Theme Article: Virtual and Augmented Reality Applications in Science and Engineering

Augmented and Virtual Reality in Surgery

Mathilde R. Desselle
Queensland University of Technology
Metro North Hospital and Health Service

Ross A. Brown
Queensland University of Technology

Allan R. James
Queensland University of Technology

Mark J. Midwinter
The University of Queensland

Sean K. Powell
Queensland University of Technology

Maria A. Woodruff
Queensland University of Technology

***Abstract*—Augmented and virtual reality are transforming the practice of healthcare by providing powerful and intuitive methods of exploring and interacting with digital medical data, as well as integrating data into the physical world to create natural and interactive virtual experiences. These immersive technologies use lightweight stereoscopic head-mounted displays to place users into simulated and realistic three-dimensional digital environments, unlocking significant benefits from the seamless integration of digital information with the healthcare practitioner and patient's experience. This review article explores some of the current and emerging technologies and applications in surgery, their benefits and challenges around immersion, spatial awareness and cognition, and their reported and projected use in learning environments, procedure planning and perioperative contexts and in the surgical theatre. The enhanced access to information, knowledge, and experience enabled by virtual and augmented reality will improve healthcare approaches and lead to better outcomes for patients and the wider community.**

The hospital of the future will see the seamless integration of digital health information into routine clinical practice over the coming years. With paper-based patient records now obsolete, archaic manual processes for collecting and monitoring patient's health are being replaced with automated, patient specific approaches, and many countries have already begun the digital health transformation. Augmented reality (AR) and virtual reality (VR), having recently seen rapid

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improvements in hardware capabilities, are now being broadly adopted across multiple safety critical industries such as telecommunications, defence, nuclear power, and aviation, but have yet to be introduced widely into health care. The hardware technologies and accompanying software are however evolving quickly to cater for the specific demands of medicine and healthcare practice, and are set to become pillar platform technologies both within but also outside of the hospital, integrating care beyond the physical confines of the hospital and into the community, defragmenting the patient care pathway.

Hospitals produce enormous amounts of patient data and have versatile knowledge and training capacities. Yet often only a fraction of the available information is applied at any given time to the patient care continuum and for medical training. AR and VR offer an unparalleled means to interact with digital information, breaking down barriers between the real world and the digital world. The enhanced capacity to integrate digital healthcare with clinical practice will invariably lead to improved service delivery and better medical outcomes.

AR and VR are part of a spectrum of immersive technologies that utilize a digital display placed in front of the user's eyes to present computer-generated content. A common feature involves head-tracking, using cameras and/or sensors to accurately track the position and orientation of the user's head. This allows the user to look around and have the viewpoint and perspective of the digital scene updates naturally, creating the illusion of immersion within the virtual environment.

While similar in many respects, the differences between AR and VR lie in their fundamental approach to delivering three-dimensional (3-D) digital experiences. AR employs a transparent display that allows for the integration and overlay of digital content over the real physical world, where both the real and virtual environments are visible together. With VR, the real world is completely occluded by the head-mounted display; providing a fully immersive experience that replaces the real environment with a 3-D virtual interactive environment.

Stereoscopic displays allow depth information to be conveyed to the user and provide spatial context, allowing sizes and distances within the virtual environment to be communicated and understood instinctively. For interaction, some systems provide simple pointing or handheld controllers and others employ cameras or tracking sensors to allow simple hand gestures, or full-articulated hand and finger tracking; allowing for more natural interactions with digital content in a similar manner to how one would interact with real physical objects.

Used in a medical context, both approaches offer the potential to integrate, visualize, interact with and share healthcare information in real time. In combination with digital healthcare software and hardware solutions, AR and VR enable more fluid interactions between people, data, and machine. Whether immersed within a completely virtual environment, or an AR experience integrated within the real world, the ability to efficiently and conveniently place digital information into the environment exactly where it is required, allows for the users' attention to remain better fixed on the task at hand. Coupled with appropriate user interfaces, this feature can also reduce the complexity of accessing digital information and provide a more natural and intuitive method of exploring and analyzing patient data in a relevant spatial context; thereby enhancing the ability to deliver better health outcomes. As researchers and developers continue to build new capabilities, the applications of AR and VR in routine clinical practice will further disrupt current methods, and lead to solutions that are more effective. An illustration of the application of AR in the hospital of the future is shown in Figure 1, where real-time patient data and 3-D representations of anatomical data can be overlaid in front of the view of the surgeon.

