COMPARING THE EFFECTS OF TRADITIONAL, VR, AND CUSTOM-MADE INPUT DEVICES ON USABILITY, COGNITIVE LOAD, AND PRESENCE ON VIRTUAL LAPAROSCOPIC TASKS

INVESTIGATING THE POTENTIAL OF LOW-COST, CONSUMER-LEVEL VR TECHNOLOGY FOR MEDICAL SIMULATION AND TRAINING THROUGH LAPAROSCOPY SIMULATION

BY

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The above committee determined that the thesis is acceptable in form and content and that a satisfactory knowledge of the field covered by the thesis was demonstrated by the candidate during an oral examination. A signed copy of the Certificate of Approval is available from the School of Graduate and Postdoctoral Studies.

ABSTRACT

Digital simulators are essential in medical education, allowing to train procedures that are otherwise impossible or difficult to recreate in real life. Laparoscopy training, a procedure that allows a surgeon to access the inside of the abdomen using a laparoscope, has been based on videos, lectures, advanced computer simulators using robotics and computer simulation, cost-effective box trainers, and most recently, computer applications and Virtual Reality (VR). However, computer simulators rely on controllers, keyboards, mice, and gamepads that lack adequate laparoscope representation. This thesis investigates how keyboard/mouse, VR controller, game controller, and a custom-made 3D printed controller in the form of a retrofitted laparoscope integrated with a womb impact usability, cognitive load, presence, stress, and performance when performing fundamental laparoscopic tasks focused on aiming and lasering. Preliminary results indicate that the use of user interfaces with higher representation positively influences presence while improving usability and increasing cognitive load.

KEYWORDS: Virtual Reality, Laparoscopy, Simulation, Immersion, Input

AUTHOR'S DECLARATION

I hereby declare that this thesis consists of original work of which I have authored. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Bill Ko September 29 2023

STATEMENT OF CONTRIBUTION

The work described in Chapters 3 and 4 was performed at the GAMER research lab at Ontario Tech University in Oshawa, Ontario. My contribution to this research involved the conception and development of the VR simulator for laparoscopy, designing the study, recruiting participants, collecting and analyzing data, and contributing to the writing and review of the manuscript. More specifically, I was responsible for developing the virtual environment, programming task scenarios, and designing the user study to explore the effectiveness of different input devices on the VR simulation. None of the input devices used were developed by me, but I assisted in a part of the development of the makerspace controller. Additionally, I conducted a statistical analysis of the results and presented my findings to the research team in writing. My contributions helped drive the research outcomes and contributed to our understanding of the potential of low-cost, consumer-level VR technology in medical training through laparoscopy simulation. I hereby certify that I am the sole author of this thesis and that no part of this thesis has been published or submitted for publication. I have used standard referencing practices to acknowledge ideas, research techniques, or other materials that belong to others. Furthermore, I hereby certify that I am the sole source of the creative works and/or inventive knowledge described in this thesis.

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ACRONYMS

Abbreviation	**Full Form**
VR	Virtual Reality
IVR	Immersive Virtual Reality
CPR	Cardiopulmonary Resuscitation
MIS	Minimally Invasive Surgery
DIY	Do It Yourself
HMD	Head-Mounted Display
USD	United States Dollar
3DUI	3D User Interface
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses

Continued on the next page

Abbreviation	Full Form
VIORS	Virtual Immersive Operating Room Simulator
MERSQI	Medical Education Research Study Quality Instrument
MAPs	Movement Analysis Parameters
SOFA	Simulation Open Framework Architecture
SLP	Selective Laser Photocoagulation
TTTS	Twin-to-Twin Transfusion Syndrome
HDRP	High Definition Render Pipeline
URP	Universal Render Pipeline
MRTK	Mixed Reality Toolkit
SDK	Software Development Kit
CSV	Comma-Separated Values
BPM	Beats Per Minute
SUS	System Usability Scale
NASA TLX	NASA Task Load Index
VRPQ	Virtual Reality Presence Questionnaire
ANOVA	Analysis of Variance
HR	Heart Rate

1

INTRODUCTION

1.1 OVERVIEW

Laparoscopy is a minimally invasive medical procedure that allows a surgeon to access the inside of the abdomen and pelvis of a patient. Given its minimally invasive nature, the procedure does not require large incisions on the skin, resulting in a faster recovery time and fewer postoperative complications, in addition to fewer life-threatening risks [9]. This is a common procedure with several variations, including cholecystectomy, nephrectomy, adrenalectomy, bariatric surgery, anti-reflux, colectomy, appendectomy, hernia repair, and hysterectomy, having an estimated 14 million laparoscopy procedures performed worldwide over 2020 alone. [66].

Developing the motor skills necessary for the use of laparoscopic equipment is necessary for laparoscopy surgery. These abilities include the use of tools such as laparoscopic forceps to move tissue or activate a laser (by pressing a pedal) [5]. However, such movements must be done with a high amount of stability and precision of hand movement to avoid damaging surrounding tissue. Due to the complexity of the techniques involved, as well as the risk to patients in the event of an error during the procedure, laparoscopic training has historically relied on physical simulators such as manikins or training dummies [56].

1.1.1 *Laparoscopic Training*

Traditional methods of medical education for laparoscopy can involve hands-on practical training as well as classroom-style lectures. Classroom-style lecture content involves the usage of lectures and videos in a didactic form to provide information to learners. The hands-on component of laparoscopic training can occur in a variety of methods, including an apprentice shadowing a surgeon during a live operation, practicing on simulation dummies such as manikins, to simulation systems such as box trainers or commercial VR simulation systems. Each of these practice methods has its own advantages and disadvantages, such as price range variances, fidelity, accessibility, and ease of use.

1.1.2 *Simulation*

In the context of learning, simulation is defined as the use of fabricated models to simulate a real-world scenario for the purposes of hands-on practice or training [41]. Simulation-based learning allows learners to practice real-world scenarios otherwise impossible in the classroom, without the associated risks or limitations associated with harm to the patient or the practitioner, access to specialized equipment, exposure to rare medical conditions or procedures that would be present in a live scenario [73]. Simulation-based learning has been used since the 1960s when physical mannequins were used to practice administering anesthetics. The initial cost of simulation equipment was quite high due to the high cost of producing accurate human body models. Simulation in the context of training can be defined as the use of fabricated models to imitate a real-world scenario for the purposes of hands-on practice or training [41].

Simulators for medical training have high costs ranging from thousands to tens of thousands of dollars. [42] However, with technological advancements progressing rapidly in the digital age, both the prices of physical simulators (e.g. training manikins) and the rise of cheaper digital simulators (such as the consumer-level prototype examples explored in Chapter 2), have made simulation-based learning increasingly accessible. Simulation-based learning now includes various methods of imitating real-world use cases, including but not limited to digitally recreated environments using Virtual Reality (VR) and lower-budget skill trainers. [62]

Recent developments in VR are enabling novel training methods in which immersion and interactions can further support learning and skill development [67]. However, contrary to high-end VR simulators integrating haptic devices with advanced robotics [27], consumer-level VR frequently uses controllers, hand tracking, and custom-made specialized user interfaces employing 3D printing to replicate laparoscopic interactions. As an illustration, the CollaVRLap simulator [13] utilizes immersive VR with HTC Vive controllers for gestural interactions with its virtual environment, which functions as virtual hands. Similarly, the VR-CPR training application uses more general positioning tracking of the user's hands within the VR space to train for cardiopulmonary resuscitation (CPR) procedures [1].

Current commercial simulators will often use custom hardware built specifically for the purpose of running the simulation application. For example, the LapSim and LapVR simulation systems both make use of custom hardware with user controls that emulate the manipulation of a laparoscope. These controls have handles that match what a user would be gripping during a live laparoscopic operation, which then allows for the user to match those movements during simulation operation. Other commercial simulators, such as the LapMentor, can be operated using game controllers, which can improve ease of use for trainees aiming to familiarize themselves with the operation procedures while using an input scheme they are more proficient in handling.

The selection of VR input devices has become a popular research topic in medical simulation, given that, while all of these user interface devices allow users to perform the same tasks, the input methods are different from the medical instruments used in real life. Due to the various input devices used in VR, the development of transferable skills is a major concern, since VR controllers, keyboard and mouse, and hand tracking lack proper instrument representation and correlating maneuverability [21]. To further emphasize this point, consumer-level VR currently requires the usage of a controller with five buttons (e.g., trigger, grip, A, B, and home) and a clickable thumbstick that supports haptic input in the form of vibration. Such a controller is different from a laparoscope in both the availability of tactile inputs such as buttons, and how the device itself is held and handled.

1.1.3 *Consumer VR*

The COVID-19 pandemic has had a significant impact on the landscape of medical education, imposing sudden and drastic restrictions on access to research laboratories and other in-person medical facilities to gain practice and training experience. The need for remote and immersive learning options as these restrictions were imposed has accelerated the adoption of VR for educational purposes. As medical institutions sought alternative methods of teaching and training, VR provided a safe and effective way to deliver medical education remotely. Medical students and professionals made use of VR technologies readily available at home to continue practicing in immersive clinical situations without the risk of in-person contact. These at-home VR technologies included recreational and gaming-level VR systems available at retail. As a result, the adoption of VR in medical curricula was significantly accelerated during the pandemic and has continued since. As this technological transition continues, it becomes imperative to explore the impact of input devices on immersion within the VR context. Surgical procedures that require specialized tools and training, such as laparoscopy, remain a gap in the research on how immersion can affect the efficacy of these educational aids. Understanding how devices such as keyboards, mice, gamepads, and other possible hardware options contribute to the immersive quality of virtual surgical procedures is essential to optimize the educational potential of VR in the medical domain. By investigating the role of input devices, educators and researchers can refine the design and implementation of VR-based medical education, ensuring that the immersive experiences provided align seamlessly with the evolving needs of learners in the post-pandemic era.

1.2 PROBLEM STATEMENT

VR technology is characterized by one-size-fits-all hardware, and while the use of VR simulators increased during the COVID-19 pandemic, continuous efforts are being made to improve accessibility [48]. Even with accessibility measures in place, including height, reach, and locomotion customization, some people are unable to use VR due to stereo-depth blindness (the inability to sense depth) and vertigo, which can cause simulator sickness. These issues, which are the result of experiencing VR, extend beyond the recreational space to medical education. As a result, non-immersive VR (VR through a conventional monitor without the requirement of a headset) has become a well-known area of development and study to determine the effects of immersion and user input devices when conducting virtual training tasks [17]. For example, simulation scenarios that focus on operational procedure, such as radiotherapy device operation, retain non-immersive input methods[54].

