligand fluo-CGP12177, that some cells exhibited a very high expression of β-adrenoceptors but were low in α-adrenoceptors. This leads to the hypothesis that smooth muscle cells could be subdivided into α- and β-expressing on the basis of fluo-ligand binding (Fig. 6b; Daly et al. 2010). A similar heterogeneity of receptor distribution (of muscarinic receptors) has now been reported in the vascular endothelium (McCarron et al. 2017). Thus, imaging studies are revealing receptor distributions that previously were not imagined (Daly and McGrath 2011).

8 Tunica Intima

The inner layer of vascular cells (the endothelium) are crucial for normal vascular function. These cells release both vasoconstrictor (endothelin) and vasodilator (nitric oxide) substances. Both of these vasoactive factors are extremely potent. If the

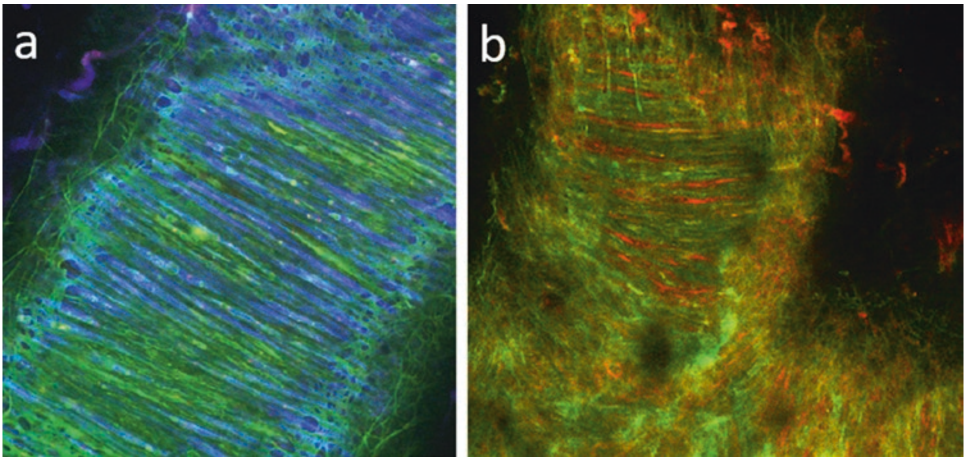

Fig. 6 Mouse mesenteric artery incubated with (**a**) green-fluorescent prazosin (BODIPY FL-prazosin) alone and (**b**) in combination with red fluorescent CGP12177. In both images green fluorescence indicates cells expressing α_1-adrenoceptors in image (**b**) it can be seen that α- and β-adrenoceptor expressing cells can be found side by side. Both images are extended focus (z-projections) of multiple 2D images

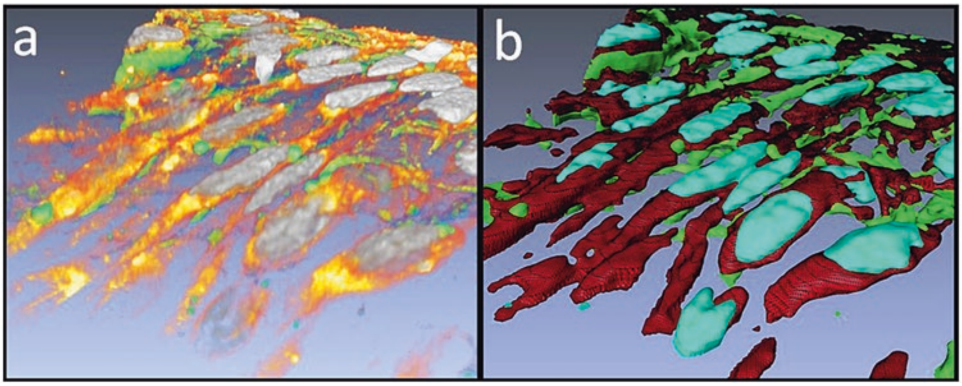

Fig. 7 Vascular endothelium of human sub-cutaneous artery. The endothelial cell nuclei have been stained with Syto 61, a far-red fluorescent stain. (**a**) A 3D volumetric render of the endothelial cell layer showing the nuclei in grey, β-adrenoceptors in red/yellow and the internal elastic lamina structure in green. (**b**) The image volume in (**a**) has been converted to an iso-surface mesh suitable for importing into animation or virtual reality

endothelium is dysfunctional as may be expected in some hypertensive conditions (Konukoglu and Uzun 2017) then the resulting increased vasoconstriction will exacerbate the hypertension.

As previously stated, the muscarinic receptor distribution on the endothelium is heterogenous. The generally accepted model for adrenergic control is that the vascular endothelium has a compliment of β-adrenoceptors. It is also expected that α_2-adrenoceptors would be present and we have found additional fluo-ligand binding evidence for endothelial α_1-adrenoceptors. Application of red fluorescent-CGP12177 revealed β-adrenoceptors on the endothelial cells of human sub-cutaneous arteries (Fig. 7). Incubation with the fluorescent α_1-adrenoceptor ligand did not reveal significant detectable binding in these experiments.

The positioning of the endothelial cells on the internal elastic lamina is crucial for communication with the inner layers of smooth muscle. Communication happens via small holes in the lamina (fenestrae) which facilitate the formation of Myo-endothelial junctions.

9 3D Imaging and Virtual Reality

When confocal microscopes first became commercially available (mid 1980s), their ability to generate large z-series data sets of images far outstripped the ability of computers to reconstruct the data. 3D modelling and deconvolution (correction) of image volumes was painfully slow. That has changed in recent years as gaming PCs have become far more powerful and dedicated graphics cards offer GPU processing power that is the equivalent of late 1990s graphics workstations. Today, for around £2000 you can purchase a fully immersive VR system with which to visualise biomedical data.

CLSM data has to be processed in a particular way before it can be fully animated or viewed in VR. For volumetric rendering the image channels need to be composited in imageJ and saved as .nifTI file format. This enables volume visualisation in VR. If the data is thresholded and segmented it can be converted to an iso-surface mesh. The mesh can then be imported to other utilities that can reduce the mesh size but maintain detail. The mesh can also be sculpted and covered in realistic looking materials referred to as UV mapping. The details and complexities of the animation and rendering process is out with the scope of this chapter but more detail can be found in Daly et al. (2014) or at the authors website (www.cardiovascular.org).

The most exciting new development for confocal microscopy is the arrival of commercially available VR headsets. Most regular confocal users will have amassed a collection of 3D image volumes, most of which will just be archived. The author has found that visualising complex data sets (i.e. the adventitia in Fig. 3 or nerve network in Fig. 4) in VR has revealed features that were previously missed when viewing on a 2D screen. Having the ability to walk around, or through, a data volume gives a truly different insight into the relationships of the various structures. It really has to be experienced. This technology is breathing new life into old datasets and releasing their true potential (Fig. 8). There is certainly a significant learning curve to be negotiated in becoming competent with the software (i.e. Unity3D & MAYA) but YouTube hosts plenty of tutorials on both.

10 Conclusion

The last 25 years have brought enormous changes in microscope technology, computer hardware, software and visualisation equipment. In 2003 the author took a confocal data set to the Glasgow Science Centre VR theatre. This comprised a

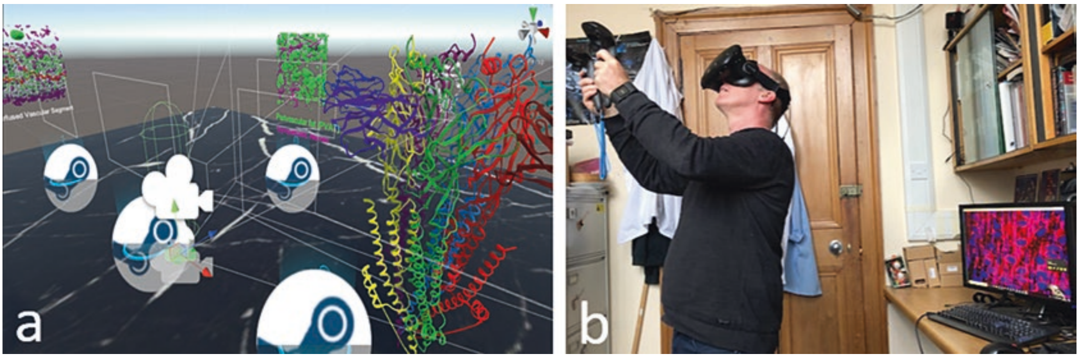

Fig. 8 Using the UNITY game engine to deliver Virtual Reality visualisation of CLSM and protein structure datasets. (**a**) A screen shot of a UNITY scene showing the positioning of three different datasets and the central position of the VR camera. (**b**) The author examining a CLSM dataset of endothelial cells inside the lumen of a blood vessel

large curved screen, stereo projectors and an Onyx3 Reality monster SiliconGraphics computer (total cost £800,000). On first viewing a confocal dataset using the current HTC Vive VR headset, the author was stunned by its potential.

