EXTENDED REALITY DIGITAL TWIN SURGICAL TRAINING

Abstract

Design Report
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Authenticity Statement

This is to certify that to the best of my knowledge; the content of this report is my own work. This report has not been submitted for any subject or for other purposes. I certify that the intellectual content of this report is the product of my own work and that all the assistance received in preparing this report and sources have been acknowledged.

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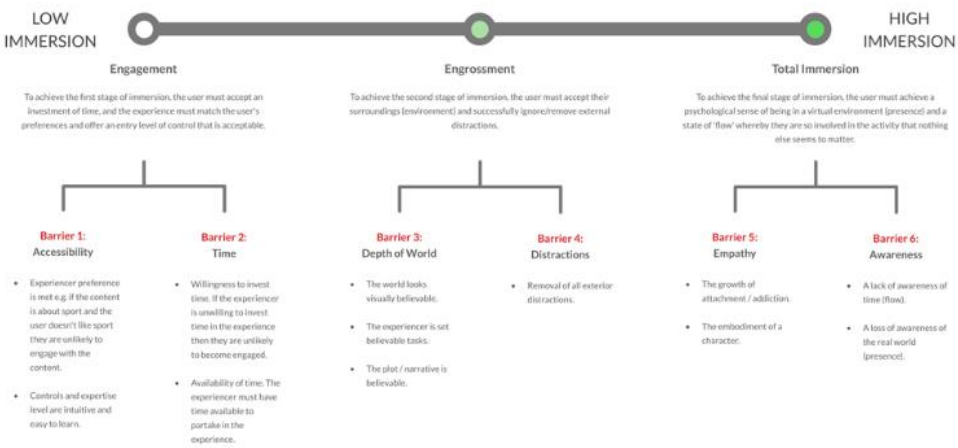
Introduction

Extended reality (XR) is an umbrella term that refers to technologies that create immersive experiences that link or integrate the digital and real worlds, these technologies are virtual reality (VR), mixed reality (MR) and augmented reality (AR) (GAO, 2022).

VR can have varying meanings but for the scope of this report has been limited to a mediatory computer system that allows humans to visualise, manipulate and interact with complex data (Isdale, 1993) the most popular form of this is through a system which incorporates a head mounted display (HMD) with audio and tactile input and feedback, this setup allows for the user to fully enter a digital environment with the goal of interacting with virtual objects (Autodesk, 2022) VR is separated from AR and MR as it does not interact with or interfere with non-virtual objects with the exception of the apparatus being used to immerse the user (Autodesk, 2022). VR systems have the potential to create ‘total immersion’ where the user can enter a state of ‘flow’ where nothing else seems to matter allowing the user to fully focus on the VR subject matter (VRG n.d.) this can enable better learning environments for use in educational settings (Fiani et al., 2020).



Reality scale (VRG n.d.)

AR is when digital objects and elements are imposed onto the real world, these objects and elements can be manipulated by the user and are designed to fit simultaneously into a real space (Speicher, Hall, & Nebeling, 2019) AR hardware can be like that of VR but can also use handheld devices (HHD) such as mobile phones using installed software to take advantage of existing hardware such as the AR game Pokémon Go (Niantic, 2022) AR headsets also use HMDs along with an array of inputs such as external video to reproduce an external image to impose digital elements and objects an example of this is the Apple Vision Pro (Apple, 2023).

The MR is distinguished from AR as the mixed reality solutions also allow interactions with physical objects as well as digital objects and elements, where interacting with a physical object could produce a digital and or physical response to the input (Speicher, Hall, & Nebeling, 2019). However, there are more definitions of MR (Speicher, Hall, & Nebeling, 2019) but to narrow the scope of this report this is the definition that will be used.

Table 2. Differences between VR, AR, MR and XR specific to spinal procedures.

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Characteristic	VR	AR	MR	XR
Virtual components (MRI, CT imaging)	✓	✓	✓	✓
Real environmental components (patient)	X	✓	✓	✓
The user is present in the experience location (the operating theatre is visible through HMD)	X	✓	✓	✓
User interaction with real and virtual components (the surgeon can manipulate the patient and the images projected by the HMD)	X	✓	✓	✓
Real and virtual components interact with each other (the virtual input is altered based on changes in physical environment)	X	X	✓	✓
Multiple systems integration (imaging system, integrated with HMD, other instrument sensors and larger health service network)	X	X	X	✓
Tactile/multisensory feedback (instrument sensors and feedback modalities)	X	X	X	✓

CT: computed tomography; MRI: magnetic resonance imaging; HMD: head-mounted display; XR: extended reality; AR: augmented reality; VR: virtual reality; MR: mixed reality.

Table of XR characteristics (Sakai et al., 2020)

The demand for surgeons in Australia has been increasing in over the years with the average age of active Australian surgeons in 2010 being 52.1 years old with on average 61.67 % being under the age of 55 (RACS, 2010). While there is no mandatory retirement age for surgeons in Australia the table bellow from the Royal Australasian College of Surgeons shows that 21 % of surgeons in their age range begin to retire between ages 60-69 and 71 % retire between the ages 70-79 (RACS, 2017). With an aging population the demand for more young surgeons to be trained will increase (McPake & Mahal, 2017) and new technologies in XR could be incorporated to help young surgeons train. The aim of this report is to explore the potential use cases of extended reality as another tool to be integrated into surgical education for both those in training and those teaching.

Table 2. Characteristics of the active Australian surgeon by specialty

Specialty	No	% Female	#Average Age	% under 55	% under 65
CAR	160	5.6%	52	62%	89.5%
GEN	1423	11.6%	53	56%	78.9%
NEU	201	10.9%	51	69%	85.8%
ORT	1116	3.0%	51	64%	84.8%
OTO	398	9.0%	52	61%	81.2%
PAE	85	20.0%	56	51%	80.7%
PLA	356	12.1%	52	65%	81.9%
URO	332	6.9%	50	67%	87.7%
VAS	165	7.3%	52	60%	82.7%