The current adoption of VR technologies for medical simulation provides virtual hands-on experiential learning that does not rely on high-end specialized equipment available in laboratories [57]. The most common method of interacting with virtual environments is through the use of VR controllers. Despite a growing body of research on 3D user interfaces (3DUI) and human factors for digital interactions [50], there is still a gap in understanding how different user interfaces impact user experience in terms of usability, immersion, task completion and performance, which can help establish best practice to take advantage of the shortcomings of any given user input device when using consumer-level VR headsets for simulated laparoscopic procedures. This gap is exacerbated by the continual introduction of new input devices into the consumer market without a comprehensive assessment of their impact on the user experience for medical simulation. The lack of a proper understanding of how different user input devices impact the user experience carries a risk of producing VR environments that are not engaging and helpful for skill development. Although there is a growing body of research on the general effectiveness of VR in medical education, specific investigations into the nuanced impact of different input devices on user experience in simulated laparoscopic procedures are relatively limited. Many studies may focus on the overall efficacy of VR without delving into the fine-grained details of user interface interactions, as seen in the literature review in Chapter 2.

Understanding the effects of various user input devices is critical, as the learning curve for laparoscopic procedures versus open surgery is steeper [53], with additional difficulties in motor control that are not present in open surgery. For example, the limited field of view of a laparoscope can hinder a surgeon who must operate with limited visibility of the surgical field. The visual output from the laparoscope display, being mounted on the opposite side of the incision point from where the fetoscope is inserted, would be effectively mirrored in the direction of the operator's hand movements. Without practice, obstacles such as these can cause disruption to the operation procedure, so practical experience is a key factor in carrying out MIS surgeries safely and efficiently. Furthermore, existing studies predominantly center on learning outcomes in VR simulation. The current body of research tends to prioritize learning aspects rather than delving into the nuanced realm of task representation or human factors such as immersion, which significantly influence the cultivation of transferable skills. This disparity becomes apparent when contrasting with research conducted on high-end laparoscopy simulators, where a more comprehensive understanding of the impact of various user interfaces on skill development, beyond mere learning, has been demonstrated [62].

1.3 THESIS STATEMENT

Due to increased adoption rates in recent years as a result of rapid technological improvements and reduced pricing, consumer-level VR technology has the potential to continue revolutionizing medical simulation and training. However, its impact on the user experience when using various user input devices that are not representative of a laparoscope is not yet fully understood. This thesis focuses on investigating the impact and differences of using a keyboard and mouse, game controller, VR controller, and a custom-made user interface representing a laparoscope on a user's sense of immersion when performing aiming and lasering tasks in an immersive VR laparoscopic simulator. The research question that this project aims to answer is "How do different input devices affect usability, performance, and immersion in a VR simulation for aim and laser tasks?" While task performance is important to assess the viability of educational aids, it is not the only aspect that can affect the user's experience. Immersion and usability can be significant factors in impacting whether a learning experience is engaging to a user [71], which then can further impact a user's desire to interact and make use of the simulation system. The associated hypothesis with this research question is that "Input devices that better replicate the task being performed will positively affect usability, cognitive load, performance, and immersion more than a non-immersive input device."

1.4 THESIS SUMMARY

In Chapter 2, a literature review is presented using PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses). This chapter comprehensively analyzes and synthesizes existing research, focusing on the key aspects of laparoscopy, simulation, and virtual reality. The PRISMA framework will guide the systematic search, selection and evaluation of relevant scholarly articles, ensuring a digestible but clear approach to the review process, while identifying key themes, trends, and gaps in the existing literature.

In Chapter 3, the research methods and materials employed in the study are presented. This chapter elaborates on the development process behind the VR simulator application, as well as the methodologies behind the study design and data collection processes. The goal of detailing these processes is to ensure that the research can be replicated by other scholars. Any ethical considerations and measures taken to address potential biases will also be discussed.

Chapter 4 presents the results of the study and engages in a comprehensive discussion of these findings. The results section presents the data collected through the methodologies listed in Chapter 3 in a concise and readable form, using variance analyses, graphs, and summaries. The discussion will involve a critical analysis of the results in relation to the research objectives and the existing literature reviewed in Chapter 2. Conclusions, limitations, and avenues for further research will be highlighted, demonstrating a deep understanding of the subject matter and its broader implications.

2 RELATED WORK

2.1 OVERVIEW

The adoption of VR technologies in medical simulation and training has increased in recent years thanks to consumer-level solutions. Broad access to VR has made it possible to design, develop, and deploy solutions that were not possible due to costs, portability, and performance [2]. Additionally, there has been an increasing interest in exploring the psychological and physiological effects of VR on users to improve the effectiveness and impact of VR solutions. In this chapter, a review of the existing literature on immersive VR technology, with a focus on its use in simulation for immersive medical training pertaining to laparoscopy is presented.

2.2 BACKGROUND

Educational simulators for medical training allow a wide variety of applications for learning, practicing, and performing surgical procedures [73]. Simulators, both physical and digital, allow students and trainees to experience procedures that are difficult or impossible to practice on cadavers, swine, or real patients [64]. The sophistication and cost of these simulators can vary greatly depending on their intended use cases, ranging from "box" simulators employing household objects to digital simulations using consumer-level VR technologies, to high-end commercial simulators such as LapSim laparoscopy simulators requiring specialized spaces, training, and maintenance to operate [25].

2.2.0.1 *Medical Simulators*

Simulators have become the gold standard in medical training [7]; however, their high costs have introduced entry-level barriers for many institutions in addition to their availability. For example, during the COVID-19 pandemic, several educational programs were forced to move to virtual synchronous and asynchronous teaching with little to no hands-on experience [18]. The COVID-19 pandemic incentivized further development and research of low-end simulators, often involving consumer-level and makerspace. Existing entry barriers motivated the exploration of creative solutions for practicing procedures with various degrees of visual, auditory, and tactile fidelity [80]. Results include the development of a low-fidelity simulator for minimally-invasive surgery (MIS) consisting of a laparoscope handle put through a hole cut into the top of a plastic box, allowing a user to practice guiding a laparoscope through a small orifice. These do-it-yourself (DIY) tier simulators, known as "box trainers," allow a user to readily practice hands-on movements of a method without requiring extensive equipment setup that may not be practicable outside of a classroom or research facility [12]. However, DIY simulators also present entry barriers associated with the availability of their components, space requirements, and reproducibility [12].

2.2.0.2 *Digital Simulators*

As a complement to traditional simulation methods, digital simulators have been on the rise even before VR became consumer-level. Early digital simulators included interactive 2D and 3D computer environments and multimedia applications [29]. Examples of early digital simulation include the MIST-VR, Endotower, and CELTS simulation systems [44]. Recently, the availability of consumer-level immersive technologies such as VR has become increasingly ubiquitous. A study by Ball et al. in 2020 indicated an adoption rate of VR devices of over 60% of participants surveyed [4]. This widespread adoption has allowed the development and adaptation of complementary tools for simulation training [14].

2.2.0.3 *Virtual Reality*

VR technologies provide visual, auditory, and tactile immersion that focuses on sensory stimuli that add realism. Within this context, immersion can be defined as how much sensory fidelity a system can provide a user, directly shown by the degree to which a user feels as if they are physically present in a virtual environment, thus causing presence [60]. VR technology uses three core features to enhance its user experience: i) stimulation of the user's senses, ii) the illusion of being present in the virtual space, and iii) the ability to interact with that virtual space.

Currently, VR installments are categorized as immersive and non-immersive. Immersive VR is where immersion is achieved by using a wearable display coupled with user input devices in the form of hand-held controllers or hand tracking [46]. Non-immersive VR uses regular computer monitors or displays without needing a head-mounted display (HMD) with user input devices that can include the keyboard, mouse, gamepads, and hand tracking, in some cases achieving depth and visual immersion through motion parallax [28]. It is worth noting that non-immersive VR is gaining momentum as it allows users who cannot perceive depth, who are prone to motion sickness, or who don't have access to VR equipment to access the VR simulation.

VR hardware capabilities are improving every year, with the most notorious advancements taking place in the visual domain (e.g., resolution, field of view) and portability (e.g., standalone headsets that work without requiring a VR-ready computer with inside-out tracking avoiding the need for external cameras). When combined with graphic processing capabilities, these advances enable high-quality computer graphics suitable for applications in training and education [81]. Table 2 shows the evolution and increases of visual fidelity and price reduction over the last 5 years. Furthermore, recent VR HMDs now feature facial, body, and eye tracking along with physiological sensors that allow further capture of unique user responses with the potential to improve the user experience [28].

Table 2: Comparison of consumer-level VR headsets. Source: [8]

Model (Year)	Resolution (px)	Field of View (degrees)	Cost (USD)
Samsung Odyssey+ (2018)	1440x1600	101	$499
Valve Index (2018)	1440x1600	107	$999
Oculus Quest (2019)	1440x1600	94	$399
HTC Vive Cosmos (2019)	1440x1700	97	$699
Pico Neo 2 (2019)	2048x2160	101	$699
HP Reverb G2 (2020)	2160x2160	98	$599
Oculus Quest 2 (2020)	1832x1920	89	$299
HTC Vive Flow(2021)	1600x1600	100	$499
Meta Quest Pro(2022)	1800x1920	106	$999
HTC Vive XR Elite(2023)	1920x1920	110	$1099
Meta Quest 3(2023)	2064x2208	97	$499

2.2.0.4 *Fidelity*

In the context of VR simulation for medical education, "fidelity" refers to the degree of accuracy and realism with which the virtual environment and scenarios replicate real-world medical situations and interactions. It includes the simulation's ability to accurately replicate the detail, realism, and authenticity of a virtual scenario. A simulation's level of fidelity can often directly correlate to how immersed the user is within the scenario.

Fidelity often involves multiple dimensions of interactivity with the virtual environment, including visual, auditory, tactile, and interactive aspects. High fidelity implies that the simulation can replicate the scenario on all these aspects to a high quality. Therefore, a high-fidelity simulation will feel authentic, increasing the level of immersion the user experiences. Visual fidelity can be achieved by building the virtual environment with as much visual detail as possible, using technology such as high-resolution displays and wider field-of-view in conjunction with detailed textures and lighting in the virtual scene.

Auditory fidelity can be delivered via reproducing realistic sounds and audio cues, both in the level of detail of the audio files themselves and in the way in which they are played to a user. Modern simulators can make use of 3D sound and spatial audio to further enhance this realism by changing the way sound is localized within the virtual environment.