There is a rapidly growing body of literature relating to the use of AR and VR and healthcare. As researchers and clinicians championing the adoption of 3-D technologies in public health and defense surgical workflows, we elected for the present article to describe current and future clinical applications for AR and VR with a focus on enhancing cognition for surgical teams and assisting them in the delivery of health services. AR and VR also offers improved minimally invasive healthcare avenues and performance

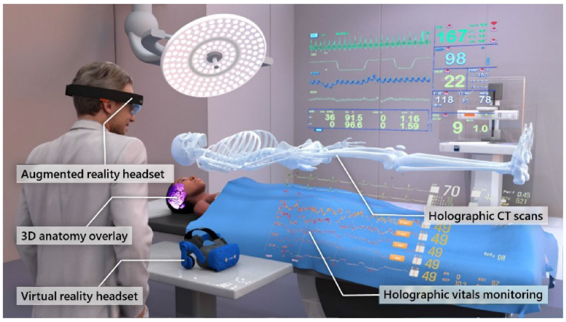

Figure 1. Illustration showing an application of AR in an operating theatre in the hospital of the future. The surgeon wears a lightweight AR headset which overlays 3-D digital imagery on the physical world. This enables the ability to completely replace traditional 2-D computer displays with floating adjustable "holographic" representations of the patients' vital statistics, and even enables the overlay of 3-D internal anatomy (from CT and MRI scans) to enable the clinician to "see" through the patient's skin.

enhancing applications for learning, skills development, treatment planning and delivery, surgery, and patient education and recovery or rehabilitation. These technologies allow for the projection of what is currently highly centralized expertise, outside of the physical location of this expertise and into the wider healthcare pathways, decentralizing and defragmenting care.

AR AND VR IN LEARNING ENVIRONMENTS

AR and VR play a significant role in training the next generation of surgical professionals. These technologies impact the development of digital learning models by enabling basic science education, scenario-based learning, crisis and crew resource management, and clinical case examination to be delivered in an engaging, distributed and interactive fashion. Education in working hours for surgical trainees, limited clinical cases, and operative experience has limited the exposure to training opportunities. Concerns have been raised regarding this now falling below the level required for mastery in some areas of practice.[1] VR and AR can potentially enhance the training opportunities to allow more rapid skill acquisition and avoid patients being exposed to surgeons on the early component of their learning curve.

The growing world population increases demand for surgical training and flexible teaching and learning methods. As the technologies mature to function in the geographic locations of need, AR and VR will support efficient and effective training in the medical classroom of the future. It will see the incorporation of AR and VR technologies to complement the lecture theatre, to augment costly cadaver dissection and prosection facilities and compliment traditional teaching approaches. Furthermore, the potential for surgical training improvements is immeasurable, whereby the students can be placed into an emergency life-threatening scenario and are taught to respond quickly and accurately, and to manage a team-based response, such that when faced with the real-life scenarios the surgeon has confidence and expertise to deal with the situation, potentially saving lives.

Knowledge acquisition in learning is supported and enacted by human memory systems. Via mental or physical actions, humans acquire knowledge and contextual information about a task being performed. This contextual information becomes crucial when someone needs to perform the act at a later time, as often the knowledge of how to perform the task only becomes apparent when the contextual information is presented to the human. This has inspired learning approaches applied in educational settings which draw upon situated learning theory, positing that education and training works best when the knowledge is learned in the context of where it will be used (situated), facilitating recall of specific activities primed by the correct context.[2] First-person simulation platforms have long been part of successful blended learning in surgical training, as prior exposure to a piece of equipment or a clinical case provides additional opportunities for hands-on experience in a risk-free environment, in the same way as an aircraft pilot would practice on a flight simulator.

VR-based surgical training has been demonstrated as an efficient and convenient teaching tool, as studies have shown that users develop comparable technical skills to those developed via standard surgical training techniques with the added benefit of demonstrably improved performance in terms of nontechnical skills and self-confidence, as shown in Figure 3(c). Piromchai, Avery, and

Laopaiboon reviewed trials using VR for surgical simulation into ear, nose, and throat surgical training programmes, suggesting VR could be considered a complementary learning tool supporting the acquisition of technical skills, improved psychomotor scores and reduced surgical time.[3] Integration of AR and VR in surgical education is shown to improve both teaching and learning experiences, and offers opportunities for remote teaching [as shown in Figure 3(a) and (b)], participation, and collaboration.