Source: RACS 2010 Annual Activities Reports; # Ad hoc IMIS report

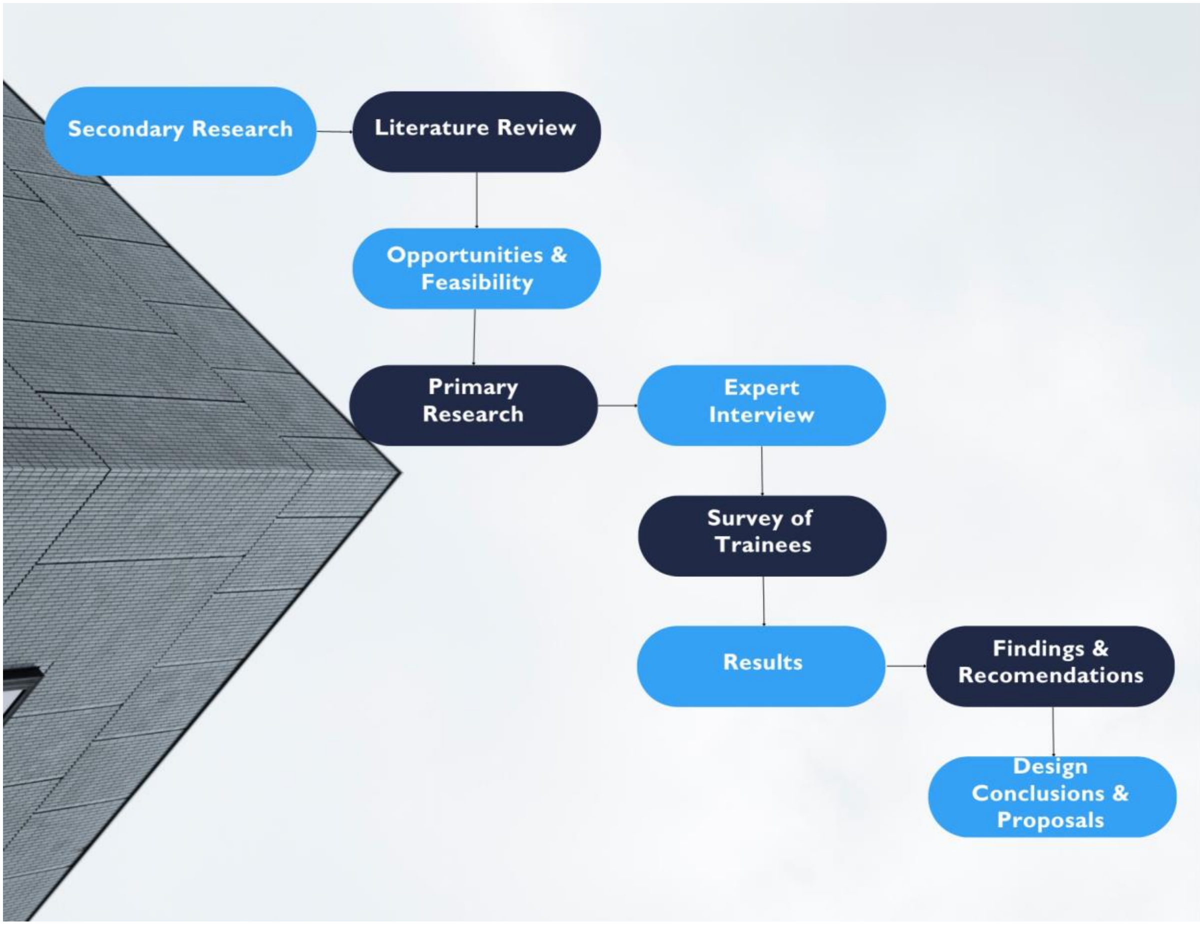
Surgeon age table (RACS, 2010)

Table 2 Age distribution and Fellowship status of Census respondents (Royal Australasian College of Surgeons 2014)

Age group	Number Mean working hours per week	Active (%)	Semi-retired (%)	Retired (%)
<40	348 Male: 49.0 Female: 43.0	348	0	0
40-49	661 Male: 51.8 Female: 45.5	661 (100)	0	0
50-59	603 Male: 51.9 Female: 47.7	597 (99)	6(<1)	0
60-69	415 Male: 41.6 Female: 40.2	327 (79)	87 (21)	1 (<1)
70-79	210 Hours NR	52 (25)	149 (71)	9 (4)
80+	30 Hours NR	3 (10)	22 (73)	5 (17)

Surgeon retirement age table (RACS, 2010)

Report Structure



Literature Review

What is enabling XR technology to improve in the surgical space?

Many different XR technologies have been transforming the industry this section will list some of the notable technologies being used currently. Conventional two dimensional (2D) medical imaging technologies mainly X-rays, computed tomography (CT) and magnetic resonance imaging (MRI) can require years of experience and training to properly diagnose and analyse, but with the diverse range of 3D modelling technologies students can more effectively and quickly absorb information (Morimoto et al., 2022) and these models are forming the basis for the virtual objects and elements being used in XR software.

Wearable sensors enable devices to not only record the data of patients but also track the characteristics of those in training for example give a score for how steady an incision is made during training and check the vital signs of the trainee and can provide inputs for the XR software.

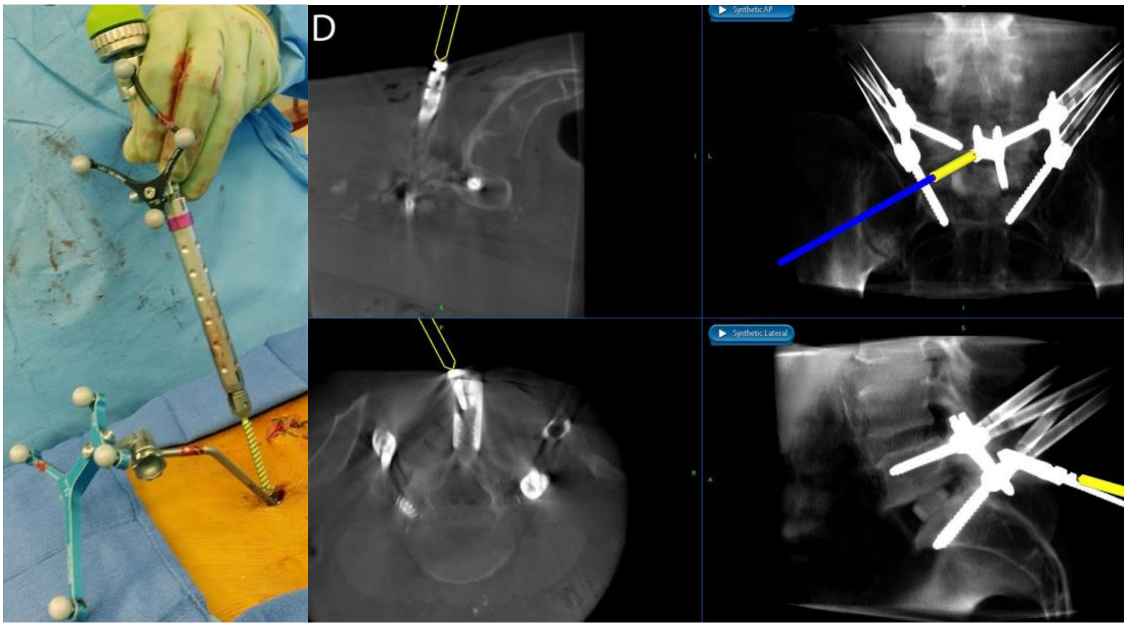
HMD's have been used in most of the studies in XR surgical situations with the ability to display information and record data inputs through video, sound and motion users can be immersed in the world to fully focus on learning.