Haptic fidelity aims to simulate a sense of touch and physical presence. Simulation tasks can be enhanced through the use of tactile feedback devices, such as haptic gloves or controllers, which provide users with sensations like pressure, texture, and resistance. This can enhance the user's sense of interaction with the virtual environment by delivering a physical response to events occurring within the virtual space.

2.2.0.5 *Input Devices*

As stated previously, visual immersion has progressed significantly. At the same time, the user input devices remain, for the most part, the same, presenting thumb sticks and various buttons to perform actions accompanied by vibrotactile haptics [65]. Currently, traditional user input devices, such as the mouse and keyboard, in addition to touch gestures for mobile devices, remain the primary input method in many computer-based simulators [65].

The current landscape of consumer-level VR technology in medical simulation has seen a strong focus on learning procedures and measuring user performance. For example, a 2021 study explores the effectiveness of an immersive VR simulation versus a traditional learning method on COVID hygiene, with a focus on the practical technique as the main metric. [6]. The adoption of VR in training has led to research and development focused on the development of psychomotor skills, which is a relevant area that can help gain a better understanding of how various user input devices impact task completion, immersion, usability, and knowledge transfer to use real-life instruments [38].

2.3 SYSTEMATIC REVIEW METHODS

The literature review was conducted following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) method to report findings related to the use of immersive virtual reality simulation for medical training within a laparoscopic context [70].

2.3.1 *Categorization*

A preliminary investigation into articles on VR simulators for laparoscopy performed through OntarioTech's implementation of the Omni academic search tool across 275 databases [77] did not produce a large enough sample of articles directly relevant to this thesis. To broaden the search bandwidth for relevance, the thesis's research question was separated into subject categories, which were defined as "Virtual reality, laparoscopy training, simulation, and immersion." Papers that involved at least three of the four categories were deemed relevant to be included. This allowed research that only shared partial overlap in subject matter to be deemed relevant for inclusion.

2.3.2 *Database Usage*

In addition to the Omni academic search tool, a total of seven databases were used to supplement the results. The Omni search tool was chosen as a primary search method because its aggregation of 275 databases allows for a wide breadth of results to be accessed, while the search engine automatically aids the search by removing duplicate entries across databases. The databases used were the following. Pubmed Central, IEEE Xplore Electronic Library, Sage Journals, and Springer Link. Search results dating beyond the past 6 years were deemed too old to be relevant and therefore discarded. Results that consisted of non-academic or informal literature such as books, online blog entries or product pages, as well as non-text-based mediums such as online videos, were also discarded.

2.3.3 *Screening and Selection*

The foremost results from the database search were manually screened for relevance according to the inclusion criteria based on categories previously defined in the Categorization section of this chapter. 23 studies were selected using the eligibility criteria listed above from the categorization subsection. The articles were then culled from this selected group if they did not have relevance to at least 2 of the listed categories. The remaining selected articles were then accessed and read in fulltext to determine potential contributions and points of relevance. Articles were compared with each other on points of relevance to determine contrasts and/or patterns. Data extraction was then carried out using a standardized table to collect relevant information from each study, including study design, participant characteristics, results and results, as shown in the Appendix 4 and Appendix 5. Appendix 4 contains reviews done by other authors, and Appendix 5 contains studies and prototype developments presented by other authors.

2.4 VR SIMULATION

Mao et al. [45] conducted a systematic review of the literature that examined the effectiveness of immersive virtual reality (iVR) for the acquisition of surgical skills in medical students, residents, and staff surgeons. The review used the Medical Education Research Study Quality Instrument (MERSQI) scoring tool [72] and the Cochrane methodology [10] as standardized evaluation systems to assess the quality of each article. The study found that while there is promising evidence for iVR simulators that effectively complement traditional surgical training, the quality of the evidence is limited. Most studies had small sample sizes and were conducted in single centers, limiting the generalizability of the findings. Furthermore, the high heterogeneity in the simulators, training specifications, and assessment tools also limited the strength of the conclusions that could be drawn.

A major drawback of traditional and high-end simulation systems was made apparent during the COVID-19 pandemic when classes and laboratories moved to online synchronous settings in order to comply with physical distancing mandates [63]. Such restrictions led to the development and adoption of VR as a solution that provides immersion that is not possible with traditional 2D media and 3D computer graphics on a screen [4]. Ball et al. examined the uses and gratifications of VR during the pandemic, including device ownership and variability, and investigated the importance of social interactivity within VR to increase adoption intentions. This was done by a survey of 298 Amazon Turk users in the fall of 2020. The article highlights the potential of VR to mitigate the challenges caused by the pandemic and identifies areas for future research, such as additional exploration of potential uses of VR and examination of VR uses with more nuance using qualitative research methods.

Kantamaneni et al. (2021) provided an updated review of the literature related to the efficacy of VR simulators for laparoscopy training [37]. This article presents a traditional review of relevant studies and academic writings over the past ten years. The study methodology involved conducting a literature review in three databases, including MEDLINE, EMBASE, and Cochrane Library. The authors used MeSH terms to search for published articles, filtering for recency and relevancy. The significant results of the review showed that VR simulators are an effective training methodology for laparoscopy training, with promising results. Participants trained using VR simulators were found to perform surgical tasks accurately, faster, and with improved confidence and multitasking ability during surgery. Instructor feedback and deliberate practice of trainees as supplementary factors, along with the early introduction of haptics in VR, resulted in the most effective outcomes of VR training. The authors also compared box trainers with VR trainers, since they are cheaper training aids, and concluded that although box trainers could act as a cheaper alternative to VR training, more research is needed to determine conclusively whether they could provide similar results.

The systematic review by Pallavicini et al. [55] of VR applications geared toward healthcare during the COVID-19 pandemic provided a summary of the state of VR adoption for healthcare purposes according to the PRISMA guidelines. The review concludes that VR has the potential to improve the accessibility and effectiveness of remote medical education and training. However, the authors also note that the quality of the evidence remains limited, particularly due to the heterogeneity of the included studies and the lack of standardized outcome measures. Furthermore, the authors advise that further research will be needed to explore the long-term impact of VR on medical education and training.

2.4.1 *Understanding VR simulation*

Multiple studies [32], [62], [58] have been conducted using commercial VR simulators such as LapSim or RobotiX Mentor, as well as prototypes built using makerspace components, to determine the face validity of digitally recreated virtual environments for training purposes. Face and construct validity evaluations, such as that conducted by Perez-Escamirosa et al. [62], compare these simulators with other alternative training methods. A key goal of these studies is to determine whether such simulators were effective tools for learning within the scenarios that were emulated virtually. The performance of participants for a simulated task is evaluated before and after experiences with these simulators, determining whether training on these simulators has an effect on the participant's performance.

Hovgaard et al. investigated the face validity of a VR robotic surgery through a study using the "Guided Vaginal Cuff Closure" procedure [32]. The study recruited 11 novice gynecological surgeons without prior experience with robotic surgery and 11 experienced gynecological robotic surgeons with more than 30 robotic procedures completed. Participants completed the training module 'Guided Vaginal Cuff Closure' six times each. The simulator tracked metrics such as unnecessary needle punctures, time elapsed with instruments out of camera view, and more generic metrics such as time elapsed. The study investigated the validity evidence for 18 preselected simulator metrics. The researchers used Cronbach's alpha to assess internal consistency. Using the contrasting groups' method, a pass/fail standard of 75/100 was established. The mean composite score of experienced surgeons for all six repetitions was significantly better than that of novice surgeons, confirming the validity. Four novice surgeons passed this standard (false positives) and three experienced surgeons failed (false negatives).

Perez-Escamirosa et al. (2020) [62] present the validation of a virtual immersive operating room simulator (VIORS) for procedural training of laparoscopic motor skills. The simulator uses an Oculus Rift VR headset paired with modified VR hand controllers, altering the user's hand positions to emulate handling real laparoscopic instruments. 45 participants including surgeons, residents, and medical students were recruited for the validity study. The participants were categorized into three groups based on their level of expertise: 27 novices, 13 intermediates, and 5 experts. Qualitative data was collected with a questionnaire on immersion, realism, and general experience using the VIORS system. Instrument movement data was recorded and analyzed using 13 movement analysis parameters (MAP), and questionnaire data was evaluated using NASA-TLX. Participants gave positive feedback on the realism and procedural training capabilities of VIORS, and the results showed that the simulator was effective in distinguishing between participants with varying skill levels. The construct validity of the simulator was demonstrated through statistically significant differences found in nine MAPs. In addition, the participants experienced moderate mental workload during the laparoscopic cholecystectomy procedure.

2.5 LAPAROSCOPY SIMULATION

Minimally Invasive Surgery (MIS) or laparoscopy focuses on procedures characterized by the least amount of damage, pain, and risk of infection to achieve fast recovery [83]. Training for laparoscopic procedures is critical to prevent errors from arising during procedures that can be dangerous to the patient, and has traditionally been done with box trainer systems [39]. The articles reviewed in this section further detail examples of digital simulation pertaining laparoscopy. The research in this domain integrates haptic interfaces with MIS instruments add-ons aiming at maintaining the same hand positions and physical movements as real as possible.

2.5.1 *High-end MIS Simulators*

MIS surgery simulation in medical training often makes use of the latest in technological development to maximize the realism of the procedure experience and the immersion of the user. High-end simulation systems that use such cutting-edge systems are often proprietary to the manufacturers, relying on both software and hardware specifically built for the simulator, as opposed to mid- and low-end simulators that will use consumer-level or DIY components. Examples of high-end simulators, such as the LapSim laparoscopic simulator system, will make use of advanced technological features that enable realistic and immersive training scenarios for surgical learners [20]. High-end commercial simulators may offer haptic feedback, which provide a realistic sense of touch and force feedback to the user, enhancing the simulation's realism. These simulators also allow for customized training, as users can adjust the simulator's task difficulty and parameters to meet their specific training needs and skill levels.

Hagelsteen et al. (2017) conducted a study to investigate the efficacy of VR technology in the use of laparoscopic skill acquisition [26]. To do this, a single-blinded trial was conducted with a group of 20 participants who were all regarded novices in laparoscopy. Participants were selected and evenly distributed among a test and control group according to previous experience in laparoscopic surgery, as well as other background factors such as familiarity with video games. The trial was carried out with the LapSim VR simulator in conjunction with the Simball box trainer. Participants underwent two sets of laparoscopic tasks on the Simball trainer, with the non-control group undergoing a practice course on the Lapsim simulator in between. The group that practiced on the LapSim had a faster learning rate compared to the control group, with an overall faster completion time on three of the four Simball tasks after the training course. Although this study only used a fairly small sample size and placed a large emphasis on completion time, which can easily be influenced by external factors, it still highlights the promising potential of VR technology in educational settings.