We are right at the beginning of a new era for biomedical visualisation. The technology is young and can only get better. With imaging devices producing bigger and better data sets, and visualisation reaching higher resolution standards every year, the future of BioImaging is almost unimaginable.

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Which Tool Is Best: 3D Scanning or Photogrammetry – It Depends on the Task

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Abstract

In many educational and clinical settings we are increasingly looking into methodologies for accurate 3D representations of structures and specimens. This is relevant for anatomy teaching, pathology, forensic and anthropological sciences, and various clinical fields. The question then arises which tool best suits the task at hand – both 3D scanning and photogrammetry are options. For the use in medical education the aim is to create 3D models of anatomical specimens with high quality and resolution. Various qualitative and quantitative criteria determine the performance fidelity and results of 3D scanning versus photogrammetry. In our work we found that photogrammetry provides more realistic surface textures and very good geometries for most specimens. 3D surface scanning captures more accurate geometries of complex specimens and in specimens with reflective surfaces. The 3D scanning workflow and capture method is more practical for soft specimens where movement of the sample can lead to distortions. Overall, both methods are highly recommended dependent on the nature of the specimen and the use case of the 3D model.

Keywords

Medical education · Anatomy · Photogrammetry · 3D scanning · 3D learning · Digitization

1 Introduction

Over the past decade there has been an increase in the use of digital media to represent the human body (Brazina et al. 2014). While some of these media are based on 3D modelling and artistic representations, others like the NIH Visible Human project are based on 3D reconstructions of sectional data (Tam 2010). Another approach is to digitize selected pro-sected anatomical material for the use in digital 3D applications,

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which range from virtual and augmented reality to online libraries where users can interact with the digitized pro-section.

There is an increasing demand for 3D digitized anatomical material for medical education so that access to a virtual anatomy lab is possible for students (Saltarelli et al. 2014; Azer and Azer 2016) The technology also finds applications in anthropology, forensics, and comparative vertebrate anatomy.

Here, we seek to compare the usability of two common methodologies for the 3D digitization of anatomical specimens: photogrammetry and 3D scanning.

For this study we used specimens from the osteology teaching collections from the University of Victoria and the University of British Columbia. The brain specimen was from the University of British Columbia Body Donation Program. All specimens are used in accordance with the policies set out by the respective departments.

2 Overview of Photogrammetry

The principle underlying photogrammetry is to capture multiple overlapping digital photographs from different angles which are then digitally reconstructed into a 3D object. Points of reference in the 2D photographs are identified with specialized software and the distances between them measured, triangulation of these points allows for the creation of a 3D mesh. Realistic and accurate surface texture is achieved through an overlay of the original photos onto the 3D mesh (Linder 2016; Incekara and Seker 2018; Jebur et al. 2018). Once a model is completed it can be used in various 3D environments.

2.1 Equipment and Setup

Camera One of the most important tools in photogrammetry is the camera (Katz and Friess 2014; Evin et al. 2016).

Table 1 Camera settings for photogrammetry

Parameter	Setting	Rationale
File format	Jpeg	Industry standard, largest file size selected, resulting in file sizes of about 8 MB
ISO	100	Smaller ISO results in sharper images
White balance	Set to the lights used to illuminate the specimens	Better color capture
Light metering	Set to the center of viewfinder on the specimen	
Aperture	f20–32	In order to keep good focus on the entire specimen, large objects need a smaller aperture
Shutter speed	Determined by aperture	Controlling for shutter speed is necessary for consistency across photos.
		Slow shutter speed will require the use of a tripod.

In this process, the manual settings were adjusted for file format, ISO, white balance, light metering, aperture, and shutter speed (see Table 1). The goal of these settings is to capture, sharp and precise photographs of the specimen, with the background out of focus. These settings will facilitate a more precise 3D reconstruction. Consistent lighting, apertures and shutter speeds for each specimen helps to maintain consistency across photos. Typical settings used for the acquisition of our anatomical specimens are summarized in Table 1.

Specimen setup Even lighting of the specimen during a full 360-degree rotation is critical for good results. Lights need to be positioned around the specimen for optimal illumination with a maximum reduction of shadows.

Two hooded 5000 kelvin LED lights at about 45° to the side were positioned and adjusted to minimize shadows on the specimen. If needed, two additional lights with flexible necks were added to the setup. For consistency the lights were not moved once we started capturing photos and all lights had the same color temperature, with white balance set to those lights.

The specimen was placed on a turntable so that the stationary camera on a tripod easily captured the specimen from all angles by rotating the specimen. In order to ensure the ideal overlap between the photos taken, the turntable was marked every 8°, resulting in 45 photos per 360° (Fig. 1).

During the photo acquisition process multiple orientations must be captured by flipping the object to reveal previously missing surfaces to the camera.

The specimen was placed on a contrasting color background to help the photogrammetric software separate the specimen from the background itself.

2.2 Software Post Processing

Software The post-processing with a photogrammetry approach is almost always the rate-limiting step in acquiring a 3D model (Katz and Friess 2014; Evin et al. 2016). The computer algorithm determines point of similarity in each photo and compares these points across all photos, making a point cloud. At this stage, the computer program will also calculate the distance and angle of the camera when each photo was taken (Foster and Halbstein 2014; Jebur et al. 2018). An example of this is shown in Fig. 1. The distances between these points are then calculated and a process of triangulation results in the mesh framework for the model. Finally, the program overlays a texture on the model using a jpeg file created from the photos. The photo alignment process can be quite time consuming due to the complexity of the calculations (Foster and Halbstein 2014; Jebur et al. 2018). Due to this, the quality of the photographs, number of images, lighting, and orientations chosen in photo acquisition are crucial to successful 3D reconstruction (Foster and Halbstein 2014). The software used in the described photogrammetry approach is Agisoft PhotoScan (PS) Standard Edition software version 1.4.4, which is a commercially available 3D photogrammetry program.

The basic computer requirements as suggested by Agisoft for Photoscan, and used in our process, are an Intel i7 Processor or equivalent, 16 GB RAM and a Nvidia GeForce GTX980 GPU.

The Post-Processing Post-processing can be broken down into five steps: masking of photos, alignment of photos, building a dense cloud, building a mesh, and building a texture.

In the masking step the software recognizes and removes the monochromatic background to isolate the model. This is done both automatically and through manual adjustments on an as-needed-basis with the selection tools. A uniform background while capturing the specimen will decrease the time needed for this step.

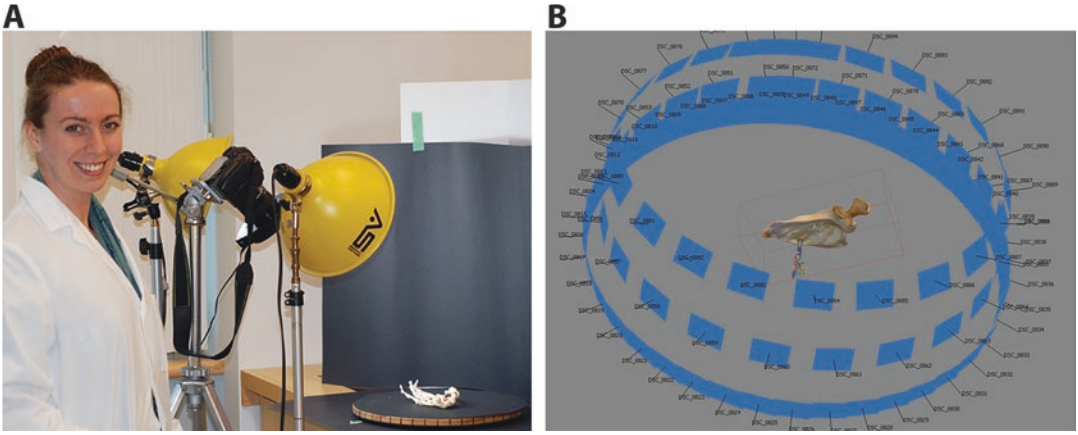

Fig. 1 The photogrammetry process. (**a**) Photography of the specimen. (**b**) Creation of the digital model

The photographs are then processed for alignment, geometric reconstruction, and texturing steps. First, the aligned photographs result in a rough representation of the model as a "sparse point cloud" comprising data points that represent the external surfaces of the specimen. This rudimentary depiction allows for preliminary construction of a 3D model before adding more complex and time-consuming processing step. At this point, the user checks to confirm that the sparse point cloud adequately represents the specimen without error and artifacts. The model is then further processed generating a "dense point cloud" using more data points.

For the creation of the 3D mesh and surface texture all external features of the model must have been captures from various orientations. Each orientation is referred to as an individual "chunk" in the PS software.

The point clouds for each individual chunk are then aligned and merged into a single model.

Following the merging of chunks, a mesh and texture are developed for the 3D model – This step overlays a more shaded and colored representation of the specimen over the 3D model. The digital model can then be exported into the file format best suited for the intended 3D application.