Current applications of XR in Surgery Today

Due the advancement in microchip technology of the past few years VR, MR, and AR have had the opportunity to be used in medical settings more often. VR has been adopted by some practices to reproduce human body structures, pathophysiology and varying clinical situations, where it has been mostly used for medical education, surgical planning, and intraoperative guidance (Morimoto et al., 2022). AR in surgical settings is typically utilised by imposing digital images onto real images on digital displays (Morimoto et al., 2022). MR technologies on the other hand have seen more attention as they can mitigate VR and AR's inability to truly interact with the physical environment (Morimoto et al., 2022). The study *Intraoperative 3D Hologram Support With Mixed Reality Techniques in Liver Surgery* at Tokushima University used three dimensional (3D) polygon data and mapped it onto Microsoft's HoloLens headset from CT scans, this intraoperative hologram assisted in helping the surgeons locate tumour locations, however this data was not used for navigation rather as a way for the surgeons to compare the patients real anatomy to that of the hologram before the procedure (Saito et al., 2020). Another study used MR and VR navigation in urological surgery and found that compared to conventional surgery, the ability to navigate helped in shortening tumour resection time and had a reduction in bleeding for partial renal surgery, as the surgeon could intuitively experience a sense of distance for organ dissection helping them navigate tumours, peripheral organs and surrounding blood vessels, the HMD used was again Microsoft's HoloLens which was able to record point of view (POV) video for educational purposes (Yoshiyuki et al, 2019). These examples show the potential of XR technology in surgery the apparatus that was chosen in both studies being Microsoft's HoloLens (Microsoft, 2023), which is a choice that made sense, hand gestures can be used so no non-essential tools could affect the cleanliness of the operating theatre, while video outputs were instead projected onto the glasses not a displayed using a secondary camera monitor setup so that the surgeons would not experience the latency of a display which could affect their actions during an operation or create dizziness. While HoloLens was an appropriate headset for task it also has many limitations such as a narrow field of view and reduced response time when using hand gestures to interact with models and more (UploadVR, 2021) and has since been discontinued as a product line by Microsoft.

AR Guide used in surgery (Yoshiyuki et al, 2019)

Some MR tools such as Medtronic's StealthStation surgical navigation system that uses optical and electromagnetic (EM) tracking with a probe guiding instrument that can be used in conjunction with CT scans, MRI, radiographic fluoroscopy (RF) imaging or other digitised landmarks on a body to find exact locations for surgery such as the appropriate entry angle for a drill on a patients' skull, this data is then displayed to surgeons live on a large display (Medtronic, 2020). The study *A new 3-dimensional method for measuring precision in surgical navigation and methods to optimize navigation accuracy* used the StealthStation for the precise placement of pedicle screws in thoracolumbar deformity patients with 153 of 158 (97%) screws being adequately inserted of the 5 ill positioned screws there was found to be no neurological or other complications in any of the patients (Kleck et al., 2015). These studies show that the use of XR tools in assisting with surgery can be positive and have a reliable success rate and are mostly used to navigate a patients' anatomy either during an operation with MR tools like Medtronic's StealthStation and Microsoft's HoloLens or during preparation using VR tools or headsets.



AR surgical navigation screw insertion (Kleck et al., 2015)

XR in surgical education today

VR and AR technology have been used to teach medical students and residents using 3D holograms, this has become a much cheaper way for students to learn human anatomy through visuals compared to cadavers and provides a more immersive experience than textbooks and videos but lacks the touch, feel and smell of cadavers that someone may experience during an operation (Morimoto et al., 2022). These models can expose detail or show procedural steps to students who are studying or practicing for an operation and have been found to help improve their understanding and awareness using stereoscopic vision in the simulations that may help accelerate the learning curve and contribute to accurate and safe surgery for patients (Fiani et al., 2020) (Ghaednia et al., 2021).

XR technologies have also been used for surgical observations, live or as a recording from the POV of the surgeon allowing students to see the processes and procedures when not present for a routine observation. This teaching technique has been used both in nursing ward visit training and for teaching students about shoulder arthroscopy or arthroplasty (Bala et al., 2021) (Ponce et al., 2014). The main advantage of XR in 'tele-education' is the accessibility to the students but may also require the cooperation and permission of the patient.

Surgical simulation using VR or AR technology has been used to educate users using various methods and either categorised as VR simulations or AR guided. The VR simulations used 'phantom models' (PM) for training while the AR guided simulations could also use PM's and cadavers, the participants in these varying studies were residents, trainees, medical students, surgeons, radiologists, operators, and anaesthetists with the outcome goals of the training being accuracy, time, radiation exposure, workload scores and questionnaires (Morimoto et al., 2022). The main benefit of XR surgical training for simulations is a more realistic and immersive learning environment based on real surgical procedures using tools that provide high fidelity feedback systems (Morimoto et al., 2022).

Based on the literature above XR education for surgeons is divided into 3 branches XR learning models, XR tele-education, and XR surgical simulation each sitting in its own tier on the VR immersion scale of engagement, engrossment, and total immersion respectively. There are design opportunities in all 3 however XR surgical simulation for training has a large potential as the apparatuses either used VR PM's or AR with cadavers and PM's, opening the possibility for MR surgical simulations to provide better user feedback for education and improving trainee dexterity.

Research

Methodology and Methods

The objective of this research is to understand how surgeons interact with tools, patients, and other staff during an operation, but also find out how they train and prepare for an operation, this information would be necessary as the design outcomes may have needed to create total immersion as part of a virtual environment. The first method chosen was an expert interview with a primary and potentially secondary user of XR surgical technology a surgeon the qualitative data collected would create a base line conventional surgical experience and draw from their knowledge as a practicing surgeon but also as a former resident and vocational trainee.

The interview was conducted with the surgeon over zoom in 30 minutes, with questions being sent ahead of time to prompt the interviewee, notes were taken, and a video recording was used as backup for the data collection for review.

The data collected would then be used to inform the second method of research a survey made for primary and secondary users as it would be difficult to find respondents if the survey was just limited to surgeons and trainees. These secondary users would be other medical professionals who help during operations such as anaesthesiologists or surgical technicians who are also present during an operation and could give insight into communication and preparation. The survey would collect qualitative and quantitative data as the topic area is broad that giving set options when not necessary could lead respondents into answers or skipping questions, so text box answers were primarily used, and selection answers were only used for quantifiable data such as length of time or age.

To increase the completion rate of the survey it was shortened down to an estimated completion time of 3 minutes and was comprised of 10 questions. The distribution of the survey was done through industry contacts at the Herston Biofabrication Institute (HBI), Centre Medicale Internationale (CBI), and Healthscope where contacts would be able to share the survey to their colleagues in the surgical field, the survey was also posted online for 3 weeks through (Facebook, Reddit, and email) to exclusive community group chats where all the posts are moderated and there were selection criteria to join the group to reduce the chance of fraudulent survey responses, clinics that provided surgery were also emailed with a survey link and description of the project in bulk email waves.