Peral-Boiza et al. (2019) developed a VR screenspace simulator for urologic surgery that uses two 3D mice to control a virtual ureterorenoscope, to perform virtual surgery in the urinary tract [59]. A 3D mouse consists of a puck-shaped controller that can be moved along six axes: up and down, left and right, forward and backward, as well as rotational movements around these axes. Extensive pseudocode for determining the flexibility of the endoscope were detailed to highlight the physics systems used to emulate the flexibility of a real uterorenoscope, and then implemented in OpenGL for a digital visualization of the instrument's insertion. 3D models of the urinary tract were generated from CT scan slides. A usability test with a Likert scale questionnaire was conducted with 10 clinicians without prior experience with the simulator. The system scored adequately in usability, with the exception of automatic flexion, which is difficult to maintain stability with the 3D mouse. Despite this, the system scored an average of 4.4 to 4.6 out of 5 for its usability, being concluded to be very adequate for robotic surgical training.

2.5.2 *Mid-end MIS Simulators*

While high-end simulators such as the LapSim device can deliver a high-fidelity immersive experience for medical training, such simulators may not be available to potential users outside of a research lab or training facility due to high costs and limited availability. [52] However, consumer-level VR has increased fidelity as technology advances and hardware improvements are developed. Therefore, simulation experiences using the said consumer-level VR hardware have become more financially accessible as their retail prices drop. Simulators that use consumer-level digital platforms such as retail VR are defined as mid-end simulators, as they pose less of a financial barrier for potential users than high-end commercial simulators. However, there remains a gap in research on the efficacy of these simulators compared to high-end simulators with superior user interface and hardware fidelity. Both studies by Parham et al. and Javaux et al. [36], [57] evaluate the validity of their prototypes in contrast to other popular simulators, although they confirm the validity within their own group of participants using performance metrics and self-reported feedback.

Khan et al. (2016) present a low-cost VR simulator for laparoscopy skill training, dubbed SmartSIM [39]. The development of this simulator was described in three parts: the mechanical interface, the controller circuit, and the software application. The Mechanical Interface consists of the physical components handled by the user during the simulator operation, involving a laparoscopic forcep attached to a custom-built passive haptic feedback arm. A custom arm was built instead of using a commercially available arm such as the Omni due to cost. The controller circuit involves the switches and electronic components used to relay the movement of the mechanical interface to the virtual environment, and the software application handles the virtual environment displayed to the user on a digital screen. The virtual environment uses the Simulation Open Framework Architecture (SOFA) physics engine, an open-source physics library intended for use in medical simulators. The simulator objectively evaluates user performance through metrics such as completion time and error rate, as well as relatively compared to the benchmark performance of expert surgeons. The SmartSIM system was validated through use as part of MIS training workshops in a Pakistani hospital. SmartSIM was determined to demonstrate higher degrees of usefulness for MIS skill training compared to box trainers and commercial simulators such as LapSim.

It should be noted that while digital simulation can be a replacement for physical simulators at home or outside the research lab, it can also be an aid to increase the haptic experience delivered by physical simulators with the benefits of mid- and high-end simulators, such as user metrics and visual aids, to physically simulated procedures [33]. For example, Huber et al. developed a novel immersive VR simulator using an HTC Vive 2016 for laparoscopy, which places the user within a virtual operating room that allows a sense of presence while performing simulator tasks as if the user were within a real operating room [33]. This virtual operating room is used to augment an integrated LapSim commercial simulator, increasing the immersiveness of the surgical procedure's setting. A preliminary study with 16 surgical personnel was conducted as participants to evaluate the efficacy of this VR simulator. Participants performed general laparoscopic training tasks using LapSim, and the performance results did not show significant differences compared to those achieved with standard LapSim outside of VR. However, participants expressed greater enjoyment and greater immersion in tasks within the immersive VR setup.

A study by Parham et al. (2019) aimed to develop a low-cost virtual reality surgical simulator for surgical oncology as an educational tool to improve task performance [57]. The simulator was developed using standard commercially available VR software and Oculus Rift hardware to provide high-quality visuals and surgeon hand interactions. A VR reproduction was created to accurately replicate the operating room using a 1:1 scale matching of real-world elements, including equipment, instruments, and supplies. The internal anatomy was designed as a VR replica of the human female pelvic anatomy, including organs, veins, and other vessels, the peritoneum and connective tissue. A tray containing the surgical instruments and a tray to discard the used instruments were included, and the surgeon's hands could move anywhere within the operating room area or the patient area. The development-trial cycle was considered crucial to understand the impact and limitations of the simulator to increase surgical training, and clinical studies successfully demonstrated that a low-cost simulator has a realistic and effective impact on surgical oncology capacity. This article did not publish the results of their validity evaluations, but concluded that the development of a mid-end simulator that reflects the reality of surgical oncology is shown to be achievable using consumer hardware. It was concluded that the simulator can help train the surgical workforce, enhance safer surgery, and ensure higher quality standards.

HoloPointer is an educational aid tool developed by Heinrich et al. (2021) intended to enhance the learning experience using VR screenspace simulators such as the LapSim laparoscopic simulator [30]. The system makes use of the Microsoft

Hololens augmented-reality HMD in order to draw a raycast to the screen, marking a cursor location on the screen for another user to see without interfering with the controls of the simulator itself. This allows a nearby instructor or supervisor to provide more efficient advice to the trainee operating the simulator. The tool was evaluated against traditional verbal and gestural instruction in a sample size of 10 novice trainees on the LapSim simulator, during the performance of a virtual cholecystectomy. Procedure time, efficient movement, and error rates were tracked as metrics. The tool was deemed an effective educational aid, helping to minimize error rates without significantly prolonging the procedure time.

Javaux et al. (2018) developed a hybrid fetoscopic skills trainer with a physical box simulator augmented with digital sensors to combine the benefits of physical fetoscopic box trainers and VR simulation [36]. The physical components of the simulator involved a synthetic phantom of the mother's body wall that covered an opening in a box. The body contained a small opening to slide a fetoscope and a plastic cannula through. Two fetoscopes were used for this simulator: a straight fetoscope, intended for placentas in the back of the womb, and a curved fetoscope, for placentas on the side wall. Both fetoscopes were equipped with Aurora position sensors and 6DOF trackers to digitally track the position of the fetoscope. These outputs were passed to a nearby computer that would display a simulated fetoscope output as if the fetoscope were inside a womb. Lastly, a foot pedal was used to operate a virtual fetoscope laser. The face validity test in this simulator involved 8 participants (2 experts, 2 intermediates, and 4 novices). Participants performed basic fetoscopic skill tasks (maneuver and symbol identification), as well as a fetal laser ablation procedure using the Solomon technique. The three categories of participants indicated a positive experience with the simulator, with a median score of 3.50 out of 5 for all aspects of the qualitative questionnaire. The authors concluded that data were scarce because only specialized fetal therapy centers are able to perform this pathology. However, the data collected from this face validity study indicated that such a hybrid simulator was a viable platform for fetoscopic skill training.

2.5.3 *Low-end MIS Simulators*

A "low-end MIS simulation" refers to a simulation approach that uses basic or cost-effective tools, such as box trainers and makerspace devices, to replicate minimally invasive surgical (MIS) procedures. This simulation method is designed to provide learners with hands-on experience and skill development in a resource-efficient manner, particularly suited for educational settings with limited budgets or access to sophisticated equipment. Low-end simulators are characterized by bringing down the costs of simulation with the purpose of providing affordable and accessible tools for training. For example, box trainers often consist of a box or enclosure with ports through which instruments and cameras can be inserted. Learners practice performing surgical tasks, such as suturing or manipulating objects, within the confined space of the box trainer. Makerspace devices such as basic sensors or robotics can be used to technologically augment these simulators. Although these approaches may lack the advanced features and sophistication of high-end simulation systems, they offer an entry point for learners to develop foundational skills in minimally invasive surgery. Recent years have seen an increase of interest in low-end simulators as makerspace and immersive technologies become more affordable [16].

Alvarez-Lopez et al. (2020) presented the development of a gesture-based educational simulator for MIS using VR, dubbed SIMISGEST-VR [2]. Designed as a low-cost portable simulation system for MIS, this simulator uses a combination of MIS forceps with a LeapMotion controller, in which users would grasp the MIS forceps and operate the virtual environment by moving the forceps as they would in a real procedure. The LeapMotion controller would translate the user's movements into the virtual environment to interact accordingly. This simulator allows the user to practice through tasks that are equivalent in motion to those used in a real laparoscopic procedure; for example, grasping and moving objects between one place and another, or cauterizing targets using a laser. The SIMISGEST-VR simulator was evaluated with a face validity study of 30 participants undergoing the various tasks available on the simulator. The content validity survey asked users to rate the simulator on a Likert scale of 1-5, with 5 being a high degree of realism and 1 being very low. The simulator scored averages of 3-5 in all categories, indicating a positive experience with using the simulator to emulate a real procedure.

Thinggard et al. (2017) investigated how access to take-home practical training aids (box trainers) impacted trainee learning of laparoscopic skills [75]. The study used a mixed methods approach to investigate the training patterns of junior physicians participating in a laparoscopy curriculum, which involved practicing on box trainers at home. Quantitative data on training patterns were collected through logbooks, while qualitative data on the use of box trainers were obtained through focus groups and individual interviews. The results showed that 14 out of 18 junior physicians used a combination of training modalities, four using box trainers before switching to virtual reality simulators. Twelve participants only trained at home, five used the simulation center and the home training center, and one exclusively used the simulation center. Participants typically trained at the beginning and toward the end of the course, with a period of no training in between. Although feedback was found to be lacking, self-rated was used as a guide for unsupervised training, and the ease of access for the box trainer was mentioned as a benefit that outweighed the lack of feedback from a supervisor. Mandatory training elements affected when and how many participants trained. In general, the participants used an individualized approach to training at home, mixing their at-home training with more formal practice at the simulation center. Self-rating helped guide unsupervised training, where feedback was not available. The timing and frequency of training were determined by curricular requirements and tests.