Figure 2. Origins of AR and medical applications. (a) Screenshot of Krueger's 1983 Videoplace. The participant's image is digitized to create a silhouette. Processors analyze the image's posture and its relationship to other graphic objects in the system. Here, the user is typing a sentence by selecting letters displayed at the top of the screen. (Distributed on Youtube by VintageGG, from documentation produced by the Museum of Natural History, Vernon USA, 1988). (b) Detecting and marking feeder veins with the vein-viewer prototype (Miyake *et al.,* 2006, reproduced with permission from Vein Imaging: A New Method of Near Infrared Imaging, Where a Processed Image Is Projected Onto the Skin for the Enhancement of Vein Treatment, Dermatologic Surgery, 32(8), pp. 1031–1038). (c) AR has applications for overlaying realtime 3-D internal anatomy in-place over the patient. (Top left) AR overlay of models as viewed from remote HoloLens; (top right) confirmation of perforator location with audible Doppler ultrasonography. (Bottom) Overlay with bounding box; arrows highlighting perforators position. Adapted from Pratt *et al.*, 2018, distributed under a CC-BY 4.0 license.

USE CASES IN PROCEDURE PLANNING AND PERIOPERATIVE CONTEXTS

By relaying and integrating patient-specific data and enabling clearer observation through life-like 3-D and novel interactions, AR and VR can allow for contextual and detailed preplanning of medical procedures, better identification of incidentals, collaborative postoperative review, and advanced remote interaction.

Surgeons generally use a range of 2-D digital information. This 2-D projection of 3-D patient information means surgeons must themselves form a mental 3-D image and imagine the procedure and potential complications.

Many research and clinical projects investigate the use of AR and VR in the context of multidimensional exploration of medical imaging information, such as computed tomography scans (CT) or magnetic resonance angiography, and magnetic resonance imaging (MRI) data as shown in Figure 2(b). The goal is to inform diagnostic and treatment planning with the ability to reconstruct and visualize complex images in 3-D and simulate procedures. This is especially relevant in the context of surgical planning as a complex patient-specific procedure can be rehearsed and different scenarios envisaged, such as tumour resection margins and distance assessment, as evaluated by Hansen *et al.* in using an AR approach in liver surgery.[4]

The key to acquiring knowledge is that it be stored in a person's memory for later retrieval, either as an explicit memory (a visually recallable memory in time) or as an implicit skill recall (bodily responding to the tasks at hand without recourse to visual memory).[5] Both factors are important in the present healthcare applications domain as the health professional may need to access memory associated with recall of specific case histories, and, in addition, have a strong implicit sense of muscle memory with regards to manipulation of instruments and the human body being treated. Just like a space agency simulates a spacecraft's trajectory before hitting the take-off button, or actors rehearse their play before hitting the theatre stage. For example, UCLA and Surgical Theatre use Oculus Rift headsets to test-run technical and sensitive neurosurgeries.[6]

AR and VR also offer new avenues for patient communication with orientation to hospital settings and 3-D models integrating patient-specific data. They can assist in decision-making and in the understanding of complex procedures, as part of an induction process allowing for imaging information and familiar scenes to be viewed and interacted with. This helps to better inform the patient, to reduce anxiety and to smooth out

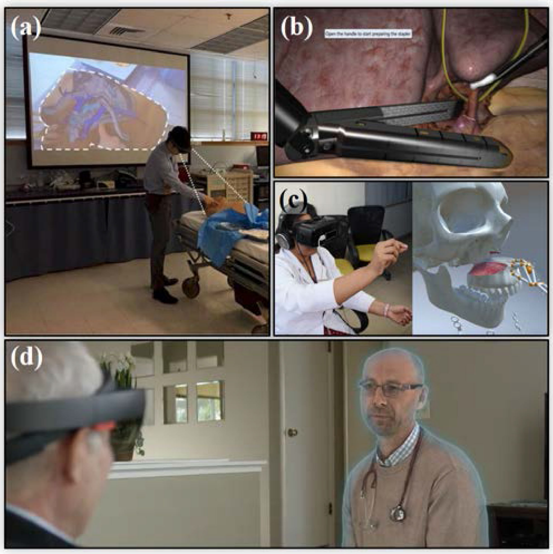

Figure 3. Virtual and augmented reality for training and telepresence. (a) Wireless broadcasting of augmented reality/mixed reality (AR/MR) headset first-person-view videostream for shared anatomic visualization during central venous line training (Kobayashi *et al.*, 2018, distributed under a CC-BY 4.0 license). (b) VR training application showing the 3-D model of the surgical tool and anatomy during a VATS lobectomy test (Jensen *et al.*, 2007, reproduced with permission). (c) VR application showing the interaction with 3-D models of the maxillofacial anatomy to improve medical trainees' self-confidence (Pulijala *et al.*, 2007, reproduced with permission). (d) Silver Chain envisioned the use of the Microsoft Hololens for virtual hospital services in 2017. Here, a doctor is projected as a hologram via the headset worn by the patient (reproduced with permission from Silver Chain Group, Osborne Park, WA, Australia).