Surgeons in Training, University Study

Study Consent (Progress 0 - 40%)

By participating in this study you agree that you have read the participant's information sheet: https://drive.google.com/file/d/1dFnzJeOm1dwk5G85tmee0R6pjmEOUZgo/view?usp=sharing

1. What is your specialty in the medical field?

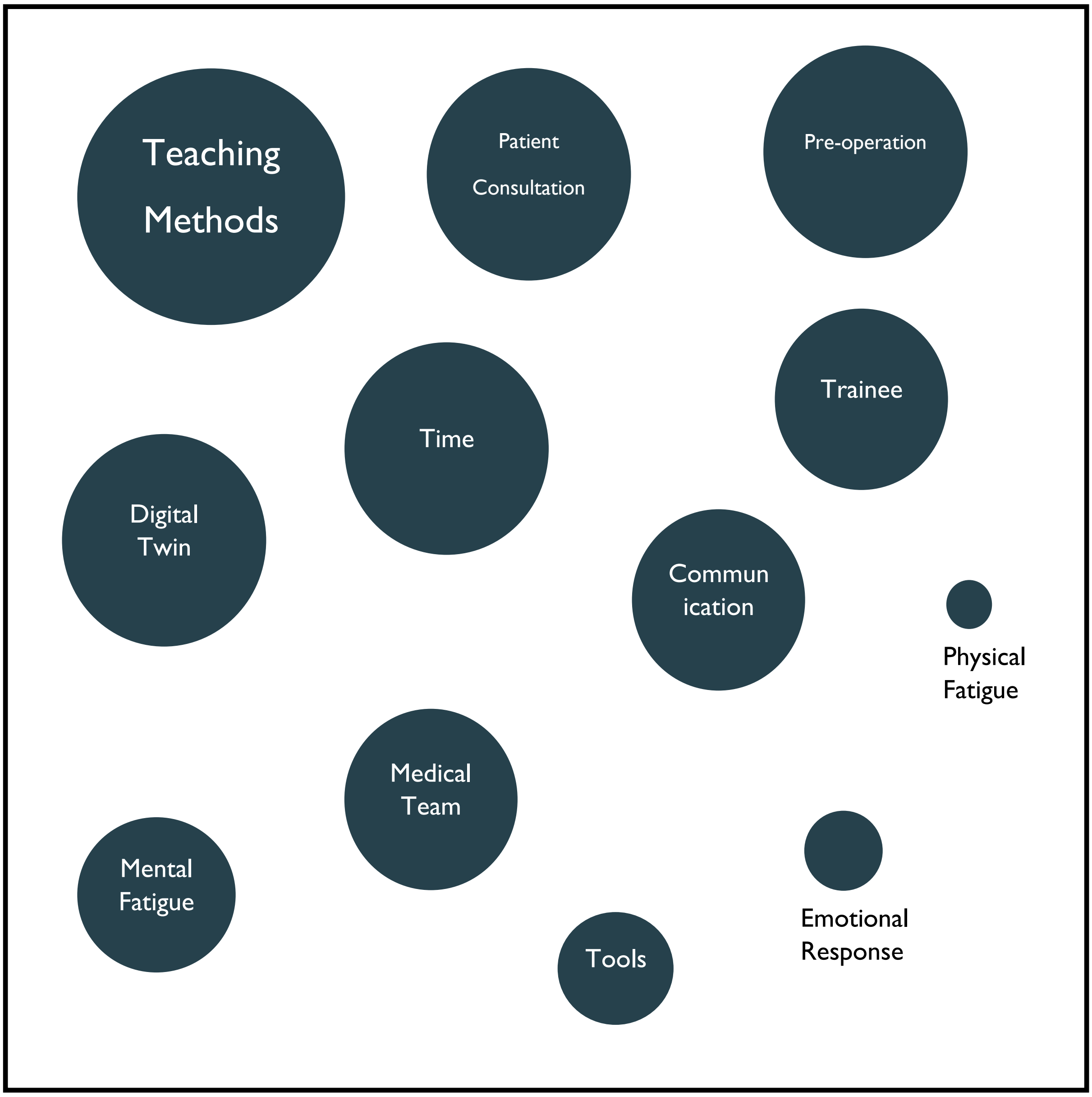
2. Are you currently in training or have you completed your training?

Analysis and Findings

Expert Interview

The subject of the expert interview was an oral and maxillofacial surgeon with 15 years of practice and 9-10 years of post-graduate study specialising in head, neck, and reconstructive surgery. The interview used thematic analysis but categorising responses, each theme was given a weight based on the amount of time the interviewee spent or looped back to a topic, the themes and weights have been visually represented bellow.

Figure Interview Thematic Analysis



Theme/Topic	**Comments on topic**
Time	I perform many different procedures which vary in time anywhere from 15-20 minutes for a biopsy to 9-10 hours for an operation. There are some consequences to training as an apprenticeship I must make judgment calls during a surgery based on my perception of the trainee's skill level, the best-case outcome during this training method is a slower procedure which is fine, anything which may lead to a poorer quality outcome for the patient is not an acceptable outcome. Time is also used for pre operation planning, team meetings, patient consulting, and procedural checks. What effects the length of the surgery besides the procedure itself is the communication to the other team members so they can remove or retrieve equipment during the operation.
User (trainee, student, etc)	The trainees in the room will typically include the understudy of the surgeon, and an anaesthetic trainee. Depending on the person being trained different goals should be considered, e.g., most trainees have already had operating room experience so that does not need to be replicated during a training simulation. It could be possible to incorporate nursing staff into training XR training sessions as a secondary user for communication.
Communication	What effects the length of the surgery besides the procedure itself is the communication to the other team members so they can remove or retrieve equipment during the operation. It could be possible to incorporate nursing staff into training XR training sessions as a secondary user for communication. Communication helps speed up a procedure but not critical to learning.
Pre operation	Consultations with the patient and make sure they have no more questions, booking, communicating with teams and departments to prepare for surgery, consent forms, final checks to prevent mistakes. Team meetings to discuss a treatment plan, modelling, virtual surgical planning, prebend metal implants etc…
Teaching methods	The typical way a student prepares for an operation is by reading textbooks, watching videos, going over procedural steps, and reviewing the anatomy for the area of the operation. Apprenticeship style learning is the current method we currently use, which has real life consequences and is limiting in how many people you can train at a time. Cadavers are not a real representation of the human body during surgery, as there is no blood so it doesn't bleed and the preservation methods also affect the texture, feel and colour. They are also very expensive to acquire.
Patient care/ consultation	Assuming preparation is done, visit patient in holding bay, make sure they have no final questions, final checks, consent forms, patient goes to operating room, final checks to prevent mistakes ensure that patient, staff, consent form, and equipment are all in agreement. Most mistakes are made when a surgeon loses focus, deviates from their plan, or has a bad plan. (Many more comments made but would be repetitive refer to appendix)
Physical fatigue	Typically, I don't feel physical fatigue of pain, only my back when bending over to supervise a trainee as the setup is not that ergonomically optimised. I can get hand cramps while performing microsurgery.
Mental fatigue	It is more mentally taxing than physically taxing staying focused for 10 hours
Emotional response	Part of the job is to not use your emotions as decisions should be made objectively. I feel mostly relief after a procedure is finished.

	I sometimes have feeling related to if I think the surgery is worth while as it may not be beneficial to the patient and could harm them or may just be a waste of time given the perceived outcome.
Medical team	A normal medical team would consist of: Surgeon 1 or 2, trainee, junior doctors, Surgeons perform procedure and teach trainee and junior doctors perform minor parts of surgery. Nursing team, responsible for equipment and safety, surgical counting Anaesthetic team, Anaesthetic doctor, anaesthetic trainee, anaesthetic technician, responsible for sedating the patient and monitoring them.
Tools and equipment	(An extensive list of tools was provided by him refer to appendix)
Digital twin	For XR surgical simulations: My knowledge on this is limited but I imagine that it would be challenging to develop feedback, practicing would be better than watching, and its good because consequences are virtual. If it can be set up with some tactile feedback, you would have to look at the instruments used. How can you replicate that experience, depending on who you're trying to teach, teaching a high school student is different from a trainee, most people training for surgery have had an operating room experience before and are just there to learn how to do the operation, learn technical steps of surgery, planning, error avoidance, corelating that with imaging or planning.