3 Overview of 3D Scanning

3D laser scanning is a process where millions of data points are accurately recorded with a 3D scanning device and placed in a dense vector point cloud. Two cameras are placed at an angle from each other to record any fluctuations in the projected light. A third camera records color. This process records volumetric full-field data that contains geometric mesh information and color data. The 3D scanner and associated software can record millions of points of data per minute and assemble it into a 3D model in real time. The model can be manipulated within the software and altered and once a final mesh has been generated, a texture map is applied and the object is ready to be exported and shared.

Unlike photogrammetry, where there are clearly defined steps, 3D scanning mostly falls on a continuum where each step is revisited so that all data is picked up within the margin of error tolerance. Key algorithms that must be performed include: Scanning, Global Registration, Outlier Removal, Fusion and Texturing. The order of performing these algorithms is not fixed and can vary dramatically based on the environmental (setup) conditions and object's complexity. This process is cyclic, and the operator must double check their scans and reanalyze their procedure throughout data acquisition.

3.1 Equipment and Setup

3D Surface Scanner We used an Artec Space Spider 3D scanner, which is an S-Type Laser scanner utilizing the blue-LED technology, where the camera acts as its own light source. This eliminates the need for complex lighting setup. The design of the scanner emphasizes resolution and accuracy, at 0.1 mm and 0.05 mm respectively. The scanner records a frequency of 7.5–8 frames per second. The Artec Space Spider is specialized to record small objects, which is likely to occur in a medical environment. Together these features allow for a 3D scan in even adverse environmental conditions with low lighting conditions.

A mid-to-high range Alienware laptop with: 16GB of RAM, an i7 processor and an nVidia GTX 1060 graphics card was used to reconstruct the scanned vertex points into 3D models. The Artec Space Spider scans up to 1 million data points per second which can be very resource intensive.

Specimen Setup Typically, we placed the specimen on a turntable which provides additional stability allows the software to pick up more data points/polygons which will benefit the overall quality of the model. It is important to have a clear differentiation of the object from the background, we used a high contrast monochromatic backdrop when scanning. The scanner has a specific range of distance from the object for optimal data recording. A test scan after configuring all settings is advised. Custom ranges can be adapted to fit the operator's requirements.

Software Artec Studio 12 Professional is the interactive development environment provided by the manufacturer. This software is actively involved in data processing during the scan and scanning parameters are adjusted here. While one of its primary functions is to provide a platform to interpret the recorded data from the scanner, it also provides mesh and scan modification functionality. The program can overlay textures recorded simultaneously with the object geometry information. The recorded mesh can be exported from this proprietary software into other widely used formats, most catered towards CAD software.

3.2 The 3D Scanning Process

The 3D scanner acquires several scans of both the object and the surroundings. Each one of these scans is stores as a separate object within the software. In a first step, the surface the object was placed on while scanning has to be erased so that the only entity remaining in the scene is the object of interest. In a next step, all scans are automatically aligned within the software to create a single object with no incorrect or overlapping polygons.

Once these scan modifications have been completed, mesh modifications can start. The 3D mesh of the object is typically jagged and irregular. The *Global Registration* function registers all recorded data points on a global coordinate system, this results in increased accuracy in placement of each vertex on the mesh relative to other vertices. The software provides an option to apply this function to either just the geometry, just the texture, or both at the same time. In order to prevent the final product's texture to be offset from the mesh the of global registration for both the mesh and the texture should be selected. *Global Registration* compares every single vertex relative to another, consequently, some scans will have high error value. In an effort to retain overall geometry, the software will automatically disregard these scans and the 3D mesh will be left with big holes. These holes must be filled by rescanning the missing surfaces, thus completing the cyclic methodology analogy.

Once a reasonably complete mesh has been assembled after *Global Registration*, an *Outlier Removal* function can be performed if needed. The function should be performed if a turn-table was not used and all the scans were recorded while the scanner was moving through the environment and around the object. The resolution of the *Outlier Removal* function used in many of the presented figures is 0.1 mm. This function removes many vertices which were outside the error tolerance range and were treated as outliers. This may result in more empty holes thus requiring the operator to return to the scanning process. The resolution used in this process will be the same resolution that must be used during subsequent operations.

Following *Global Registration* or *Outlier Removal*, a *Fusion* function must be run in order to construct a basic skeletal structure of the object. Onto this base, the texture will be applied. Artec Studio 12 Professional offers 3 different types of fusion functions: sharp, smooth, and fast fusion. All the presented figures are scanned layers fused using the *Sharp Fusion* function for maximum accuracy. During *Smooth Fusion* the smoothing algorithm may a loss of important geometry. *Fast Fusion* may not use certain data points, sacrificing quality for speed. A cursory inspection of the resulting fusion layer should be performed to mark and fix any artifacts that may have occurred during the *Fusion* process. Artifacts occur due to a number of issued including: misalignment of scans, not enough data rescanned after the *Global Registration/Outlier Removal* function, mismatch of resolution used during *Outlier Removal* and *Fusion* functions, or too high/low resolution used during either process.

Texturing the 3D mesh is the rate-hindering step for 3D scanning. The speed at which this algorithm proceeds is highly dependent on the specifications of the computer being used, especially the memory (RAM). Once all the artifacts have been cleared from the base mesh (post-*Fusion*), all the scans that were used to construct that fusion layer must be selected since the color data is stored on the scan layer itself. The resolution of a texture map at 2 K, 4 K, or 8 K can be selected. The resolution of the texture map that is applied is directly proportional to the time the *Texture* function will take to finish. When the texturing is finished, the user has access to adjusting the applied texture map on the 3D mesh. The options available include: Brightness, Contrast, Hue, Saturation, and Gamma Correction – typical digital photo post production parameters that are then applied to the entire object.

Completed meshes can be exported as OBJ, PLY and STL (commonly exported formats), which transfers into another renderer or CAD software for further editing. Additionally, the exported files are very easily integrated in to an AR/VR or any other interactive environments which is potentially useful for detailed and educational anatomy experiences. The scans themselves can be exported as well; in case the operator would like to use another 3D scanning/editing software. Any texture placed on the 3D mesh is exported as an unwrapped UV map in one image file, the format of which can be chosen.

4 Comparison of Photogrammetry and 3D Scanning

In order to compare both photogrammetry and 3D scanning, 3D models were created of three anatomical specimens: a brain, a skull, and a scapula. The same cadaver brain was imaged by both methods; however, both the scapula and skull were different but comparable specimens. The two imaging systems were assessed on the quality of the 3D products, applicability, usability, accessibility, time requirements, and technical requirements.

In general, the photo acquisition process in photogrammetry and the scanning with the surface scanning was consistent between models. There were slight adaptations to each approach, given the variability in model type and shape, yet the difficulty to obtain raw data was not that variable between specimens. It was easy to navigate the specimens with both the surface scanner and the DSLR camera. The time required to do each of the acquisitional processes were very comparable, taking less than an hour for each specimen.

Post-processing for photogrammetry presented infrequent challenges in acquiring the finished product, with exception of the scapula and brain. The brain was easy to reconstruct, yet there were a few steps that required re-evaluation and repeated processing due to the slight change in orientation of the cerebellum relative to the rest of the brain. The skull with calvarium cut was a simple reconstruction and was low effort in the software processing. The scapula imaged with 3D photogrammetry posed significant challenges and the final model was left with holes in the subscapular fossa. The time required for photogrammetry software processing was not necessarily assessed, as the time required depends on the computational power of the video card, model variability, software operator competency, and given that there were no mistakes in the post-processing. However, if there were no errors encountered and no extra steps were required, we were able to complete models in around 2 h with our video card.

3D scanning the scapula was fairly simple, as long as a high contrast background was chosen. In order to emphasize the damaged holes that were too little to get picked up by conventional ‘sweeps’ of the scanner, the high contrast background helped the software interpolate missing vertex points. These vertices were then reconstructed as holes in the scapula mesh. Due to the large vertex count of the skull with calvarium cut, the post processing was longest. 3D scanning and especially post-processing of the scans tends to be very computationally intensive. Therefore, the main challenge with the skull with calvarium cut was the waiting time, caused by the [relatively] low memory installed. Hardware aside, a variable time over the tested samples was observed. Therefore, a precise amount of time taken to post-process a model should not be associated with 3D scanning technology. We completed our 3D scanned models in 1–2 h of time. In a more general perspective: given that the object is fairly complex (assumed to be likely in medical scenarios), and no errors require retracing of steps, approximately 30 min from start to finish can be expected to reconstruct a model.