Chauhan et al. (2021) discuss the evaluation and usability study of a low-cost laparoscopic trainer named "Lap-Pack" [11]. The Lap-Pack uses household materials and disposable instruments for a simple box trainer, to which a camera module is attached, which can be used to integrate a laptop computer as a laparoscope display output. The study was conducted in two stages - Stage I, which involved the assessment of skill transfer of 7 rural surgeons from North East India, and Stage II, which focused on the usability and comparison of Lap-Pack with another box trainer known as the Inovus Pyxus HD. Eight surgeon trainees were evaluated on two Fundamentals of Laparoscopic Surgery (FLS) tasks, then surveyed using the Likert scale questionnaire. The results demonstrated that Lap-Pack is an effective and affordable tool for training in laparoscopic simulation, with consistent usability scores from the questionnaires. The authors also discussed the limitations and potential improvements of the device. The study provides valuable evidence for the use of low-cost laparoscopic trainers in low-income settings and is a useful resource for researchers interested in developing similar devices.

Crihfield et al. (2022) assessed the development of laparoscopic skills in medical students and novice OBGYN residents using take-home laparoscopic trainer boxes[15]. The study included 74 participants who performed a laparoscopic peg transfer task, then took home a Lap-Tab box trainer [79] for 3 weeks to practice without guidance and returned to perform the same task. The study aimed to evaluate whether the box trainers were useful for unsupervised self-learning. The results showed that an improvement in task scores was observed after training, and the number of training sessions but not the total time training correlated with improved scores. Furthermore, the study showed that the participants were still able to improve with self-directed learning alone, and the participants improved similarly, regardless of previous surgical experience. There were no significant differences between the mean initial scores and the mean final scores for students and residents, suggesting that laparoscopic trainer boxes are just as effective in developing skills in medical students as simulation centers. The study concluded that take-home laparoscopic trainer boxes with self-directed learning offer a potential solution for the development of laparoscopic skills and the ability to overcome financial and time barriers.

Fathabadi et al. (2021) created a laparoscopic box-trainer dataset, IFCL.LBT100, for precision peg-transfer tasks using an intelligent laparoscopic box-trainer system

[22]. This involved recording 35 videos from different camera angles and manually labeling more than 5000 extracted images with bounding boxes for instruments and objects. The data set was divided into 80% for training and 20% for evaluation. The training framework used a feature learning network, using the SSD ResNet50 VI FPN architecture for object detection. A momentum optimizer with a learning rate of 0.04 was used. The input was images of size 1280*720 pixels at 30 FPS, yielding bounding boxes and class labels (e.g., OnPeg, OutPeg). TensorFlow and Python were used for implementation, supported on a GPU-based computing environment (NVIDIA GeForce GTX 1660 GPU). The test was carried out by three trainees with different levels of skill from three different perspectives, and the results showed that image recognition was able to detect and track objects in the three subjects. This data set allows future box trainers using consumer hardware, such as a personal laptop with a couple of cameras, to use object tracking features, which could aid self-learning and assessment using box trainers for laparoscopic tasks.

Ulrich et al. (2020) proposed a cost-effective and versatile laparoscopic training platform designed using a simple wooden board cut to the size of a large shoebox [76]. Metal pegs with eyehooks serve as ports, and Velcro provides stability for FLS inserts. The open design accommodates various laparoscopic setups and tasks, allowing learners to practice complex skills. The study was conducted within an academic hospital's OBGYN residency program. Usability and acceptability were evaluated through a survey of faculty and trainees. The results revealed positive feedback, with the majority agreeing that the platform was easy to use, useful for improving skills, and valuable for assessing laparoscopic abilities before live surgery. Additionally, the platform was also well rated for realism on laparoscope movements.

2.5.4 *Task Representation*

Medical simulators generally focus on properly replicating a procedure so that students can practice under conditions that allow them to participate in the development of motor skills that can be transferred to real practice [16]. The following examples illustrate various use cases where task representation was achieved in digital simulation using a combination of computer graphics and haptics. The simulators were developed to ensure proper motion representation so that any actions performed with the simulator match the physical movements needed in real life. A major component of these simulators is the use of commercial haptic feedback interfaces that provide friction or object collision in the virtual environment.

Korzeniowski et al. (2021) created a VR simulator prototype designed specifically for training core manual skills in laparoscopic pediatric hernia repair [40]. The apparatus included a real-time software program responsible for simulating a hernia suturing task, a laptop computer, a non-immersive monitor display, and two Simball input devices that imitate laparoscopic instruments. A Simball is a haptic user interface device that provides users with tactile feedback and force sensations in VR simulations, enhancing grasp and touch-based interactions within digital environments. A study was conducted using a questionnaire from 36 pediatric surgeons to determine the realism of the simulator, in which subjective feedback was collected on the validity of the face and content. On a 5-point Likert scale (with 1 indicating "very unrealistic" and 5 indicating "very realistic"), the overall simulation realism was rated an average of 3.08. Participants were most satisfied with visual realism (rated at 3.33) but were critical of virtual tissue behavior. The simulator demonstrated good content validity, with scores of 3.61, 3.64, and 3.89 indicating its usefulness as a training tool for hernia repair, suturing in general, and learning fundamental laparoscopic skills, respectively.

Elessawy et al. (2021) aimed to evaluate the validity of the LapSim laparoscopic simulator and its impact on the performance of surgical trainees in laparoscopic procedures [20]. Participants (n = 63) were grouped based on their level of experience into three categories: 16% were residents, 46% were specialists, and 38% were consultants. The face evaluation demonstrated that the design and tasks were well received and realistic and that 54% of the participants gave the tissue feedback a moderate rating. The constructive evaluation showed that the abilities of the participants improved during the training session and the designed task was effective in differentiating between experienced and inexperienced surgeons based on performance scores for task I (transfer of pegs) and task II (a laparoscopic salpingectomy task). Both tasks showed improvement, with a significant increase in score and a reduction in time. The study also found that those with a high score before the test recorded a high score after the test, indicating a significant pairwise comparison and correlation, demonstrating a statistically significant result ($p < 0.001$). The predictive evaluation demonstrated the benefits of training four weeks later on the surgeons' ability to implement the learned skills into daily practice, perform the procedure, suture, reduce operative time, and manage complications. The VR simulation was found to be highly effective in terms of realism, training capacity, and maintaining enthusiasm for training, as well as being clinically and critically relevant.

Vamadevan et al. (2022) conducted a study investigating the effect of haptic versus non-haptic virtual reality simulators on the time required to achieve proficiency in laparoscopy training programs [78]. The study was designed as a randomized controlled trial, in which participants were randomized to proficiency-based laparoscopic simulator training using either a haptic or non-haptic simulator. 36 residents without prior laparoscopic experience were recruited from surgical departments in Denmark. Participants from the haptic group completed a follow-up test where they had to reach proficiency again using the non-haptic simulator, while participants from the non-haptic group returned to training until reaching proficiency again using the non-haptic simulator. The study showed that haptic virtual reality simulators reduced the time required to reach proficiency compared to non-haptic simulators. However, the skills acquired by trainees on the haptic simulator were not transferable to the conventional non-haptic setting. In contrast, the group that trained using the non-haptic simulator reached the required proficiency level significantly faster during the follow-up test. The study concluded that while the skills acquired using haptic simulators may not transfer fully to the non-haptic setting, haptic virtual reality simulators do reduce the time required to reach proficiency compared to non-haptic simulators.

2.6 conclusion

In conclusion, the use of VR simulators in medical training has shown generally positive results in terms of face validation, and participants are often satisfied with the design and realism of the tasks during self-reported post-test questionnaires. Positive face validity defines whether a system has the ability to measure what it claims to measure or whether it seems to be a reasonable representation of the concept or trait it is intended to evaluate. In the case of a surgical simulation or a skill trainer, this involves the ability to discern between users of varying levels of surgical skill. This applies both to commercial simulators and to prototype simulators that have undergone face validation studies. However, there are still gaps in research on the use of retail-level commercial VR systems as educational aids, particularly between immersive VR and non-immersive VR mediums. Digital Simulation has broadened its range of accessibility, with simulation applications moving away from solely within the high-end research lab space to consumer-level hardware in mid- and lower-end simulator prototypes. This increased range of access comes with a wider variance of devices, as different versions of VR hardware hit the market. Research remains to be done on the effectiveness of different forms of hardware on the user experience, both as an output medium (such as the use of immersive VR) and through novel input interfaces as seen on prototype simulators. However, there remains a disproportionate focus on visual fidelity within the medium in contrast to enhancing fidelity for other senses, such as touch. Despite a growing body of research on 3D user interfaces (3DUIs) and human factors for digital interactions, there is still a gap in understanding how different user interfaces impact the user experience in terms of usability and immersion that can help establish best practice to leverage the shortcomings of any given user input device when using consumer-level VR headsets for laparoscopic simulated procedures. While there are numerous evaluations of simulator systems to determine their effectiveness as educational aids, the majority of these evaluations are taken from the perspective of task performance. There is a gap in evaluating human factors to simulate tasks in immersive VR, evaluating the quality of the experience through user-centric design. The lack of a proper understanding of how different user input devices impact the user experience carries a risk of producing VR environments that are not engaging and helpful for skill development. When there is an excessive emphasis on task representation in VR simulations, it can lead to a neglect of the overall user experience. Users may find simulations less engaging and enjoyable, which can affect their motivation to participate and learn. Engaging and motivating users is essential for effective self-learning, which is a key goal of using simulators for medical training. Therefore, understanding the effects of various user input devices is critical, as any impact on task realism and/or immersion can impact skill transfer to a real-life MIS procedure.

As new advancements are made with respect to computer-based training using immersive technologies, it will be important to continually evaluate the efficacy of VR simulators in medical training and ensure that they remain relevant and useful tools for healthcare professionals. With a generally positive trend towards confirmation of validity for commercial simulators, ongoing research can further streamline the development of these simulation applications, reducing costs where possible while retaining validity as educational aids to improve access. Prototype simulators are pushing the boundaries of user immersion by testing new hardware and software, allowing for higher fidelity simulations at a fraction of the cost of older high-end simulators. Virtual reality simulators have the potential to revolutionize the way medical training is conducted, providing safe, effective, and immersive training experiences that can prepare healthcare professionals for a wide range of scenarios and challenges they may face in their practice.

3

CHAPTER 3

3.1 OVERVIEW

This chapter presents the materials and methods used to develop the simulator and conduct the user study. These methods are conducive to the simulator development, and the user study.

3.2 LAPAROSCOPY OVERVIEW

The development of the laparoscopy simulator is based on the manipulation of a 0 degree fetoscope with a camera connected to a digital monitor output, providing a panoramic view. This system includes a secondary laser fiber used for selective laser photocoagulation (SLP), in which a laser is directed through this fiber to coagulate and interrupt anastomotic blood vessels. Figure 1 shows a high-level overview of the surgical procedure setting, highlighting the main interaction that requires participants to manipulate the fetoscope to identify and laser areas of interest.