Survey

The survey had a very unsuccessful deployment over the 3 weeks with only 1 response by a medical student who is a potential primary user but not the target that the survey was aiming for was recorded. As many of the questions had qualitative responses and there was not a significant sample size of respondents none of the responses could be categorized and analysed quantitatively and it was decided as a compromise to analyse the 1 response as an interview to compare perspectives between the industry expert and a medical student. As the expert interview response is what informed the survey questions there was some overlap in question types however it was not one to one and the weight of the data was skewed towards the expert interview.

Question	**Response**
What is your specialty in the medical field?	Student
Are you currently in training or have you completed your training?	Currently in Training
What training methods were used for surgery during your education?	Lots of placement hours, workshops for skill such as suturing, hand ties
What is your most common procedure? if still in training which procedures have you observed or taken part in? (For either of these indicate the time length of the procedure)	skin excisions- varied time
Do you experience fatigue while preparing, during, and/or post-surgery?	Yes, during surgery
If you answered Yes to the last question, please provide details of the fatigue (i.e., physical (location of strain and cause), mental, emotional, etc.)	Physical- neck pain from flexion
Which tools during your procedure require the most practice or are difficult to use?	Laparoscopic camera and tools

Do you ever struggle to remember the steps in a procedure?	No
How easy was it to learn to communicate with your team during an operation when training?	Neither easy nor difficult
What is the worst aspect of surgery for you?	The sterile field

Relevant findings and research limitations

The research has been limited due to the surveys sample size making it impossible to find trends however, a comparison of results can be summarised, similarly to the surgeon the student does have some physical 'pain' from bending over when performing a procedure and did not mention any mental fatigue this may be due to differing fields, or a lack of experience. The surgeon said that planning and procedural steps are some of the most important aspects of surgery and recommended helping in this way using XR, however the students response said that they had no issues when it came to remembering the steps. The student said that they had trouble with laparoscopic camera equipment and tools the most this could be integrated into the XR experience and stated that the sterile environment was the worst aspect of surgery to them, assuming this refers to preparation and or sterile operation techniques this could be integrated into the XR system in tactile feedback such as replicating the feel of being double gloved.

This research has not found anything conclusive due sample size but can point the discussion and design implications towards developments in the areas of communication, tool practice, immersion through tactile feedback, procedure recall, procedural execution, preoperative models, and virtual surgical planning.

Discussion

The research findings help target the areas that surgeons and students believe to be missing or struggle points of surgical education from the interview and survey data these were XR education that involved:

- Communication training potentially with other surgical team members such as the nursing or anaesthetic team.
- Tool practice both for dexterity and fatigue endurance and operative steps for complex equipment.
- XR simulations that create immersion through physical feedback systems.
- XR assisted procedural recall for use in real and simulated surgical scenarios.
- Preoperative modelling and virtual surgical planning used with XR technology.

The literature review showed potential technology types that could be used and are being used for some of these opportunities, however there was a lack of studies that used real MR simulations, these MR simulations could be used to improve immersion compared to PM's and be less expensive that cadavers. The immersion created by feedback in MR systems could give users more focus for example if they were physically drilling a hole in an imitation skull while using MR, this would also allow for better tool control for laborious procedures. An MR simulation also has the potential to produce/ leave behind physical models of a skull for example that could be compared with other students or graded by their supervisors.

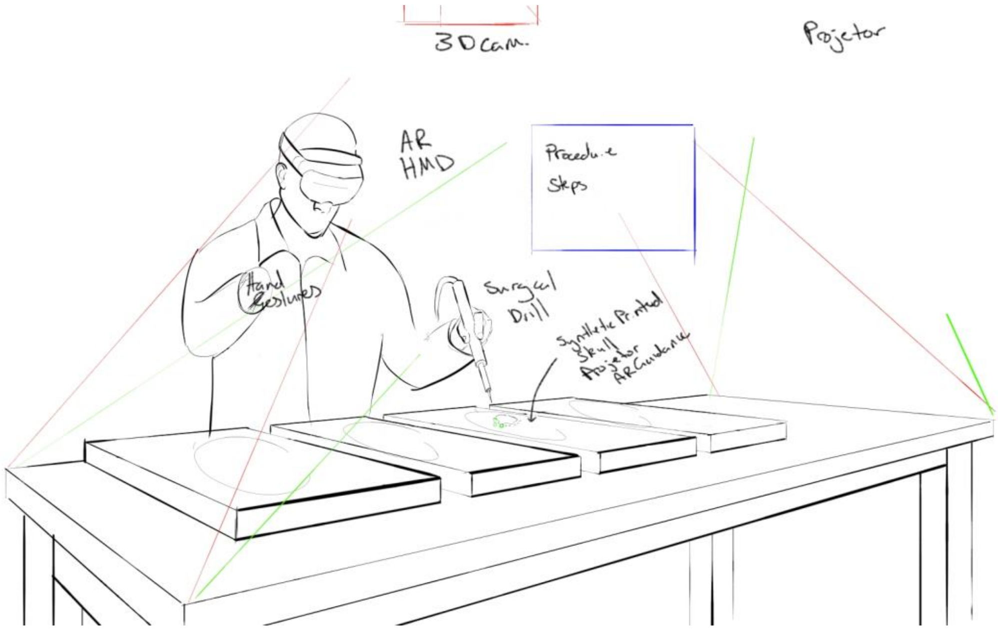
The literature also showed accelerations in the learning curve from the use of VR and AR surgical modelling which is what one area found in the research that the surgeon would like implemented however it seems as though systems like this have already been developed and are being integrated currently in anatomical education but could be adapted as part of preoperative training as a software solution for existing headset products. The same can be said for procedural recall however the recall can also be integrated into the tooling and physical model that may be used in a MR setting.

XR surgical simulations could also incorporate currently used AR technology such as Medtronic's StealthStation to plan surgical steps during a simulation such as entry angle and could consult with a training radiologist who could practice their medical imaging diagnosis.

Further research should be undertaken with a statistically significant sample of survey participants to find trends based on potential users that were missing during this research. Along with more investigations on specific tooling for different surgical specialties and general surgery.

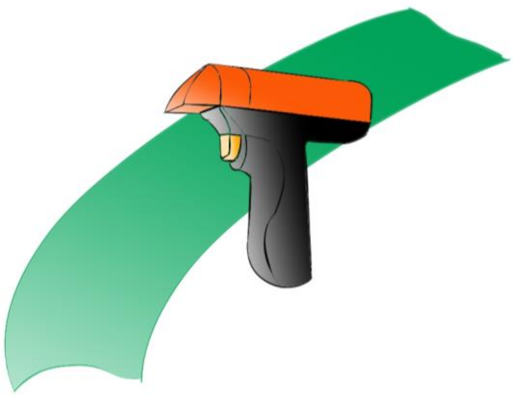
Design Implications

Concept 1: MR dissection sample table



This concept makes use of the opportunities to train for dexterity and fatigue by using sample organs printed using the J750 Digital Anatomy 3D Printer to create objects that provide a close to real feel for human organic material. A 3D camera and projector can project information such as guides or navigation marks to help the trainee while the AR headset would help the user with procedural steps based on the task. This would also help train the student because it would use real tools however the experience would not be the most immersive experience. Samples can then be assessed by the teacher and compared to the work of other students.