4.1 Brain

The human brain was a specimen that was very effective at comparing the two methods: it had an intricate surface texture with small details like the cranial nerves and it was a soft tissue specimen, every move of the specimen would result in some distortion, in particular of the cerebellum. We wanted to assess how these features challenged the 3D reconstruction. The models of the brain generated by both the 3d scanner and photogrammetry were accurate and provided real-life representations of the specimen. The morphology was accurate in both methods looking at the gyri, sulci, lobe dimensions, cerebellar cortex, blood vessels, arachnoid mater and granulations, and brainstem components (Fig. 2). Similarly, the literature has shown that 3D surface scanning and photogrammetry can successfully replicate the geometry, color, and texture (Evin et al. 2016). We had similar overall geometry with both methods, which has been demonstrated as extremely comparable average variation distances between models in the literature as well (Evin et al. 2016). In the same study, it was found that the specific 3D scanner used would pick up more fine detail in some regions of a wolf crania. Despite this, surface scanning was unable to accurately reconstruct some of the cranial nerves. Similarly, photogrammetry was unable to accurately reconstruct the two pins used to secure the olfactory nerves. The challenge posed by the pins were likely attributed the shininess that leads to poor triangulation from previous data points. Even though these morphological differences were clearly demonstrated between the two imaging processes, they were quite insignificant. The differences were minor and all structures could still be identified.

For the surface texture of the model, the photogrammetry method resulted in a much more robust and realistic representation of the brain surfaces (Fig. 2). This has been corroborated (Evin et al. 2016), the authors found that the surface scanner had softer contrast and a lower-fidelity color map. Although the texture differences in our models were visibly significant, these differences did not negatively influence the anatomical labeling. The finer detail of the photogrammetry texture was mainly aesthetic.

The brain demonstrated the challenge of working with a soft tissue specimen. In photogrammetry, the software relied on looking at multiple overlapping images to find common data points to triangulate and stitch 2D images. This required consistent specimen morphology. In the case of photogrammetry, the software was not able to compensate for even a slight change in geometry with the brain. This was due to trying to achieve the full 360-degree view of the brain, which required flipped of the specimen for additional camera angles. However, the loosely connected interface between the cerebellum and brain stem (along with cerebral hemispheres) posed an issue with shape change. The position of the cerebellum relative to the forebrain would shift depending on whether the specimen rested on its superior or inferior surface. The resulting discrepancies in position of the CNS components relative to each other posed challenges for the PS software to stitch the “chunks” to reconstruct the brain; however, we still managed to produce a very successful brain model, albeit more difficult. The surface scanning method in this case did not struggle with this slight change in shape.

When working with soft tissue, changes in specimen orientation can lead to distortions of the specimen and possibly lead to 3D model reconstruction failure. Overall, the 3D scanner provided more consistent results and was able to compensate for distortions due to shifts in soft tissue better (Fig. 2). When setting out to complete a 3D model it is important to keep in mind

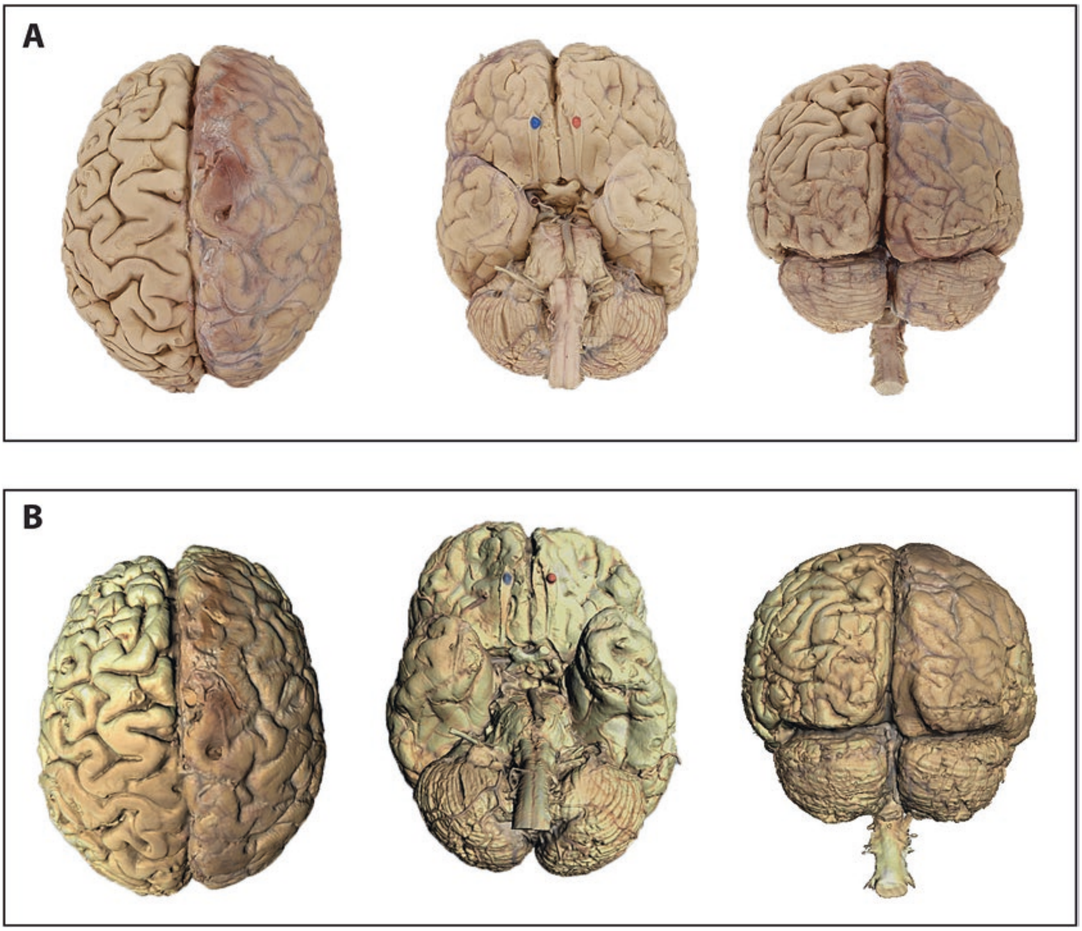

Fig. 2 Comparison in 3D data acquisition of a brain. (**a**) Photogrammetry screen capture, note the distortion in the pins holding the olfactory bulb and the accuracy of the cranial nerves in the brainstem. (**b**) 3D Surface Scanner screen capture, note the accuracy of the 3D surface and the relative lack of detail for the cranial nerves emerging from the brainstem

what the purpose of the scan is and a 360 scan may not always be necessary.

4.2 Skull

The skull specimen was chosen as an example of hard tissue with intricate surface detail. The surface scanner and photogrammetry were extremely accurate in replicating these features throughout the skull, yet with a few minor inaccuracies (Fig. 3). Both methods did well with reconstructing the many deep and shallow foramina, overall skull geometry, and cranial fossa. However, the zygomatic arch was a difficult area for photogrammetry to successfully reproduce, whereas the palatine bone and central maxillary incisors from the inferior view posed challenged for surface scanning (Fig. 3). This misrepresentation did not however compromise the anatomical labeling. However, the surface scanned model also depicted a fused palatine process of the maxilla with the palatine bone in an indiscriminate fashion. The inability to distinguish the palatine bone from the palatine process of the maxilla would negatively influence labelling and interpretation of that area, thus would likely require additional scans or software editing. Neither discrepancy was noted in the photogrammetry model reconstruction (Fig. 3).

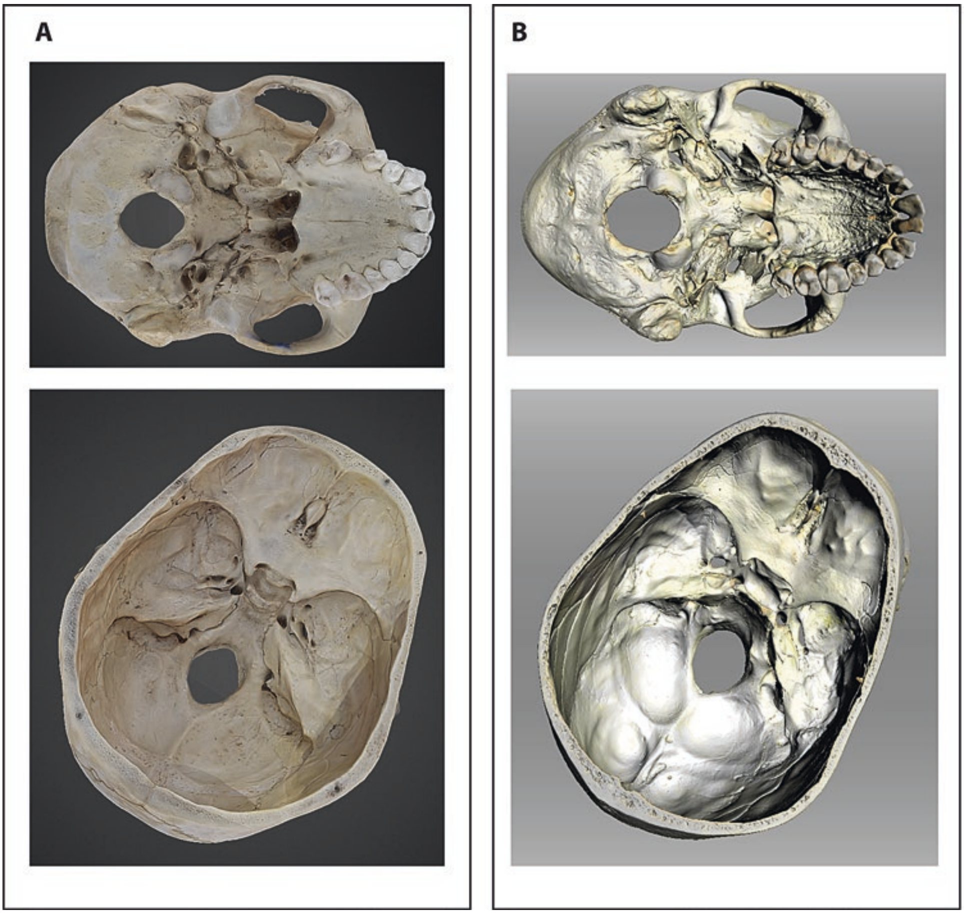

Fig. 3 Comparison in 3D data acquisition of a skull. (**a**) Photogrammetry of the base of the skull and the cranial cavity, note the lack of detail for the foramina and the concave surfaces. (**b**) 3D surface scan of the base of the skull and the cranial cavity, note the detailed geometry of the surfaces