3.3 SIMULATOR DEVELOPMENT

The VR simulator for laparoscopy that focuses on aim and laser maneuverability was developed using the Unity game engine and the HP Omnicept VR headset. The simulator was made compatible with various input devices, such as traditional user input devices including a keyboard+mouse and a gamepad, in addition to a 3D-printed laparoscope (also referred to as a makerspace controller).

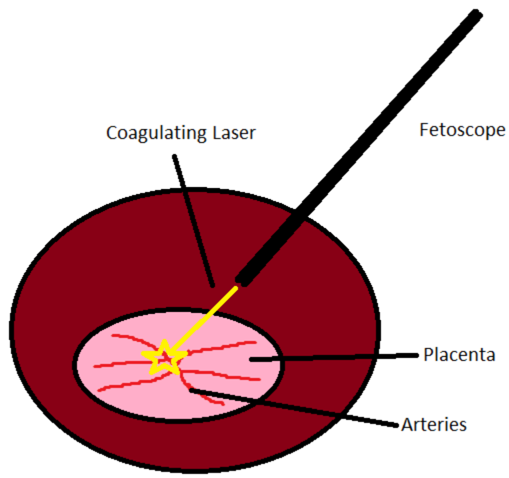


Figure 1: Laparoscopy laser ablation visual representation

The laparoscopy simulator consists of a simulation module that articulates the virtual representation of the procedure with the interactions to ensure that the fetoscope behaves as its real counterpart by taking inputs from the chosen devices. Finally, a metrics tracking module records and outputs data from the user's simulation experience to an external file for analysis. Figure 2 shows a high-level system architecture overview in which the modules and their corresponding inputs/outputs can be seen looping back to the user.

3.3.1 *Input Devices*

The virtual fetoscope manipulation is performed using the following four input devices: i) a VR controller, ii) keyboard+mouse, iii) a gamepad, and iv) a makerspace fetoscope user interface [51]. Three of the four input devices represent peripherals widely available for the use of computers, video game consoles, and VR headsets, as shown in Figure 3 and Figure 4, in addition to a makerspace controller that presents a replica of a fetoscope [51]. The included figures include highlights of

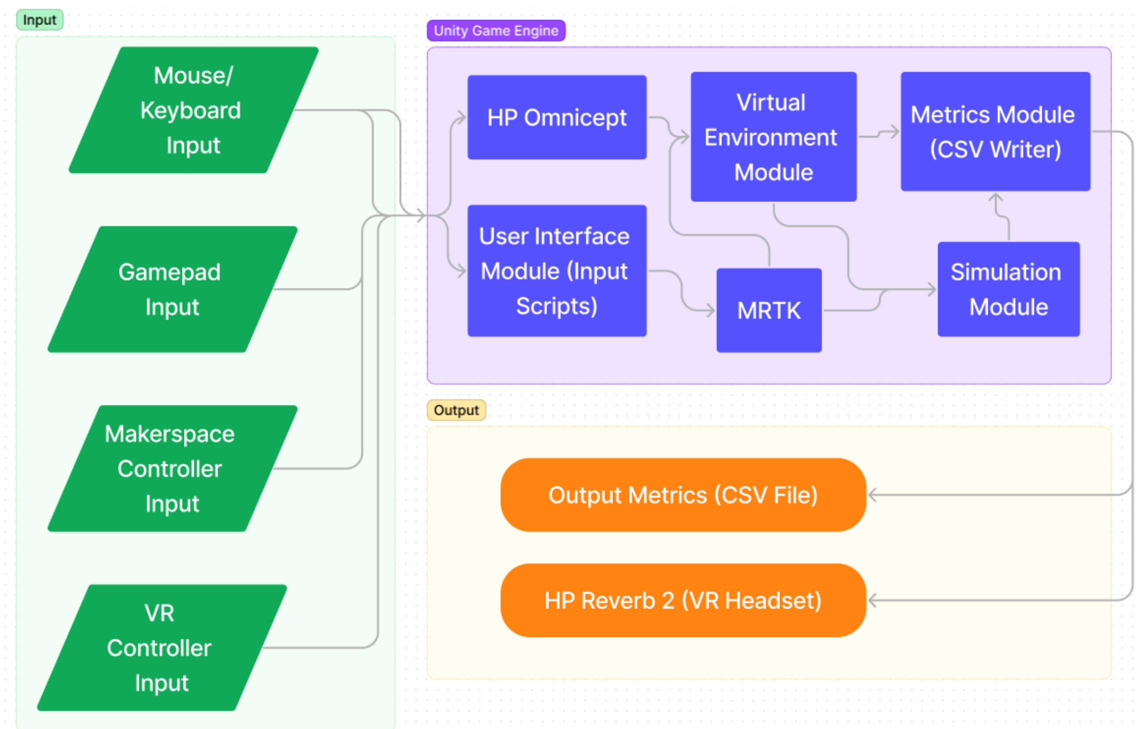


Figure 2: System architecture overview

core buttons and inputs used during operation, and how the different interfaces include analogous inputs across controller types.

3.3.1.1 *Keyboard+Mouse*

The recent use of VR for productivity [68], has seen headsets providing additional virtual screens and access to physical keyboards through passthrough (i.e., allowing the camera real-world feed to be seen in VR) or virtual keyboard representation matching VR compatible keyboards in conjunction with hand tracking [47]. This approach presents a different interaction scheme in which VR controllers, hand tracking, and keyboard + mouse can co-exist to facilitate task completion for traditional computer-based tasks focused on productivity. As seen in Figure 4, keyboard and mouse can provide analogous inputs to those of other peripheral devices while remaining a standard of everyday productivity.

Figure 3: Gamepad and VR hand controller comparison, with labels

3.3.1.2 *HP Omnicept VR Headset*

The HP Omnicept VR headset includes a pair of controllers consisting of a touch-sensitive thumbstick and buttons that use the index finger to activate actions, and a grip button on each hand controller to grab objects, as shown in Figure 3. The grip button is configured to simulate grasping objects in virtual environments using the middle finger. Additionally, the controllers feature two buttons each: A and B for the right controller, and X and Y for the left controller. These buttons serve as alternative input options within reach of the thumb, replacing the touchpad present in the previous version of the controllers.

3.3.1.3 *Makerspace controller*

While consumer-level VR controllers and traditional user interfaces allow tasks to be performed in 3D computer-generated environments, these do not properly represent the medical instruments used in simulation, which in the case of this

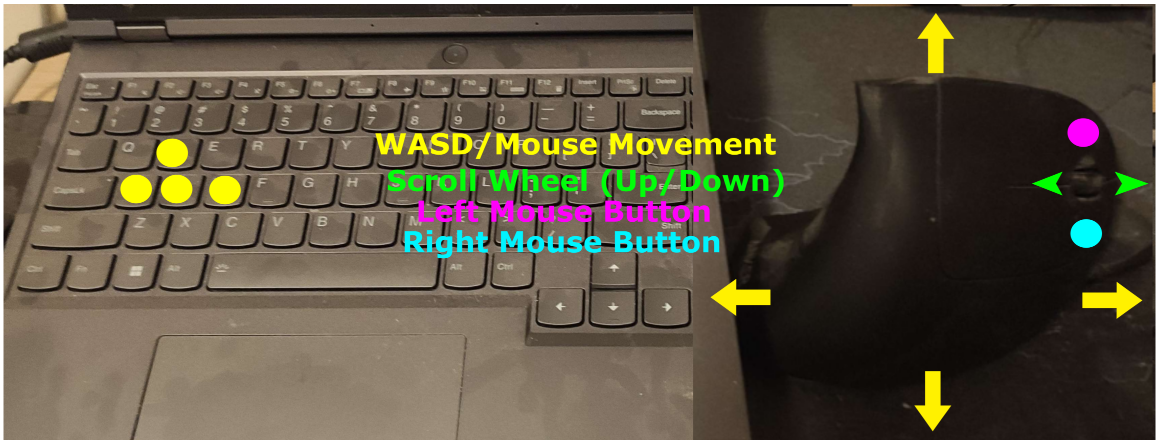


Figure 4: Keyboard for comparison, with labels

work is the fetoscope. For this reason, a custom-made user interface that better replicates the handling of the fetoscope is also considered within the scope of the research question to better understand its role in usability, cognitive load, and task execution.

The makerspace controller was developed using an Arduino Nano microcontroller with a wired USB output and a retrofit laparoscope connected to a magnetometer, accelerometer, with lineal and angular potentiometers to properly simulate movement. Electronic and mechanical components are enclosed within a 3D printed uterus enclosed as a womb to further provide an adequate representation of the procedure [51]. Figure 5 shows an image of the makerspace controller with labeled components. The microcontroller uses an ATMega4809 processor, 48KB of CPU flash memory, and a clock speed of 20 Mhz. This microcontroller communicates with each of the sensors through the I2C communication protocol. Pitch and yaw movements were performed using the ICM20948 package-based accelerometer. Additionally, this setup includes the use of a pedal connected to the 3D-printed womb using USB to activate the laser.