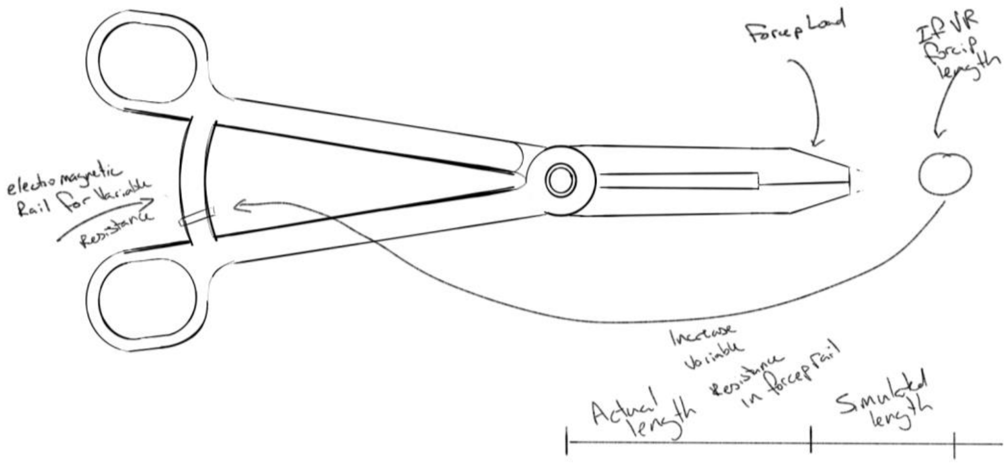
Concept 2: VR multitool



The concept of the multi tool is for use in a VR headset system where a set of tools is accessible to the user and similar tools such as different lengths of forceps are one tool that has been designed to provide different forces based on the tool you have selected in virtual reality in an effort to recreate the feeling of leverage created by different length tools in the virtual world.

The picture above shows how a drill-based controller tool could have its top section be swapped out potentially with a tool like a surgical saw to create different types of tactile feedback.

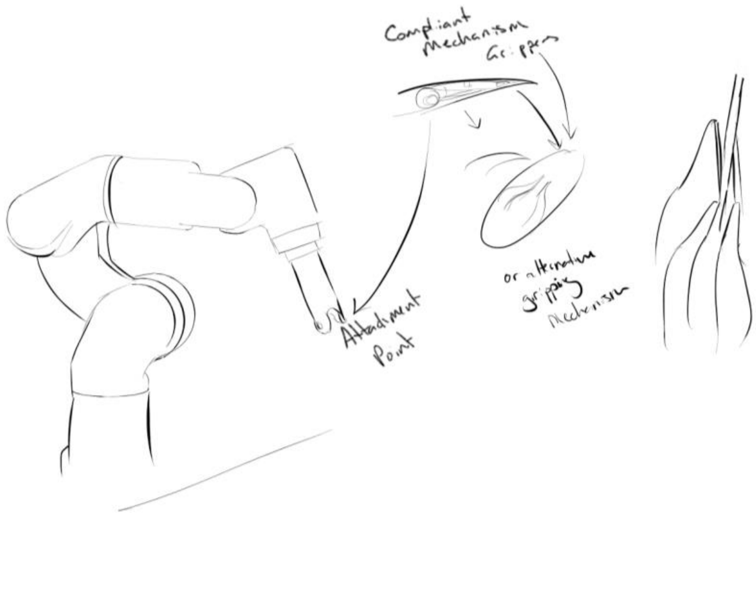
Concept 3: VR Group full basic tool set



This concept is targeting the opportunity for the surgeon and surgical team trainees to practice communication, in a VR setting, in a simulated digital theatre a team of 4+ trainees will work and communicate practicing a VR surgery this is different from concepts 1 and 2 as many basic VR tools will be catalogued designed or just be regular blunted instruments that are modified to be tracked. This way the student has to communicate to the team which tools they need or do not need, and the nursing team would have to prepare and swap out these items.

This is an example of one of all the basic tools that would be redesigned where an electromagnetic rail provides resistance to the forceps to imitate changing length loads inside the VR simulation.

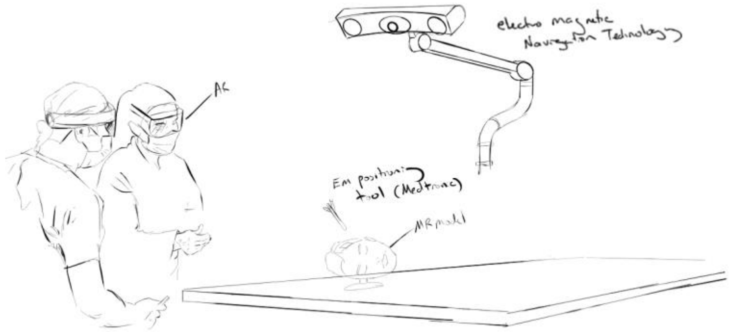
Concept 4: VR tactile resistance robot



This concept aims to help the student train in an immersive environment where a system of robot arms provide resistance to redesigned blunted tools, these tools will look normal inside the VR headset in the digital space, and the robot arm tracks the redesigned set of tools and based on data from the simulation can dock and redock from the took and apply force and vibration at varying levels.

This concept is using a compliant mechanism grip to apply axial and shear force to a needle the robot arm would swap out grip as the user changed tools so that it could apply appropriate force while the user experiences the VR Simulation

Concept 5: MR Virtual mapping and planning simulation



In this concept a body/ body part has been designed for surgery and diagnosis, here 2 or more students such as a surgeon trainee and a radiologist assess the body part using an AR headset, where they can view the internal mapping of the body part to help diagnose and create a surgery plan. This will also incorporate mapping tools such like that of the Medtronic StealthStation using EM in the AR world to map out entry incisions.

Here the design head would be considered from a previous procedure and utilise existing EM navigation and AR technology to create a mixed reality mapping experience.

Conclusion

The need for the implementation of this technology is rooted in the aging population in Australia and the average age of surgeons being skewed towards the older population, this is fine but to avoid a potential future where surgeon demand rises, and the medical system cannot handle it more training techniques need to be tested and implement to accelerate the rate of approved surgeon growth.

This report has investigated XR technologies and their application in the surgical field, the key technologies that make these concepts feasible and have increased their adoption in recent years, how XR technologies have been utilised in medical education. The report then began primary research starting with an expert interview which was then used to develop a survey questionnaire aimed at those who are training for or participate in surgery, although the surveys results were statistically insignificant it did help create insights in which to explore the needs of trainees and how those could be incorporated into XR training products for surgery, these findings were immersion through mechanical feedback, communication, dexterity and fatigue training, complex tool usage, and preoperative virtual planning and mapping. Some of these findings already had solutions such as preoperative VR and AR headsets that used software solutions to help surgeons navigate and plan procedures. While surgical trainees can learn new procedures in the operating theatre under supervision, they do have access to immediate convenient training with lower consequences for failure, this gap in training education is where the XR technologies could be applied and what was investigated with in the discussion, design implications, and concept phase.

While there is no replacement for real experience during operations this opportunity could help push the medical education field not only in surgery but other medical education forward into the future. The learning improvements found in the literature are a good sign that research in this area should be continued because of its potential future.