In the photogrammetry method we found that there were multiple foramina and concave features that were distorted or misrepresented in the specimen. The anterior nasal apertures of the skull had regions that appeared distorted, likely attributable to the PS software trying to fill in what was essentially an empty space. The PS software struggled with deep holes and concavities due to inadequate lighting and the resulting shadows. The medial portion of the zygomatic arch was partially incomplete on the 3D model since the angles and orientations chosen for the skull did not allow for enough views of this internal surface. Despite this, careful planning, adapted camera angles, and additional follow-up image captures can be used to mitigate these errors in the PS software. Moreover, Sapirstein also found that deep concave regions of crania were extremely problematic. It was suggested that these errors could be reduced by more photographs in the regions, or by projecting a randomized pattern on the surface to enhance the contrast (Sapirstein 2018). Thus, good illumination/lighting needs to be consistent throughout the model and special attention should be given for areas of an object with finer detail, holes, hidden faces, folds, or undercuts.

The geometry and accuracy of the concavities and foramina in the base of the skull was accurate with the 3D scanner. The surface scanner was able to reproduce both the intricate geometry and the detail of the base of the skull with ease. The problems encountered with the palatine bone and the maxillary incisors were most likely due to incomplete scans as well as the skull itself where some of these features may not have been as apparent.

4.3 Scapula

The scapula was chosen as a specimen with simple geometry and with a very thin and shiny surface. We used scapulae that had damage in the subscapular fossa to assess whether this damage could be reproduced with ease and accuracy. We matched the two scapula specimens used for their transparency characteristics. With the surface scanner, the scapula was easily replicated with accurate representation of the geometry and the surface texture including the damage to the subscapular fossa (Fig. 4). In contrast, the photogrammetry method resulted in a model that had multiple large incomplete geometries in the subscapular fossa. The other features of the scapula that were both intact and had no transparency were accurately reconstructed with the 3D photogrammetry method.

The incomplete geometry in photogrammetry was likely due to the thin bone and lighting setup, leading to translucent changes in each photograph. As the camera changes position relative to the specimen, the light transmitted differently through the thin bone compared to previously acquired photographs. This led to aberrant data, as software compared images with little data overlap in generating the 3D projections. Due to the difficulty with the translucent changes, the software deleted the surfaces in the point cloud, which resulted in the missing geometry and ultimately the holes in the model (Fig. 4). This is an issue encountered with shiny surfaces in general: we have encountered this with cadaveric soft tissues such as the heart as well. One proposed solution to counteract translucency and shininess errors, depending on the specimen, is to spray a white coating prior to scanning and remove this coat after the scan (Camba and Contero 2015). This is not a method that is necessarily feasible when using anatomical specimens and it will require additional post-processing to match the color properly. For specimens with translucency and reflective surfaces the use of the 3D scanner resulted in consistent geometries and easier data acquisition and processing. 9.

5 Usability, Accessibility, and Resources

Photogrammetry and surface scanning differ drastically in the realms of cost, technique, learning curve, transport, and time required. Each of these domains should be considered when deciding which method would work best for certain situations. We have found that, along with our own experience and the literature, each method has their place and chosen wisely based on multiple factors.

Photogrammetry equipment is more cost-efficient: it requires simple good quality entry level DSLR camera and a tripod together with lighting equipment. The software used for the reconstruction (Agisoft Photoscan) offers educational licenses: the Standard Edition is suitable for most models and the professional Edition which has features that assist with more difficult.

As in our case, the software comes at a price, yet there are free available software packages such as Structure-from-Motion (Westoby et al. 2012). The computer hardware cost for photogrammetry is comparable to 3d scanning.

The cost of a 3D scanner is higher, but there are many models to choose from (Knibbe and O'Hara 2014) and the cost of the scanner is correlated with the quality of the scans (Camba and Contero 2015). In this study we used the Artec Space Spider since it allows for the highest accuracy when scanning detailed objects. Viggiano successfully demonstrated that cheaper 3D scanners that can be utilized to acquire a cruder, yet robust enough 3D model, but that this was not reliable in reconstructing the 3D objects for linear measurements and surface data (Viggiano et al. 2015). They concluded that this scanner was not able to accurately model smaller specimens and it was unable to acquire sufficiently detailed

Fig. 4 Comparison in 3D data acquisition of a scapula. (**a**) Photo (from anterior) and Photogrammetry (from posterior) of the scapula, note the incomplete geometry of the subscapular fossa and around the damage to the bone. (**b**) Photo (from anterior) and 3D surface scan (from posterior) of the scapula, note the complete geometry of all surfaces, including the damage to the bone

models that involve specimens with irregular and concave surfaces.

Comparing the time aspect of data acquisition, the photogrammetry approach has been found to take a variable amount of time to photograph specimens, as it depends on the model, orientations needed, and angles used. With our process though, it took less than 1 h per model, and seldom took longer than 45 min. This was corroborated by Katz as they completed the photography portion of 3D photogrammetry in 10 min for a human cranium (Katz and Friess 2014). However, they took double the time (20 min) without a turntable, thus demonstrating how useful it is in optimizing the photography process. Similarly, Sapirstein found that it typically took 10 min, and seldom 30 min for small artifacts (Sapirstein 2018).

For the post-processing time in photogrammetry it can be extremely variable, as described in previous sections. This is due to the possibility of encountering errors at each step in the software that can take different amounts of time to resolve. Independent of these post-processing errors, Sapirstein found that an operator might spend 15–45 min in the software setting up the processing (Sapirstein 2018). In addition to this, there are the computational times for each step that depends on the model complexity and performance of the video card. Over the course of a day, an experienced operator can photograph and obtain completed 3D reconstructions for 10 or more models.

Similarly to photogrammetry, 3D scanning is heavily dependent on the complexity and size of the object as well as the specifications of the computer hardware. The positioning of the sample is not as critical since the scanner is handheld. Multiple rotations where the necessary faces are exposed are required to construct a complete 3D model without any incomplete/blank polygons. The scanned models collectively (all operations included) took approx. of 1.5 h. Boehler & Marbs took approx. 45 min to scan a Stone-Age axe head which now (with present day technology) should take around 10–20 min (Boehler and Marbs 2004).

The setup time and complexity for both photogrammetry and 3D scanning were dependent on the complexity of the object. Scanning time can be significantly optimized by the use of a turntable for photogrammetry. Due to the hand-held nature of the Artec Spider 3D scanner, a turntable might not be as relevant in general scenarios. However, in a medical context where samples tend to be small in size and high in complexity, a turntable would prove very useful to capture the maximum amount of detail. Any objects with movable parts must be stabilized for both procedures to assure optimal quality.

Surface scanning and photogrammetry consisted of steps that were easy to learn for consistent data acquisition. For photogrammetry, we have found that members of our team, with no real prior photographic knowledge, were able to start taking good photos after about an hour of instruction. For surface scanning, learning how to scan was very simple since it was just a point and record mechanism, very much like a video camera. Both techniques required very little to no expertise to begin with and the operator could be trained to become proficient in relatively little time.

Post-processing with the photogrammetry software was a more difficult learning task that required more practice, although the program was very intuitive and required minimal training. The software packages for altering and controlling geometry requires a high level of proficiency, skill, and training.

Post-processing for 3D scanning occurred within Artec Studio 12 Professional. Besides file type conversion and knowledge on specific file formats, no prior technical expertise was required since all the necessary knowledge was local to the software. Through practice, the operator would gain knowledge on each of the post-processing algorithms and their effects on a 3D mesh.

Both imaging techniques were relatively portable and could be used in many circumstances. Most 3D scanner devices must be permanently connected to an external power source for use (Camba and Contero 2015). This may limit accessibility, especially in a much more rural setting without external power sources.