3.3.1.4 *Unity Communication*

The makerspace controller sends the readings of the input movements to the Unity game engine, which processes the incoming signals as serial communication. The

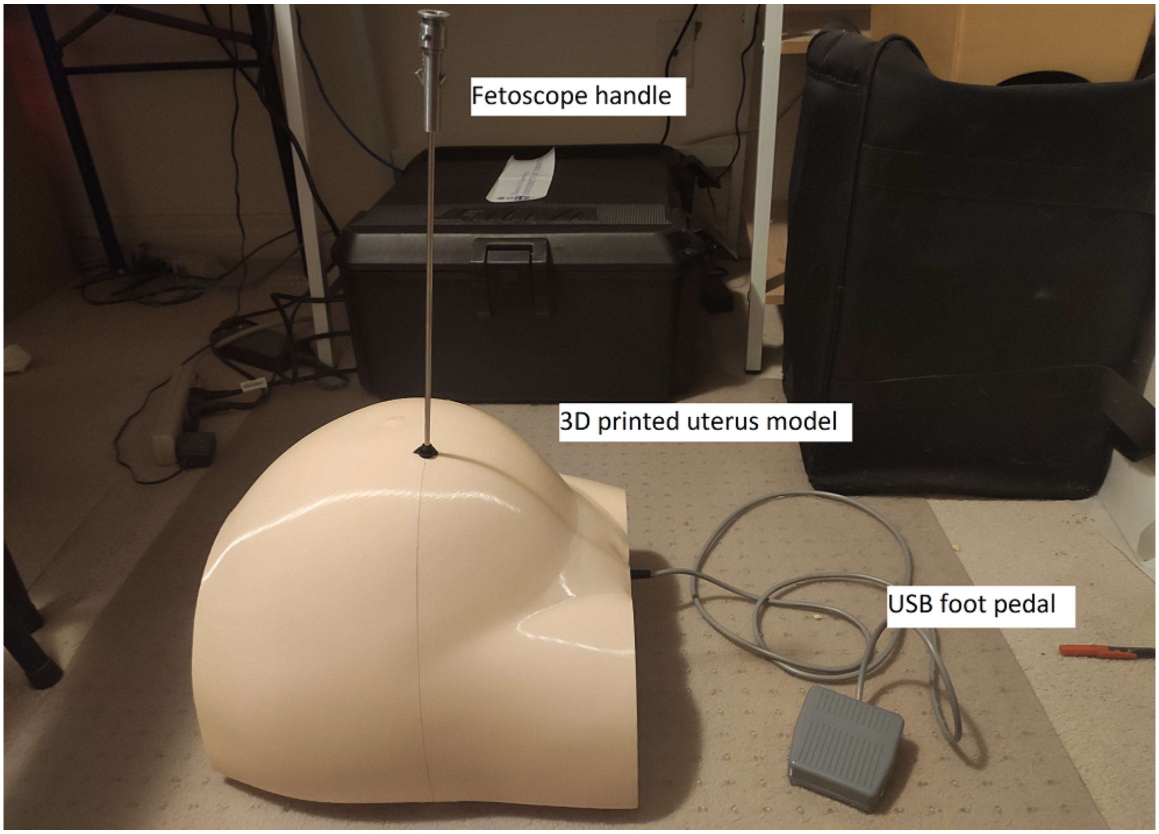


Figure 5: Custom-made makerspace interface resembling a womb housing a retrofit laparoscope connected to a microcontroller for sensing and data communication with the computer running the VR simulation

data from the controller were organized in a numerical chain and separated by commas, with a line break used to indicate the end of the series. The data sent includes the pedal status, pitch, yaw, roll, and Z position. A listener script in Unity parses numerical data incoming from the controller, which is then relayed to the relevant game objects (in this case, the fetoscope camera and laser) to move the respective virtual elements.

3.3.2 *Laser Activation*

The VR controller, keyboard/mouse, gamepad, and laparoscope custom-made controller allow controlling the position and orientation of the virtual fetoscope within the scene to perform the procedure illustrated in Figure 1. In addition to controlling the fetoscope, ablation requires the use of a pedal to activate the laser. Figure 6a, shows the user interface, with the pedal located below the table. The pedal chosen for this purpose is a generic USB foot pedal, as seen in Figure 6b. The pedal is a single tactile button and functions identically to a button press on a controller or keyboard. The activation of the pedal in the virtual scene triggers the laser firing functions that change the texture at the point of laser ablation with the corresponding audio feedback.

(a) Simulator being used with the VR headset

(b) Pedal close up of simulator being used

Figure 6: Simulator system with the makerspace controller and foot pedal

3.4 SIMULATOR ARCHITECTURE

The previous non-immersive version of the simulator featured only the simulation task environment. The Unity scene was composed of the virtual womb, and the user controlled a first-person view of the fetoscope display output. However, since the user would be operating the new version of the simulator in VR, the primary clinic space was created for the user to inhabit during operation, as a user would not be inhabiting the fetoscope directly in first person during an actual TTTS scenario. The original screen-space output of the previous simulator version was then output to a virtual screen within the clinic space to maintain the parallel to the real-life surgical scenario, as the user would be viewing the fetoscope output through monitors as the operation is performed. The following sections within this chapter further detail the development of the virtual scenario.

3.5 virtual reality

The VR development followed an iterative approach in which two prototypes were developed. The first iteration of the simulator was developed for non-immersive VR using Unity 2018.2.11f1 and compatible with keyboard+mouse and gamepads to ensure fetoscope manipulation [82]. This iteration focused on the twin-twin transfusion syndrome (TTTS) surgery procedure, which is a condition that occurs in monochorionic twin pregnancies, where twins in the womb share the same placenta [49]. TTTS occurs when blood flow between twins is imbalanced, resulting in one twin (the recipient) receiving much more blood and, therefore, nutrients than the other. If left untreated, TTTS can lead to severe complications and even fetal death. During the surgical procedure, the surgeon identifies and targets the anastomoses responsible for the imbalanced blood flow using a fetoscope with a laser fiber. Laser fiber is then used to coagulate these vessels, thereby interrupting abnormal blood flow between the twins. This process is known as Fetal Laser Ablation, or FLA. Figure 7 shows the steps of the FLA procedure, with highlights of the steps of the procedure on which this simulation is focused.

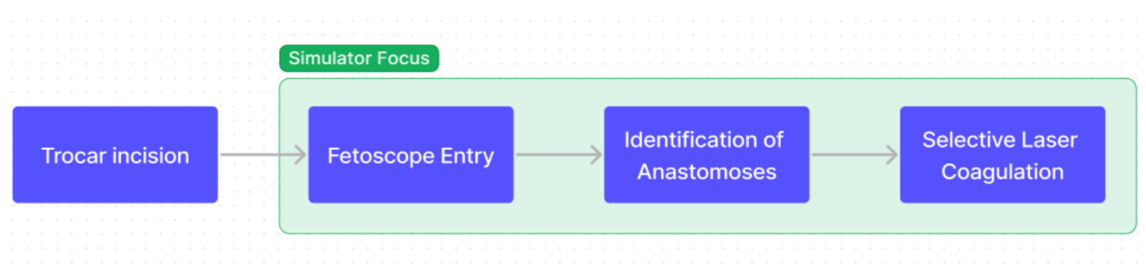


Figure 7: TTTS procedure overview

The core movements involved in FLA are centered on precise laparoscope manipulation, which is a transferable skill across all laparoscopic surgeries, as seen in the manual tasks required in FLS training [34]. Laparoscopy training focuses on precision, which in the case of FLA, targets specific arteries with minimal damage to the surrounding tissue for rapid coagulation. Laparoscopy skills can be transferred to other MIS surgeries, where precise movements and coordination between the surgeon's hands and visual feedback are crucial [34]. Therefore, FLA is a good foundational procedure on which future work can build on to further explore other laparoscopic techniques.

3.5.1 *Virtual Reality Scenario*

The second prototype upgraded the previous one to Unity 2021.1.5f1 to ensure VR compatibility with the Windows Mixed Reality Toolkit (MRTK) and the HP Omnicept VR headset. The upgrade additionally allowed the use of the high-definition rendering pipeline (HDRP), which is more suitable and optimized for the rendering of VR shadows and reflections. Additionally, HDRP allows the project to handle more complex reflections and lighting than that of the first iteration using the Universal Rendering Pipeline (URP) system, which allows the project environment to make use of darker ambient lighting and dynamic ray-traced lighting such as the light from the fetoscope.

3.5.1.1 *Aim and Laser Module*

Although the laser maneuver task requires an aim and laser, its implementation has been significantly abstracted from the actual procedure of laparoscopic surgery (in that the laparoscopic environment that would normally be seen through the fetoscope has been visually simplified into colored square planes). By simplifying the environment, the trainees can focus on mastering the laser maneuver without the added complexity of the full laparoscopic view. This can help learners become proficient in individual tasks before being visually overwhelmed by the actual surgical environment. It should be noted that the simplification of the procedure was approved by a content expert to ensure that the environment retains elements parallel to the abdominal interior to maximize immersion. For example, the target board previously shown that represents the placental surface that the laparoscopic procedure focuses on consists of flat planes with a red-pinkish coloring that are visually similar to the placenta that would have been the target of the laser during the laparoscopic procedure.

The aim and laser module were designed to ensure that the fetoscope can be used in a manner similar to its real counterpart. The project utilizes Microsoft's Mixed Reality Toolkit (MRTK) [61] as a base framework for VR interactions, which natively allows for raycast pointers coming from the headset and hand controllers to ease interactions. The fetoscope behavior driven by the hand interactions produces a ray that is used as a reference to fire the laser at the target destination. To activate the laser, Table 2 presents the mapping of buttons for all inputs when performing laparoscopy, as listed earlier in this chapter. To confirm the effects of the laser on the target location, a sprite of a burn mark is generated at the point of contact between the camera's center raycast (middle of the camera's field of view) and the target's surface.

3.5.1.2 *Virtual Operating Room*

The virtual scenario consists of two separate zones within the Unity scene. The first zone is the hospital clinic area where the user is present directly in VR. This space is primarily a set dressing intended to enhance immersion for the user, evoking presence as if the user were physically present within an operating room. The space is a single room, with an operating chair in the center of the space. An operating lamp is present in the chair, which holds a lamp and the display screens for the user to watch as they perform the operation. In addition to the operating lamp, the room is also lit with spotlights from the ceiling. The display screen contains a render texture of the fetoscope camera in the second zone, allowing a real-time virtual display as if the user were watching the digital output of a fetoscope while a laparoscopy was performed. Figure 8 shows third-person perspectives of the virtual clinic.