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Appendices

Appendix A: Expert Interview notes

Interview notes

Introduction

Trained as an oral and maxillofacial surgeon originally, (mouth face jaws and neck), dentistry and medicine, combined 9-10 years post graduate surgical training, practicing for 15 years, specializes in head neck surgery and reconstructive surgery.

Biopsy of cancer for example (15-20 min),

also managing that cancer which might include tracheostomy (breathing tube), removal of part of part face, jaw, lymph glands, reconstruction of their face using tissue from other parts of the body.(9-10 hours)

Biopsy super quick preparation, quickly sit and talk to patient about medication etc…

Operation hours of prep teams, groups of people, modelling, virtual surgical planning,

What the surgeon wants from this project

Current teaching methods, apprenticeship, Watch videos online, etc…

Potentially expanded to planning, medical imaging, ct scans/ mri, review operating theatre setup and interaction with nursing and junior medical staff, incorporate a textbook for following steps during observation, if you can review rare procedures that would be good

We are keen to hear about your experience in prolonged surgery – can you describe what you experience?

Prior to surgery what do you do? What sort of preparation and how long?

Assuming preparation is done, visit patient in holding bay, make sure they have no final questions, final checks, consent forms, patient goes to operating room, final checks to prevent mistakes ensure that patient, staff, consent form, and equipment are all in agreement.

For cancer patients they are reviewed in a multidisciplinary team meeting (not in operating theatre) discuss treatment plan

For jaw reconstruction, planning will involve modelling, and or virtual surgical planning, prebend surgical plates etc…

When he was younger he would read through the surgical procedure, as a trainee he would have written down key points of the procedure, review the anatomy of the part of the body if you haven't done an operation there in a while,

What are the things you focus on?

Staying focused for 8-9 hours, not physically exhausted but mentally exhausted, if you lose concentration that is when you make mistakes or deviate from your plan

If your planning an operation make a good plan and stick to it

Bad outcomes come from bad plans or changed plans

Focuses on steps, such as breathing tube>neck dissection, lymph gland removal>tumour removal, graft harvest>graft inset

Focus on those steps, try to keep the whole thing running by communicating with anaesthetic staff and nursing staff so they can prepare

What feelings might you experience and how/when do they change?

Not to many feelings, be an emotionless robot

Occasionally you perform procedures that you think will have poor outcome before you begin, feels like a waste of time and is potentially damaging to the patient

When its finished feel relieved

What are the relationships within the surgical room can you describe how communication occurs etc.

Surgeon 1 or 2, trainee, junior doctors,

Surgeons perform procedure and teach trainee and junior doctors perform minor parts of surgery

Nursing team, responsible for equipment and safety, surgical counting

Anaesthetic team, Anaesthetic doctor, anaesthetic trainee, anaesthetic technician

Communication starts with planning and booking, during the operation if you need something you don't have, and communicate about the next step obtain equipment and remove unnecessary equipment

What tools do you work with, over time in surgery does the way you work with the tools/implements change? Do they feel different? Or due to fatigue do you experience pain, discomfort or need to adjust how you use them?

Power tools, drills, saws, lighting, so many

I don't feel fatigue or pain just in back when bending over while supervising not very ergonomically set up

Not physically taxing, just stiff and a bit sore

Rarely get cramps in hand, typically in microsurgery

In your experience what are the affordances of the digital twin?

How can you replicate that experience, depending on who your trying to teach, teaching a high school student is different from a trainee, most people training for surgery have had an operating room experience before and are just there to learn how to do the operation, learn technical steps of surgery, planning, error avoidance, corelating that with imaging or planning

How do you feel the current fidelity of the digital twin compares to your real-life experiences?

Relationships

Tools

Sensation

What would you like to see developed/what are the opportunities for further development/what might be missing in current training systems?

Trainee will look at operation your going to do read about it watch a video, show up, supervisor will demonstrate, then they will do it, eventually he lets them do it on their own.

The information is not in one place, series of steps a range of potential complications

Aim is to skip the demonstration and expand it to a demonstration with planning interact with planning go through a range of problems /situations and how to deal with it.

For ID students how might you capture that information, incorporate that information with all the planning that might go on, and we should know how to tie the rest together

Question time

During training in the digital twin would it be beneficial for it to have other people training with you?

Useful, communication helps speed up a procedure but not critical to learning. I imagine that it would be very complicated. Could be done with nursing students or any number of members of an operating room team.

For the whole experience you seem focused on observing or understanding the procedure would you like a simulation style situation?

He said his knowledge on this is limited but imagines that it would be challenging to develop feedback, practicing would be better than watching, good because consequences are virtual. If it can be set up with some tactile feedback, you would have to look at the instruments used.

Can we look at a list of most used tools?

An equipment list will be sent to you

Issues with cadavers, colour, no bleeding, tissue texture because of no blood and preservation techniques.

Good for learning steps anatomy and part of the procedure but it is not the same experience.

End of time

Appendix B: Survey results

Page 1: Study Consent (Progress 0 - 40%)

Q1

What is your specialty in the medical field?

Student

Q2

Are you currently in training or have you completed your training?

Currently in Training

Q3

What training methods were used for surgery during your education?

Lots of placement hours, workshops for skill such as suturing, hand ties

Q4

What is your most common procedure? if still in training which procedures have you observed or taken part in? (for either of these indicate the time length of the procedure)

skin excisions- varied time

Page 2: Progress 40 - 70%

Q5

Do you experience fatigue while preparing, during, and/or post-surgery?

Yes, during surgery

Q6

If you answered Yes to the last question, please provide details of the fatigue (i.e. physical (location of strain and cause), mental, emotional, etc.)

Physical- neck pain from flexion

Q7

Which tools during your procedure require the most practice or are difficult to use?

Laparascopic camera and tools

Page 3: Progress 70 - 100%

Q8

Do you ever struggle to remember the steps in a procedure?

No

Q9

How easy was it to learn to communicate with your team during an operation when training?

Neither easy nor difficult

Q10

What is the worst aspect of surgery for you?

The sterile field

Appendix C: List of tooling

MAXILLOFACIAL HEAD AND NECK TRAY

RBWH CHECKLIST **WEIGHT 4.294kgs** **EXPIRY DATE:**

LOCATION: FND5

Product RBWHT0274 **Tray Size** Green Rectangular Large and Green Rectangular X Small

Serial no.