any in-patient processes. VR has proven useful in preoperative contexts, as demonstrated at the Henri Mondor Hospital in France where skin cancer surgery patients were immersed in VR presurgery and showed reduced stress visual analog scale scores and salivary cortisol levels.[7]

AR IN THE SURGICAL THEATRE

Merging the surgical site with digital preoperative patient-specific images improves performance compared to the use of 2-D images in image-guided procedures. Indeed, the present literature suggests an increasing interest from surgeons regarding the implementation of AR into surgery, leading to improved safety and efficacy of surgical procedures. As tissue deformation and surgical accuracy remain a technical challenge to be addressed, AR is proving useful in the delivery of surgical procedures in orthopedic surgery, as well as in the fields of neurosurgery, head and brain space, and hepatobiliary and pancreatic surgery, thanks to minimal organ movement and deformation.[8]

AR allows for the projection of CT, MRI, or ultrasound scans aligned onto the patient's body. This helps with orientation, anatomical delineation, attentiveness, and development of surgical approach.[6] As an example presented in Figure 2(c), Pratt *et al.* led a case series where they used the Microsoft HoloLens AR for extremity reconstruction surgery by overlaying computed tomography angiography scan information of the subsurface vascular anatomy on a patient's body to guide operative incisions. Without compromising on environmental sterility thanks to the self-contained nature of the device and ability to be operated by hand gestures and voice control, and with minimal procedure changes, they concluded that the Microsoft HoloLens headset proved to be a powerful tool that has the potential to reduce anaesthetic time and morbidity associated with surgery. They also found it useful to improve training and provide remote support for the operating surgeon.[9] In another AR-guided surgery case report by Gregory *et al.*, both the ability to superimpose the patient's anatomy on their body and the opportunity to obtain direct comments from colleagues streaming the procedure resulted in enhanced safety in the context of a shoulder replacement surgery.[10]

In addition, Wachs demonstrated that image-guided surgery, while allowing improved safety and surgical performance, induces attention shifts from the surgeon between the patient and the monitor, negatively affecting cognitive and motor tasks.[11] While reasoning *in situ* about the space, overlays of data using AR also prevents eye movements away from the task space and improves attentiveness to the surgical field compared to computer displays. Stewart and Billinghurst report improved attentiveness to the surgical field with a "through-the-lens" wearable display compared to a peripheral display above the eye and a standard computer monitor in a simulated surgical task.[12] Therefore, AR may reduce attention shifts and time taken to perform the task, resulting in a better perceived performance by surgeons, as overlaying data on objects and hand gestures allows reduction of cognitive distance between data and artefact in hand, supporting better reasoning about information. This is supported by eye movement research indicating loss of memory and situational awareness when moving eyes away from a work site.[8]

AR and VR also offer new avenues for surgical navigation in postoperative contexts. A computer-based system could record a surgical procedure with multiple depth cameras and reconstruct in three dimensions the dynamic geometry of the actions and events that occur during the procedure. It allows for the procedure to be re-examined for training or review purposes. Cha *et al.* proposed a computer-based system capturing and modeling 3D-plus-time data, allowing a user to retrospectively walk around the reconstruction of the procedure room with a VR headset, while controlling the playback of the recorded surgical procedure using simple controls (e.g., play, pause, rewind, and fast forward) via a hand-held controller.[13]

INFLUENCE ON TELEHEALTH AND REMOTE SURGERY

In many situations, such as in remote areas and accident locations, direct access to specialized medical and surgical expertise is unavailable. Telephones, radio communication devices, and mobile phones have long been used for enabling basic consultation with specialists; however, the ability to remotely assess the situation to give direction and advice is limited to vocal descriptions and text messages. As communication technology progressed with the development of real-time photo and video transmission hardware (such as smartphones), the ability to augment voice descriptions with visual cues became available. This combined with the instantaneous transmission of on-site patient metrics such as heart rate, blood pressure, electrocardiograph data and more, further enhance the ability to provide critical expert advice remotely. This has been successfully demonstrated in the context of portable VR for the reduction of phantom limb pain in home environments by Cole *et al.*[14] AR technology adds even greater intuitive communication capabilities with the ability to display video, data, voice, and other information over the scene via the AR headset. Modern AR headsets, such as the Microsoft Hololens (Microsoft, Albuquerque, NM, USA) and Magic Leap One (Magic Leap, Plantation, FL, USA), provide high definition video capability and real-time 3-D depth mapping, acquiring accurate 3-D information about the situation, as well as the potential for remote annotation of the image.