When using 3D scanners, the size and complexity of the object being imaged should be considered, as there are certain limitations imposed of the various scanners currently available on the market. Generally, turntable scanners are best for small objects, whereas handheld are best for large objects (Camba and Contero 2015). Using a handheld scanner does allow for much more flexibility in the acquisition process, as opposed to the rigid constraints of set-up with 3D photogrammetry and turntable scanners.

6 Conclusion

Both photogrammetry and 3D scanning have their strengths in the context of capturing 3D objects for use in medical education and other visualization applications. Both methods were comparable for objects with a simple geometry. We saw that the surface texture was often more accurate and realistic in the photogrammetry applications and we would recommend this technique for applications where the educational objectives are focused on an accurate surface texture. 3D scanning was more accurate in capturing intricate details and complex geometries such as the concavities of the base of the skull. 3D scanning also proved to be more efficient in capturing objects with translucent and reflective surfaces. When scanning soft specimens, 3D scanning resulted in less distorted geometries, although this could be compensated for in photogrammetry with more complex chunking and different post production algorithms.

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Application of Photogrammetry in Biomedical Science

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Abstract

Photogrammetry is an upcoming technology in biomedical science as it provides a non-invasive and cost-effective alternative to established 3D imaging techniques such as computed tomography. This review introduces the photogrammetry approaches currently used for digital 3D reconstruction in biomedical science and discusses their suitability for different applications. It aims to offer the reader a better understanding of photogrammetry as a 3D reconstruction technique and to provide some guidance on how to choose the appropriate photogrammetry approach for their research area (including single- *versus* multi-camera setups, structure-from-motion *versus* conventional photogrammetry and macro- *versus* microphotogrammetry) as well as guidance on how to obtain high-quality data. This review highlights some key advantages of photogrammetry for a variety of applications in biomedical science, but it also discusses the limitations of this technique and the importance of taking steps to obtain high-quality images for accurate 3D reconstruction.

Keywords

Digital 3D reconstruction · Multi-camera setup · Structure-from-motion stereophotogrammetry · Microphotogrammetry · Medicine

1 Introduction

Digital 3D reconstruction has become a vital tool in the study of the structure and functions of the human body and biomedical scientists can now choose from a range of well-established imaging techniques for 3D modelling, including computed tomography (CT) and magnetic resonance imaging (MRI) as well as laser-scanning microscopy. Photogrammetry is a less common approach for digital 3D reconstruction compared to these techniques, but due to its ease of use and cost-effectiveness, it is an interesting alternative for biomedical scientists.

The word photogrammetry is a combination of three Greek root words: “phot”, “gramma” and “metrein”, respectively meaning “light”, “something drawn” and “measure”. Collectively, these terms translate to “measuring graphically by means of light” (Ey-Chmielewska et al. 2015).

Photogrammetry is broadly defined by the American Society of Photogrammetry and Remote Sensing (ASPRS) as the science of obtaining precise information about the surface structure of an object or a particular environment

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by a recording device which is not in direct contact with the object that is being studied (Estes et al. 2001). This means that photogrammetry can be applied in every circumstance where the object of interest can be photographically documented (Luhmann et al. 2006).

Photogrammetry was first used in Medicine by American physician Holmes in 1863 to study the gait of civil war amputees in an effort to design prosthetics to aid rehabilitation (Lane 1983). However, recent advances in computer software development now allow us to use overlapping images to create detailed 3D surface models of biological structures, a procedure known as stereophotogrammetry or close-range photogrammetry (Villa 2017).

This chapter will provide an overview of the photogrammetry approaches currently used for digital 3D reconstruction in biomedical science and discuss their suitability for different applications. We aim to offer the reader a better understanding of this upcoming technology and to provide some guidance on how to choose the appropriate photogrammetric approach for their research area and to obtain high-quality data.

We have used PubMed and Science Direct as main online databases for this literature research, with key words including “photogrammetry”, “microphotogrammetry”, “biomedical science”, “stereophotogrammetry”, “photogrammetry review”, “structure-from-motion photogrammetry”, “photogrammetry review”, “photogrammetry + prosthetic”, “multi-camera photogrammetry”, “sfm vs laser scanning”, “photogrammetry + tumor”, “stereoscopic camera types” and “stereoscopy + dermatology”. We included studies on humans as well as animal studies.

2 Single-Camera Setups

To create a 3D model from photographs, images have to be taken from multiple angles. This is achieved by either moving one camera around the object (single-camera setup) or arranging multiple cameras around the object (multi-camera setup). Although the 3D reconstructions based on single and multi-camera setups are similarly accurate (Liu et al. 2015; Villa 2017), there are some basic differences in the characteristics of the approaches (Table 1).

A single-camera setup uses only one camera and is consequently cheaper and easier to setup than a multi-camera setup. These advantages might be the reasons why it is used more frequently in biomedical sciences than the multi-camera setup. There is a wide range of biomedical applications of single-camera setups, ranging from the documentation and measurement of scars and lesions (Stekelenburg et al. 2013, 2015; Villa 2017) over the assessment of lung volumes (Ripka et al. 2014) to electrode localisation for electroencephalography (EEG) (Qian and Sheng 2011).

Table 1 Overview of the main characteristic of single- *versus* multi-camera setups

	Single-camera setup		
	Non-stereoscopic	Stereoscopic	Multi-camera setup
Number of cameras	1	Usually 2	>1
Number of pictures taken per shot	1	1	Equal to the number of cameras
Resulting 3D model	Complete 3D reconstruction possible	Partial reconstruction only	Complete 3D reconstruction possible
Operation complexity	Simple	Medium	Complex
Time required for setup	Short	Simple	Long
Image acquisition time	Long	Medium	Short
IOP and EOP consistency	IOP (e.g. zoom or focus) instabilities	Fixed	IOP and mounting instabilities
Costs	Low	Medium	High

IOP internal orientation parameters, *EOP* external orientation parameters

A common type of single-camera setup is the use of a stereoscopic camera. This is a single camera that takes two pictures from different angles in one shot. As only two images are used for the 3D reconstruction, this approach yields partial 3D reconstruction rather than a 360-degree reconstruction of the object of interest.

There are different methods to achieve the simultaneous acquisition of two images in a stereoscopic camera: e.g. using a multi-lens camera or lens splitter (Ueno et al. 1989; Stekelenburg et al. 2013). However, the most commonly used stereoscopic camera in biomedical sciences is a modified single lens camera with a lens splitter (Stekelenburg et al. 2013).

Lens splitters are devices that split the lens in such a way that two images from different viewpoints can be taken in a single shot (Stekelenburg et al. 2013). They usually come with a dual light pointer system and software that creates a 3D model (Stekelenburg et al. 2015). The dual light pointer system consists of two angled light pointers. Their beams converge at the exact distance that the picture should be taken at (Stekelenburg et al. 2015). At this distance, the reconstruction from the two images acquired is the most successful as the accompanying software is designed to merge images taken from known relative 3D locations. Taking the pictures at the recommended distance assures that the 3D locations the pictures are taken at and those the software matches pictures from are the same.

There are different sizes of stereoscopic cameras available for different biomedical applications (e.g. Quantificare: 3D LifeViz® Micro for wrinkle or scar visualisation or 3D LifeViz® Infinity for maxillofacial or breast surgery). In addition, suppliers offer supplementary software that simulates the effects of potential treatment options (e.g. Quantificare). For a patient to be able to visualise their appearance after surgery is an important tool in making the decision for a specific treatment. This can be especially useful in cosmetic or reconstructive surgery (Gibelli et al. 2018).

A common issue using a single-camera setup are differing internal orientation parameters (IOPs) such as zoom or focus. Using a stereoscopic camera, an approach relatively common in maxillofacial surgery and skin assessment (Stekelenburg et al. 2013, 2015), eliminates this problem, as all pictures for a single reconstruction are taken at the same time and with the same camera. Therefore, the IOPs do not vary between the images.

Stereoscopic cameras that take only two pictures for a 3D reconstruction are particularly suitable for applications that do not require 360-degree information (e.g. in craniofacial surgery (Stekelenburg et al. 2013) when a reconstruction of the back of the head is not required). Compared to non-stereoscopic single camera or multi-camera setups, stereoscopic cameras are easy to use, do not require a lot of space and provide fast results (Stekelenburg et al. 2013) that can be discussed with the patient immediately.

3 Multi-Camera Setups

A multi-camera setup uses multiple cameras commonly mounted on a metal frame or scaffold. The additional cameras do not only make this setup more expensive, but also more complex in the setup and initial calibration, as not only IOPs of the cameras have to be matched, but also the exterior orientation parameters (EOPs, such as the position and orientation of the camera) must be considered. EOPs are concerned with the orientation of the cameras in relation to their mounting system (Habib et al. 2014). These difficulties cause a multi-camera setup to only be preferable when the object is either moving or many objects can be digitised in one setup.