Customer LEVEL 4 OR **Wrap Size** K121 **Unit**

Steriliser Group STEAM ALL **Packed by:**

Name	Supplier	Count	Total SPC	1st Count	2nd Count	3rd Count	Final Count
Instrument Pin 1							
Pin Instrument		1					
Forceps Sponge Holding Foerster 241mm		2					
Clip Ball and Socket Towel		6					
	Items:	9					
Instrument Pin 1 Scissors							
Scissors Mayo Straight 140mm	BC544R	1					
Scissors Metzenbaum Straight Black Handle 145mm		2					
Scissors Reynolds Tenotomy 150mm		2					
Scissors Metzenbaum Curved 180mm	BC606R / BC265R	1					
Scissors Metzenbaum Curved 145mm		1					
Scissors Mayo Curved Black Handle 170mm		1					
	Items:	8					
Instrument Pin 1 Needle Holder							
Needle Holder Mayo Hegar 130mm	BM012R	1					
Needle Holder Mayo Hegar Fine 145mm		1					
Needle Holder Mayo Hegar 160mm		2					
	Items:	4					
Instrument Pin 2							
Pin Instrument		1					
Forceps Artery Mosquito Curved 120mm		10					
Forceps Artery Crile Curved 140mm		10					
Forceps Artery Right Angle 140mm		1					
Forceps Artery Harrison Cripps Curved 175mm	BH337R	2					
Clamp Tissue Kocher Straight 200mm		1					
Clamp Tissue Kocher Curved 180mm		1					
Clamp Tissue Debakey Angle 125mm		2					
Forceps Tissue Allis 155mm		2					
Twister Wire 175mm		4					
Cutter Wire 160mm		2					
	Items:	36					
Forceps Dissecting Plain 200mm		1					

MAXILLOFACIAL HEAD AND NECK TRAY

Forceps Dissecting McIndoe Plain 150mm		1						
Forceps Dissecting Debakey 150mm		2						
Forceps Dissecting Gillies 150mm	BD660R / Inka 12144.15	2						
Forceps Dissecting Adson Toothed 120mm	BD511R	2						
	Items:	**8**						
X Small Autoplas Tray Scalpel Handle								
Handle Scalpel Bard Parker No. 5 160mm		2						
Handle Scalpel Bard Parker No. 4 135mm		2						
Handle Scalpel B3 Barron	BB068R	2						
	Items:	**6**						
X Small Autoplas Tray								
Retractor HH Skin Hook S 180mm		2						
Retractor HH Kilner Rake 160mm		2						
Clamp Vasc Micro Bulldog Diethrich	20-0311	2						
	Items:	**6**						
X Small Autoplas Tray Miscellaneous								
Retractor HH Cricoid 160mm		1						
Dilator Tracheal Diethrich		1						
	Items:	**2**						
X Small Autoplas Tray Periosteal Elevators								
Elevator Mitchell Trimmer 165mm		1						
Director Ligature 185mm		1						
Elevator Freer's Knife 180mm		1						
Elevator Periosteal Molts 185mm		1						
Elevator Periosteal Howarth 210mm		2						
Elevator Modified Freer 210mm		1						
	Items:	**7**						
Retractor HH Langenbeck 220x20mm		2						
Retractor HH Langenbeck 225x55mm		2						
Retractor HH Langenbeck 220x85mm		2						
Retractor HH Obwegester Ramus 220x60mm		1						
Retractor HH Volk. Rake 6 Prong Sharp 200mm		2						
	Items:	**9**						
Handle Sucker								
▲Handle Sucker Andrew Pynchon 241mm		1						
▲Handle Sucker Frazier 190mm 10fg		1						
▲Handle Sucker Frazier 175mm 12fg		1						
▲Handle Sucker Debakey-Adson 205mm		1						

MAXILLOFACIAL HEAD AND NECK TRAY

Stylet Frazier Sucker		1						
Items:		5						
Metal Tray Tag								
Metal Tray Tag With Barcode		1						
Items:		1						
Total number of Items:		101						

Legend:	Circulating Nurse Initial:
◉ - Insulated RMD	Instrument Nurse Initial:
▲ - RMD REQUIRES ADDITIONAL ATTENTION! Cannulated and/or Multi-part	OR # & Date:
*** Disassemble and flush RMD before returning for reprocessing***	Comments:
Patients UR ID Label:	

MAXILLOFACIAL OSTEOTOMY TRAY

RBWH CHECKLIST **WEIGHT 2.125kgs** **EXPIRY DATE:**

LOCATION: FNC4

Product RBWHT0296 **Tray Size** Green Square Large

Serial no.

Customer LEVEL 4 OR **Wrap Size** K101 **Unit**

Steriliser Group STEAM ALL **Packed by:**

Name	Supplier	Count	Total SPC	1st Count	2nd Count	3rd Count	Final Count
Retractor HH Medial Channel 220mm		1					
Retractor HH Lateral Channel 170mm		1					
Retractor HH Langenbeck Forked 225mm		1					
Retractor HH Langenbeck Upper 220x40mm		1					
Retractor HH Langenbeck Upper 220x60mm		1					
Retractor HH Langenbeck Upper 220x70mm		1					
Retractor HH Johnson 130mm		2					
Osteotome Volmer 155mm		1					
Osteotome Pterygoid 210mm		1					
Osteotome Curved 180x4mm		1					
Osteotome Straight 180x4mm		1					
Osteotome Rounded 180x4mm		1					
Osteotome Obwegeser Modified Single Guarded 190mm		1					
Osteotome Wood Harold 10mm		1					
Osteotome Nasal Lateral Straight 8x200mm	01-04360	1					
Osteotome Obweseger Nasal Septum 6x185mm	01-17855	1					
Elevator Modified Freer 210mm		1					
Retractor HH Ramus Vertical		1					
Retractor HH Ramus Medial Left	01-01380	1					
Retractor HH Ramus Medial Right	01-01370	1					
	Items:	21					
Metal Tray Tag							
Metal Tray Tag With Barcode		1					
	Items:	1					
	Total number of Items:	22					

Legend: Circulating Nurse Initial:

◉ - Insulated RMD Instrument Nurse Initial:

▲ - RMD REQUIRES ADDITIONAL ATTENTION! Cannulated and/or Multi-part OR # & Date:

*** Disassemble and flush RMD before returning for reprocessing*** Comments:

Patients UR ID Label:

MAXILLOFACIAL RETRACTOR TRAY

RBWH CHECKLIST **WEIGHT 1.457kgs** **EXPIRY DATE:** **LOCATION: FNC2**

Product RBWHT0301 **Tray Size** Green Square Large
Serial no.
Customer LEVEL 4 OR **Wrap Size** K101 **Unit**
Steriliser Group STEAM ALL **Packed by:**

Name	Supplier	Count	Total SPC	1st Count	2nd Count	3rd Count	Final Count
Retractors							
Retractor HH Tongue Blade Wide		1					
Retractor HH Minnesota		1					
Depressor Tongue Lachs		1					
Retractor HH Wire Cheek Sternberg		1					
Retractor HH Malleable 7mm		1					
Retractor HH Malleable 10mm SILVER		1					
Retractor HH Malleable 15mm		1					
Retractor HH Malleable 20mm		1					
Retractor HH Malleable 23mm		1					
Retractor HH Langenbeck 215x22mm		2					
Retractor HH Langenbeck 215x45mm		2					
	Items:	13					
Bone Nibbler Dbl Act 180mm		1					
Mallet 190mm		1					
Prop Mouth S With Chain		1					
Prop Mouth M With Chain		1					
Prop Mouth L With Chain		1					
	Items:	5					
Metal Tray Tag							
Metal Tray Tag With Barcode		1					
	Items:	1					
	Total number of Items:	19					

Legend:	Circulating Nurse Initial:
◉ - Insulated RMD	Instrument Nurse Initial:
▲ - RMD REQUIRES ADDITIONAL ATTENTION! Cannulated and/or Multi-part	OR # & Date:
*** Disassemble and flush RMD before returning for reprocessing***	Comments:
Patients UR ID Label:	