Another important application is in real-time remote consultation by a medical expert to improve experience and communication over geographically distributed locations. This capability enables the expert physician to interact with a 3-D representation of the patient and their medical information in novel ways and improve communication through enhanced visual caregiver instructions. Silver Chain Group, an in-home aged care services group (EMMR, SilverChain Group Ltd, Perth, WA, Australia) is developing a Microsoft Hololens mixed reality application to allow healthcare professionals to visit patients in their homes in a holographic form and to conduct remote specialist consultations, as shown in Figure 3(d). This has benefits in monitoring recovery in the patient's own environment and allows for earlier discharge from a central healthcare facility to a near home facility while still being cared for by the team at the central location.

AR hardware combined with data communication networks (satellite, 4G and 5G mobile networks, WiFi, etc.), will provide an even greater ability for patient situational assessment and remote guidance by specialist teams. For example, first responders to an emergency scene can wear an AR headset which overlays hazards or patient data over their vision. Real-time video captured by the headset can be transmitted back to the hospital where a specialist surgeon can assess the situation. The surgeon can then direct the responders using visual indicators, guides, and even video, which then appears on the responder's AR view. The visual guidance by the remote specialist enhances the capabilities of the first responders through improved situational awareness. Santomauro *et al.* explored the potential of wearable near-field display devices and annotation software in the context of interactive telepresence for trauma simulations and found that junior clinicians rated the system's functionality and the feedback from subspecialists positively.[15]

AR and VR are also radically changing practice in surgical education and remote procedural training, particularly where physical travel to the surgical site is impractical. This is particularly important in rural areas where access to health care is limited. For example, a study by Kobayashi *et al.* created 3-D holographic representations of de-identified patient CT scans to simulate "blind insertion" invasive procedural training. The learners, wearing Microsoft Hololens headsets, used the anatomic "holograms" to practice insertion training of venous catheter and thoracostomy devices with haptic feedback with instructional guidance via the headset view.[16]

The capabilities of modern AR headsets such as the Microsoft Hololens and the Magic Leap One provide significantly enhanced telehealth capabilities over the older generation AR devices such as the Google Glass, through improved immersion, image quality, field of view, and integration of 3-D imagery with the real world. The faster on-board processing and communication capabilities of these newer devices also enable a more seamless telepresence experience by providing higher fidelity transmission and rendering of 3-D models and video. Combining the AR/VR headset visualization capability with additional hardware like novel input devices such as hand gesture sensing gloves and haptic feedback further improves their suitability in clinical situations. The future of AR and VR for telehealth involves the seamless integration of real-time patient scanning and metric acquisition, haptic input devices, fast data processing and communication, sound and audio transmission, video transmission, and ultimately, the ability to real-time transfer 3-D environment scans between locations for a more complete immersive telepresence experience.

LIMITATIONS AND CONSTRAINTS

Potential limitations to the use of AR and VR in healthcare need to be considered. For example, the amount of information a surgeon has presented to them through AR during a surgery is increasing and may become distracting or imprecise due to latency issues or misalignment of imaging data or annotations.[8] Therefore, it is necessary to display only important data or provide a method to switch between different sets of information on demand. Hansen *et al.* proposed a method for the reduction of cognitive demands, where they developed a series of algorithms for silhouettes and texture gradients beneficial for distance assessment in liver surgery, with the goal to increase acceptance of AR in the operating room. However, participants in the study reported that too much information was presented to them, and the authors highlight that the usability of the visual cues correlates with the user's familiarity with the illustrative techniques, proposing their integration in surgical training.[4] Another key factor is assuring clinical staff with regard the anatomic fidelity of any images, particularly when there may be remote interventional guidance in an AR environment. Clinicians would want to know discriminatory resolution between vital structures and have confidence they would not miss any injury or other pathology. Main challenges remaining for future research include improving the experience in immersive VR/AR simulators of organ movement and deformation, human factor issues, and the undertaking of large clinical studies.[17]

Azuma *et al.*'s key 2001 review also highlighted design issues, implementation challenges, and perceptual problems—latency, depth perception, adaptation, and fatigue and eye strain,[18] which may induce unwanted adverse effects such as headaches, dizziness, or blurred vision.[19]

Basic human perception and interaction factors need to be further developed to improve the experience. Rendering of content is commonly required to be commensurate with photorealism, particularly in training environments. Another unresolved issue is the influence of audio–visual quality in aiding human cognition, and defining clearly this quality concept in this surgical context—for example, a vascular surgeon in an operating theatre and a paramedic on a car accident site might require different levels of visual detail and audio quality.