Multi-camera setups are the most time-efficient solution for 3D reconstruction if many objects of similar shape and size are to be digitised as only one setup is required with little further calibration after the initial installation. For example, Leipner and colleagues (2016) designed a chamber with 64 cameras for the image acquisition of persons in standing posture, a setup designed for victim and suspect documentation in forensics. With all objects being of similar appearance a multi-camera setup is the preferable option for this application. The object should, however, be large enough for multiple cameras to be positioned around it at a reasonable distance.

Multi-camera setups are also convenient when the photographed object moves and therefore photo acquisition must occur quickly. For example, Zemčík and colleagues (2012) used this approach to investigate the effect of manual perineal protection during birth. In this case, the object, i.e. the perineum, moved during the period of image acquisition. Therefore, a single-camera setup would have been insufficient, as it does not allow to capture enough angles of the object in the same state (Zemčík et al. 2012).

4 Structure-from-Motion Photogrammetry *versus* Conventional Photogrammetry

To create a 3D model based on photogrammetry, images have to be aligned using points that are shared between the images. Two main approaches can be used for this point identification process: conventional and structure-from-motion photogrammetry (SFM) (Fig. 1, see Table 2 for an overview of the requirements and outputs of these two approaches).

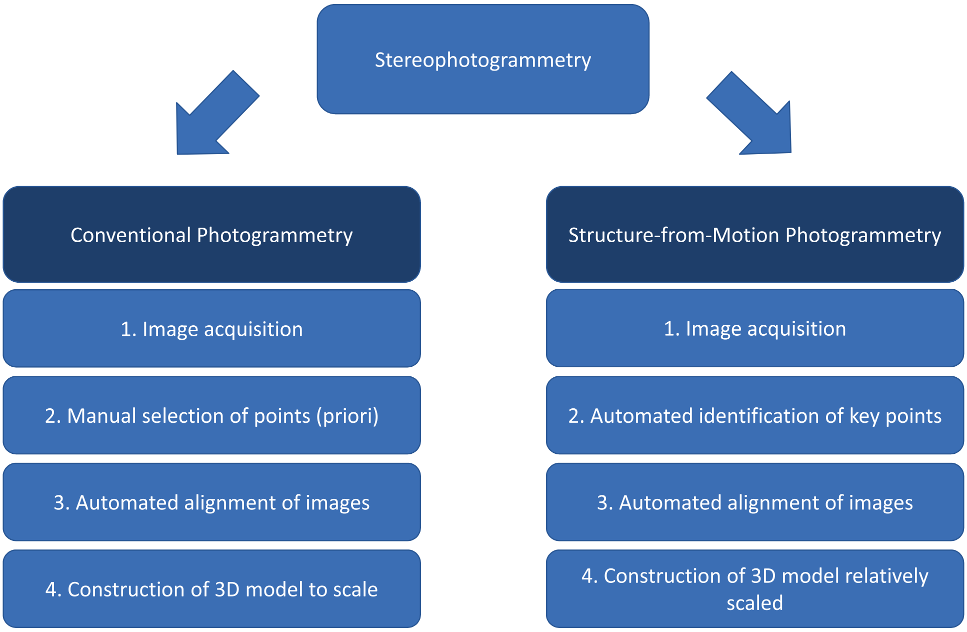

Fig. 1 Approaches used in stereophotogrammetry and differences in the image alignment process between the approaches

Table 2 Structure-from-motion *versus* conventional photogrammetry

	Structure-from-motion photogrammetry	Conventional photogrammetry
Creation of point cloud from images	Automated process using key points to match large sets of images with overlapping areas or from a video	Uses priori (network of targets with known 3D locations)
Requirements	At least 60% of overlap between adjacent pictures	Priori, network of points with known 3D locations or 3D location and pose of the camera(s)
Scale of output	Arbitrarily scaled coordinate system (scaling can be done in a separate step)	Scaled coordinate system because the priori relate it to the dimensions of the real world

In conventional photogrammetry, the distance between camera and object must be known as it is used to calculate the scale and match the pictures. For this, the software uses either known 3D locations (priori) of a network of points on the pictures or known 3D locations and orientations of the camera(s), both of which need to be manually identified (Westoby et al. 2012). In SFM on the other hand, algorithms detect and match key points in overlapping areas of the pictures automatically (Skarlatos and Kiparissi 2012).

SFM is a fairly new approach of photogrammetry, as it relies on algorithms which have recently been advanced by significantly improving their accuracy (Skarlatos and Kiparissi 2012). In this type of photogrammetry, the 3D reconstruction of the object is performed using automated matching processes (Westoby et al. 2012). Unlike conventional photogrammetry, SFM uses algorithms to detect and match key points in overlapping areas of the pictures automatically (Skarlatos and Kiparissi 2012). These key points are then arranged in a 3D point cloud (Marčiš 2013).

The reconstruction is based on information acquired either from video images or photographs taken from several angles around the object. The resulting model is created in an unscaled coordinate system, because the 3D locations extracted from the images are relative to each other rather than to scale (Villa 2017).

Leipner and colleagues (2016) and Qian and Sheng (2011) used SFM in their studies on the reconstruction of living persons in a standing position and using EEG electrode localisation. Despite some limitations depending on the specific application, the authors of both studies highlight the potential of this approach in biomedical sciences.

SFM is more user-friendly than conventional photogrammetry given the fact that the image matching process is automated. This may be the reason why, based on our literature review, SFM appears to be the preferred approach in biomedical sciences. Conventional photogrammetry is most commonly applied through camera setups such as stereoscopic cameras (e.g. Stekelenburg et al. 2013; Stekelenburg et al. 2015) with accompanying software solving the scene by considering the parameters of e.g. the lens splitter or multiple lenses, by which the camera operates.

5 Microphotogrammetry

Microphotogrammetry is a 3D reconstruction tool that uses scanning electron microscopy (SEM) instead of a standard photographic camera for image acquisition. Thus it achieves much higher resolutions (i.e. nanoscale resolution and depending on the instrument less than one nanometer) compared to other approaches of photogrammetry that use macroscopic image acquisition. Microphotogrammetry has allowed 3D reconstruction through SEM since the 1970s (Ball et al. 2017; Tafti et al. 2016).

In SEM a focused beam of electrons interacts with the atoms on the surface of a sample. This produces signals that are picked up by a detector and then converted into a 2D image of the surface topography of the sample (Ball et al. 2017). However, the lack of 3D data can limit the interpretation of the images and their quantitative analysis. Microphotogrammetry provides an approach to create 3D models of the surface topography based on these 2D images. In general, 3D reconstruction from 2D micrographs is achieved through the same basic procedure as in macroscopic stereophotogrammetry where a point cloud, a mesh and ultimately a textured 3D model is produced (Tafti et al. 2016).

Surface image acquisition and subsequent reconstruction techniques using SEM can be categorised into three main groups: (1) single-view, (2) multi-view and (3) hybrid, which is a combination of the first two. In single-view techniques, a range of electron beam trajectories captures images from a single perspective while in multi-view approaches a combination of viewpoints is used to create a 3D model. Hybrid approaches combine the advantages from both single- and multi-view approaches, but they are yet to be fully designed and validated (Tafti et al. 2015). Single-view setups are a well-studied and the most adopted approaches in the literature (Baghaie et al. 2017).

The study from Ball et al. (2017) is a prime example where microphotogrammetry has been applied within the field of bioscience by using it to study micro-invertebrates. The authors managed to create a high-resolution 3D model of an insect's head up to 1000x magnification using single-view techniques.

By contrast, Eulitz and Reiss (2015) moved away from the traditional method of 3D reconstruction using single-view methods and proposed a multi-view approach that adopts the fundamental characteristics of optical stereophotogrammetry. As in optical stereophotogrammetry, they created 3D models from series of overlapping images of the sample, in this case a rabbit kidney glomerulus. These images were produced by rotating the sample under the fixed detector to acquire data from multiple angles, a variant of multi-view techniques (Baghaie et al. 2017). The result showed an enhanced 3D reconstruction quality and better preservation of the original specimen (Eulitz and Reiss 2015).

Microphotogrammetry shows to be a promising high-resolution 3D modelling technique, however, not every microscopic object is suitable for 3D reconstruction (Tafti et al. 2016). In addition, the sample has to be small enough to fit into an SEM chamber. As in optical and macroscopic stereophotogrammetry, samples also need to be mounted in a stable way and should not undergo deformations during image acquisition. Moreover, the surface micro-anatomy of an object needs to be easily traceable by the electron beam. This means that rougher surfaces with different superficial patterns as well as bright areas are preferred over flat, smooth and dark surfaces (Tafti et al. 2016). In conventional SEM, vacuum and sputter coating are required (Faith et al. 2006). This is an invasive technique which is only suitable for *ex vivo* samples. This process obliterates the sample for most other analyses after the SEM scan. Environmental SEM, on the other hand, does not require sputter coating and leaves the sample intact (Griffith and Danilatos 1993), thus allowing the sample to be analysed with other techniques.