Rendering projections into the visual field is another factor, which poses many problems with physical dexterity [gesture recognition, of which an early technology example is shown in

Figure 2(a)] and precision in complex tasks. A promising line of display technology is being pursued by the Magic Leap system (Plantation, FL, USA), whereby a light field rendering produces a better sense of depth for visual judgement and could influence immersive system training effectiveness.

Haptics, a continuing research topic, needs further investigation. Surgery has a strong haptic element, feeding into theories of muscle memory. If the theory of embodied cognition, in particular, as it relates to situated learning is correct,[2] then research will need to seek to understand the cognitive requirements around providing AR and VR environments that support effective knowledge transfer and recall in an embodied fashion. This has implications right across the healthcare centers of the future; for the patient needing to be properly inducted into a healthcare environment or receive treatment, onto the surgeon, practicing in a simulation or performing a procedure, requiring effective interactions to support their training or procedure efforts.

The technical limitations of the current generation of devices such as a relatively small field of view, device bulk and weight, haptics, and basic 3-D environment mapping and rendering capabilities are set to be improved with each generation of device. For example, the latest Microsoft Hololens 2 (released in 2019) promises improvements around ergonomics, field of view and hand gesture tracking. Finally, Ko, Brem, and Rauschnabel argue that the positive social impacts of the headsets could be encumbered by the absence of regulation to address uncertainty among users and legal challenges such as data privacy.[20]

CONCLUSION

Advances in VR and AR are undoubtedly transforming healthcare processes, enabled by collaboration between clinicians, scientists, patients, software companies, and hardware manufacturers. Technical, cognitive, scalability, and adoption challenges are driving further innovation toward industry-specific solutions for more proactive and personalized health services. AR and VR bring new data integration capabilities that are supporting efforts worldwide toward the digitalization of hospitals, delivering unique benefits including enhanced medical training, remodeled patient experience, distribution of centralized expertise, and streamlined medical procedures. As immersive technologies advance and complementary technology platforms evolve in parallel, there is no doubt that, these areas will come together and create seismic shifts in the way healthcare is delivered. The hospital of the future will also see artificial intelligence, robotic surgery, and integrated medical manufacturing of personalized implants all taking place on site alongside medical practitioners and patients. Advancements in AR and VR are made even more compelling by their complementary nature, which will raise other platform technologies to new levels of accessibility, affordability, and efficacy, ultimately providing positive economic impact, increased training and up-skilling, and improving the quality of life for patients all over the globe.

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Mathilde R. Desselle is currently a Project Manager with the Herston Biofabrication Institute, Brisbane, QLD, Australia, with expertise in digital health, virtual reality, and medical technologies. She is a Member of the IEEE. Contact her at mathilde.desselle@health.qld.gov.au.

Ross A. Brown is currently a Senior Lecturer in games and interactive environments with Queensland University of Technology, Brisbane, QLD, Australia, with expertise in embodied cognition, expert elicitation, and virtual reality. He is a Member of the IEEE. Contact him at r.brown@qut.edu.au.

Allan R. James is currently a Senior Visualization and Software Development Officer with the Visualization and eResearch Group, QUT Institute for Future Environments, with expertise in computer graphics and human–computer interaction, augmented and virtual reality. Contact him at ar.james@qut.edu.au.

Mark J. Midwinter is currently a Military Trauma Surgeon and Professor in clinical anatomy with The University of Queensland, St Lucia, QLD, Australia, with expertise in telemedicine. Contact him at m.midwinter@uq.edu.au.

Sean K. Powell is currently a Research Fellow with the QUT Biofabrication and Tissue Morphology Group, with expertise in theoretical and computational modeling and 3-D visualization systems. Contact him at sean.powell@qut.edu.au.

Maria A. Woodruff is currently the Leader of the QUT Biofabrication and Tissue Morphology Group and acting QUT Director for the Herston Biofabrication Institute, Brisbane, QLD, Australia, with expertise in medical technologies. Contact her at mia.woodruff@qut.edu.au.