6 Why Choose Photogrammetry for Digital 3D Reconstruction?

Photogrammetry is becoming a popular technique for a variety of applications due to its portability, non-invasiveness and cost-effectiveness. Alternative methods of 3D modelling, such as 3D laser scanners, computed tomography (CT) or magnetic resonance imaging (MRI) tend to be significantly more expensive and often larger and heavier than photogrammetry equipment (Chandler and Buckley 2016; Evin et al. 2016). Furthermore, photogrammetry does not require extensive training or the attendance of a trained professional (Villa 2017). Compared to CT, photogrammetry does not use ionising radiation and therefore provides a cheap and low-risk alternative to CTs in, for example, dental or postural assessment (Saad et al. 2012). Photogrammetry can be used to minimise the radiation exposure for patients by using it in combination with conventional spinal curvature assessments and check-ups (Liu et al. 2015). As photogrammetry provides textured models, unlike CT- or MRI-based models, it is an attractive option for various dermatological applications (Stekelenburg et al. 2015). The most important advantages of photogrammetry, however, are its ease of use (Evin et al. 2016) and relative inexpensiveness making it accessible to a wide range of users. Many photogrammetry software packages are free or affordably priced and some even run on smartphones (Chandler and Buckley 2016).

In addition to these specific advantages, photogrammetry shares the advantages other digital 3D imaging techniques, e.g. concerning data storage and reproducibility of measurements. Photogrammetric datasets are easily storable and can readily be reassessed. This is highly advantageous specifically in fields such as pathology in which the original specimen or sample might be available for a limited time (Villa 2017). Any measurements taken on 3D photogrammetry models can be aided by software (Stekelenburg et al. 2013). As a result, these measurements tend to be more accurate and show higher intra- and inter-operator reliabilities compared to manual measurements (Villa 2017). Evin et al. (2016) compared to the accuracy of photogrammetry models of digitized skulls to those obtained with 3D laser scanning and showed that photogrammetry provides a reliable alternative to conventional 3D laser scanners for surface modelling. However, there are currently limited data available on the accuracy of photogrammetry models compared to other digital 3D reconstruction approaches.

7 How to Obtain High-Quality 3D Reconstructions with Photogrammetry: A Brief Guide

The wide range of applications of photogrammetry in biomedical science shows that it is a very versatile approach for virtual 3D reconstruction. However, to make best use of this powerful technique, it is important to plan a new project carefully, be aware of the limitations of the technique and take steps to optimize image acquisition and image processing. The following guidelines are based on published papers as well as the authors' own experiences.

7.1 Features of the Objects to Be Digitised

Most suitable objects for photogrammetry are compact without holes, thin protrusions or folded surfaces (e.g. the crotch area of a person). In addition, photogrammetry and especially SFM cope best with grainy textures rather than unicoloured surfaces.

Photogrammetry software used to generate point clouds has a tendency to correct for missing information by using the surrounding information to automatically fill holes via smoothing (Marčiš 2013). Thus holes or other shaded areas may be treated as part of the texture by the software which can lead to the creation of artefacts in the model (Marčiš 2013; Chandler and Buckley 2016). Another issue is demonstrated by the incomplete reconstruction of thin protrusions (e.g. thin bony processes) due to too little matching information (Probst et al. 2018). The greater curvature on the thin structure compared to a larger one causes every point of it to be seen from fewer angles and therefore in fewer images. If there are not enough overlapping images (i.e. sharing a sufficient number of surface points seen from different angles), the software cannot match the points correctly in the 3D reconstruction which leads to an incomplete reconstruction.

If objects are to be digitized that do not fit the criteria outlined above, other 3D imaging techniques such as CT or MRI scanning can be considered. Those techniques are also more suitable if the internal structure of an object is of interest. Whereas photogrammetry provides solely surface information, those techniques scans show both external as well as internal structures (Villa et al. 2017).

7.2 Choice of the Photogrammetry Approach

The most suitable photogrammetry approach depends on the application and scale of the study. Table 3 provides a brief overview of the main approaches and examples of their applications in biomedical science. It is important to carefully consider the advantages and disadvantages of each approach for a specific study before investing in equipment.

7.3 Equipment

Successful 3D models can be created from all types of cameras, ranging from simple phone camera to SLR cameras (Petriceks et al. 2018). However, the limited accuracy of models based on smartphone images must be considered. Hernandez and Lemaire (2016), for example, detected that their smartphone-based models are about 2 mm larger than the real-world object. For maximum accuracy, a professional SLR camera is therefore recommended. In addition, a camera

Table 3 The main photogrammetry approaches and examples of their application in biomedical sciences

	Single-camera setup		
	Non-stereoscopic	Stereoscopic	Multi-camera setup
Structure-from-motion photogrammetry	Documentation and measurement of model and live human and animal structures (Gibelli et al. 2018; Evin et al. 2016; Qian and Sheng 2011; Ritschl et al. 2018; Villa 2017)		Documentation of body stature and natural head position (Leipner et al. 2016; Liu et al. 2015)
	Assessment of lung volumes (Ripka et al. 2014)		Measurement of diseased tissues (Hermans et al. 2013; O'Meara et al. 2012)
Conventional photogrammetry		Measurement of skin features (Stekelenburg et al. 2013, 2015)	Analysis of the human body in movement (Zemčík et al. 2012)
Microphotogrammetry	Visualisation of microscopic animal structures (Ball et al. 2017; Eulitz and Reiss 2015)		
	Visualisation of dental implant (Glon et al. 2014)		

with a fixed focal length lens (e.g. 50 mm) is preferable compared to a variable focal length lens. If a variable focal length lens is used, maintaining the same focal length over the course of the shooting is recommended.

Using a tripod is highly recommendable, as it helps to stabilise the camera, ensuring sharp pictures. A remote control is another useful accessory as pressing the shutter button can cause vibration of the camera. Another helpful accessory is a turntable. A turntable is especially important when space around the photographed object is limited; it also helps arranging the tripod and lights in a static location. Usually a reference system is attached to the turntable to help the software with the reconstruction of the photographed object. In addition, a black background (e.g. black cloth) will simplify the masking process and it will afterwards help the software recreating the photographed object without any interferences from the background. When photographing shiny or reflective objects, a circular polarizing filter is advised to reduce the bright spots caused by reflections. An alternative method is to simply cover the photographed object with e.g. patterned tape (Hernandez and Lemaire 2017).

7.4 Camera Settings

The key for achieving a detailed and accurate 3D model is high quality images (Skarlatos and Kiparissi 2012). Using an appropriate exposure is particularly important. The light meter in the camera usually changes the actual colour of the photographed object into a neutral grey. For instance, if there are dark objects (e.g. black background) in the frame, the light meter of the camera will tend to brighten the photograph to make those dark tones look like a neutral grey. If the photographed object has many bright tones (e.g. a hand of a cadaveric specimen with some areas covered in skin, fascia or tendons) the camera will often darken the image. Therefore, the exposure needs to be adjusted manually. A constant exposure usually reduces the work in the post-processing stage. Consequently, artificial light is preferred compared to natural light. Artificial light is constant and adjustable depending on colours and tones of the photographed object. Flash is usually not recommended for photogrammetry since it creates a lot of shadows and darkness in the non-illuminated part of the scene (Marčiš 2013).

Shutter speed and aperture should also be taken in consideration. A greater field of depth is provided with a small aperture (higher numbered like f/16) and a shutter speed of at least 1/50th of a second (Villa et al. 2017). Although, they should be checked and adjusted manually depending on the object photographed and the light used.

7.5 Camera Positioning and Shooting

The optimal number of photos required depends on the size and complexity of the photographed object. Photographs should be taken from different angles to capture information from the whole surface of the photographed object (Chandler and Buckley 2016). Preferably, a photo is taken every 10–15 degrees (horizontally and vertically). A 50–60% overlap between photos is also recommended. This overlap helps the software to identify the same points in different photos (Hernandez and Lemaire 2017). The object should also be positioned with its longest axis perpendicular to the direction of the camera. Furthermore, internal orientation parameters (IOPs) such as zoom or focus must not differ between shots. However, maintaining consistency of IOPs across an entire dataset can be challenging for both single and multi-camera setups (Habib et al. 2014).

7.6 Post-processing of the Images

After image acquisition, blurry or unfocused photos should be discarded, as they usually lead to an inconsistent photo alignment. Before 3D reconstruction, using an image processing software to mask the photos (e.g. Adobe Photoshop) is recommended. In this way, the masked parts of the images such as the background will be excluded from the point cloud generation, thus reducing computational times. These steps will help optimising colour balance of the images, resulting in a more accurate 3D reconstruction and more detailed model texture.

8 Conclusions

This review has highlighted some key features of photogrammetry that make it a useful tool for 3D reconstruction in biomedical science. It is a non-invasive, low-cost technique that can produce high-resolution surface models. As different setups are possible, it is also a very versatile technique that can be tailored to different applications. However, it is important to be aware of the limitations of the technique and to take steps to obtain high-quality images for accurate 3D reconstruction.

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