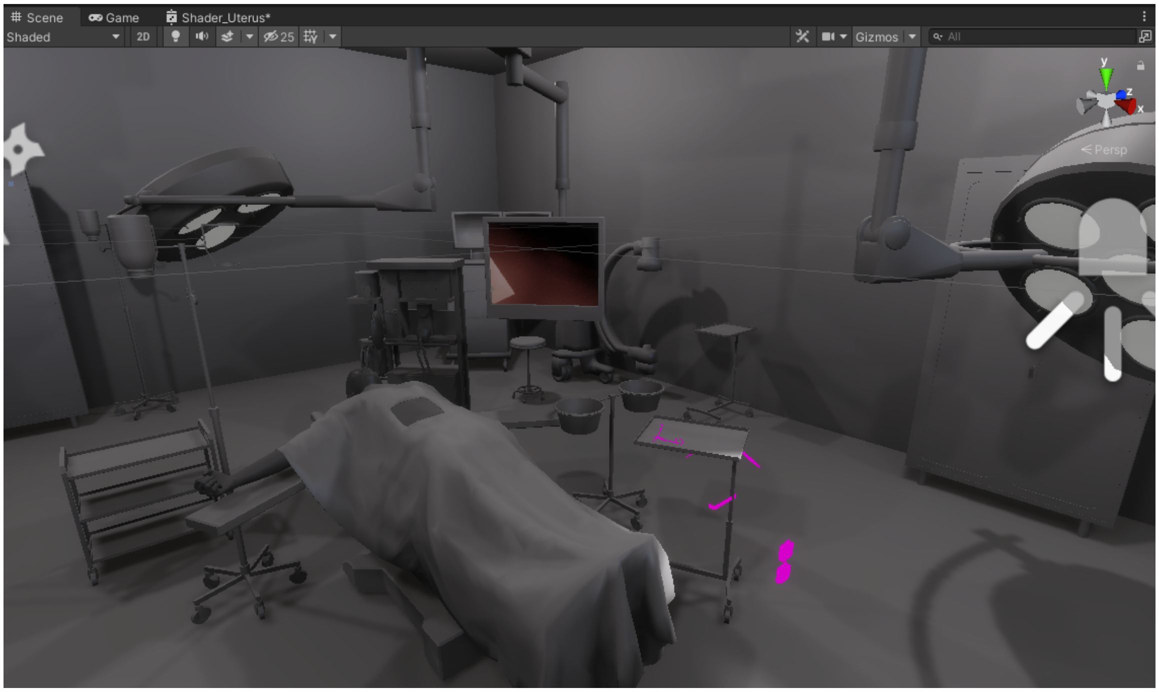
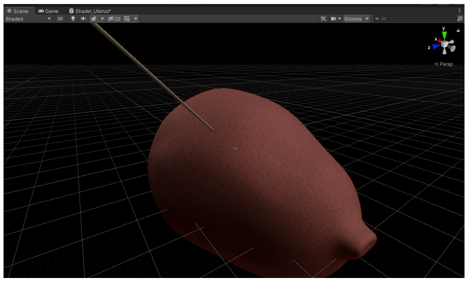


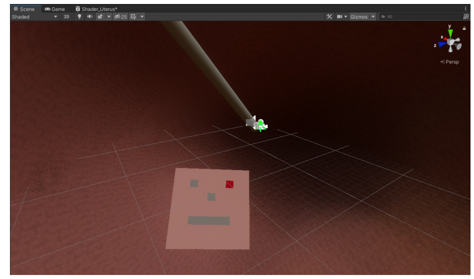
Figure 8: Third-person view of the VR clinic area

3.5.1.3 *Virtual Uterus*

The second zone contains the space where the participant performs the laparoscopic procedure. This zone contains most of the original non-immersive simulation assets that were used in the initial version of the simulation prior to VR integration. The core assets for this section include models for the surrounding uterine wall, target boards, and the fetoscope itself, with a scene camera mounted on the end of the fetoscope. Figures 9a and 9b show third-person perspectives on the virtual environment of the uterus.



(a) Third-person view of the VR uterine area



(b) Third-person view of the VR uterine area

Figure 9: Virtual uterus exterior and interior view

3.5.1.4 *Virtual Target Boards for Laparoscopy Practice*

Virtual target boards are an abstract representation that allow laparoscopy tasks to be performed. The target boards themselves are comprised of a set of flat geometric planes, with a larger plane serving as the representation of a uterine placenta, and smaller planes on top of the larger plane representing the artery locations. The smaller target objects begin as red-colored at the start of the simulation task, turning green once marked with the fetoscope laser for a short duration. The goal for the design of these boards was to be visually simple so that the burn marks from laser activation would be clearly visible on the targets, providing clear visual feedback to the user's actions with the fetoscope laser.

There are three separate target boards within the virtual scenario, each appearing sequentially once all the targets on the previous board are 'completed' by being marked by the laser until green. Figure 10 shows an example of what the target board looks like. The example board includes six targets, three of which have been marked by the fetoscope laser and are therefore green. The remaining three targets that have not yet been marked are colored red. This example also includes two floating obstacles representative of other miscellaneous tissue within the uterine environment, and should be avoided during task performance. This target board was designed using information provided by a content expert and was deemed sufficient as an approximation of a placental surface for the purposes of this simulation.

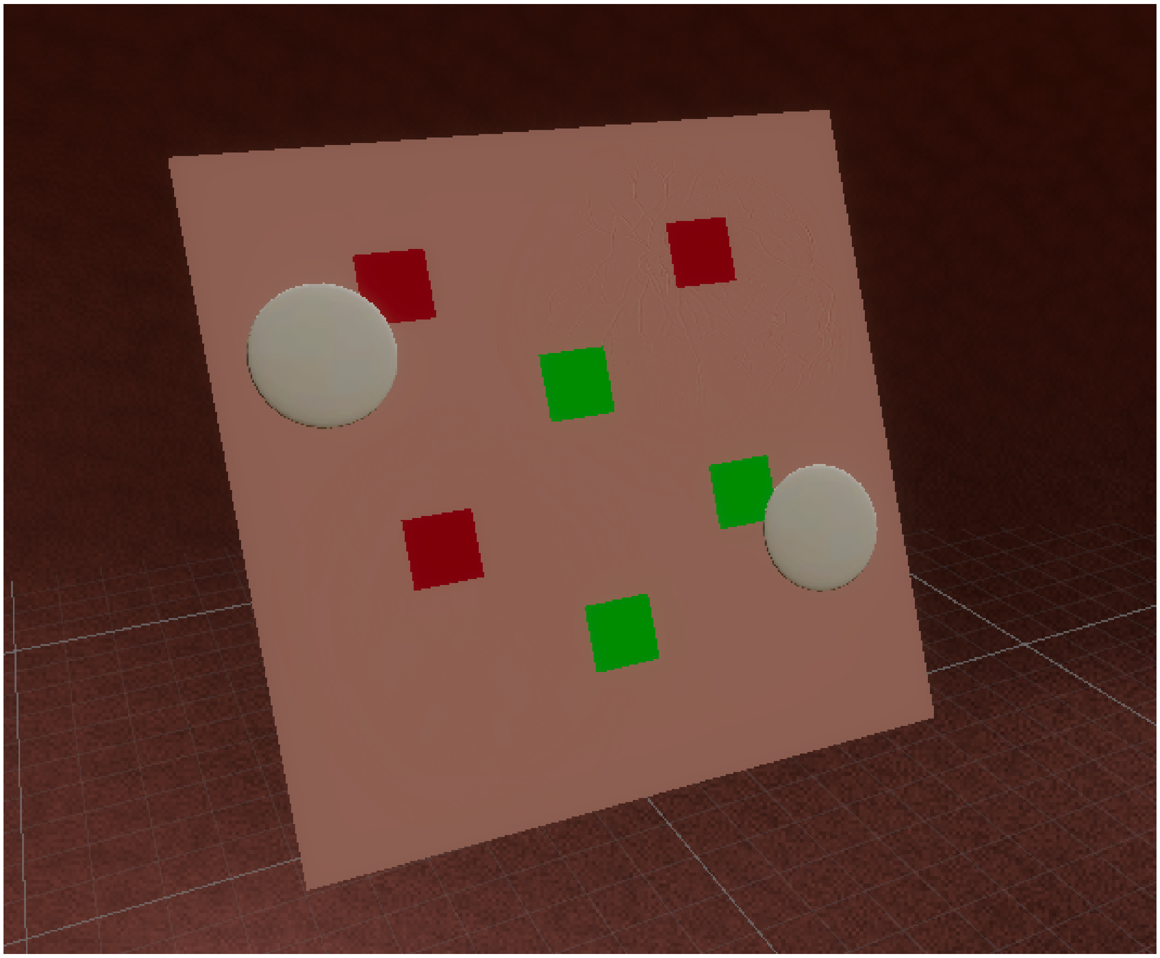
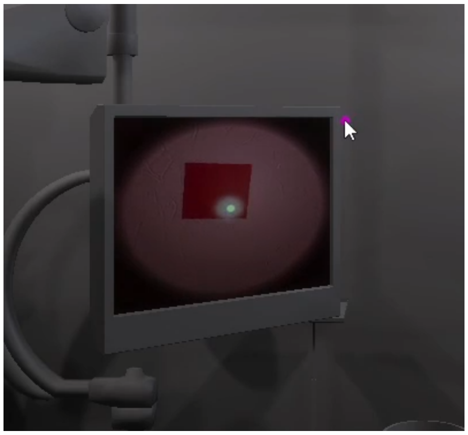


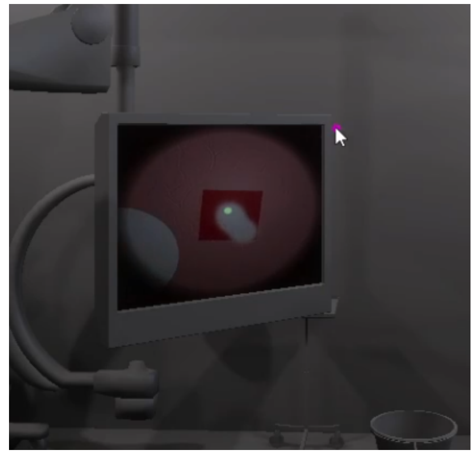
Figure 10: Target board asset within the virtual scenario.

3.5.1.5 *Virtual Laser Activation*

The final step in the laparoscopy scenario requires activating the laser using the pedal. To properly simulate this step, the virtual fetoscope laser generates a burn marking at the center of the fetoscope camera's field of view, which is also the laser's focal point when activated. The burn marking is a flat gray circular texture and is reapplied on every frame when the laser is active. While the laser is active, the resulting burn textures appear as a continuous line due to the overlapping circles, as seen in Figures 11a and 11b.



(a) Spot laser activation



(b) Laser ablation

Figure 11: Fetoscope uterus exterior and interior view

3.5.2 *Laparoscopic Interactions*

The fetoscope requires user inputs that allows proper manipulation to convey and enable its appropriate operation. Inputs gathered from the human input devices include: i) sideways movement (x/y/z), forward/backward movement (x/z), and laser toggling (foot pedal on/off or dedicated keypress). As each input device has a different button layout, the mentioned actions are mapped differently depending on which input device is being used. Table 3 shows which inputs are mapped for the use case of each input device.

3.5.3 *Simulator Interaction Implementation*

When the fetoscope is operated, motion is handled by two separate scripts. A *FetoscopeMovement* script is attached to the shaft of the fetoscope object, which handles the forward/backward movement of the fetoscope. Movement is handled by Unity's *CharacterController.Move* function, which allows smooth movement along a single axis. This function is called when the position of the fetoscope controller is greater or less than that of its counterpart in the game and will move the controller

Table 3: Simulator interactions

Motion	**KB+M**	**Gamepad**	**VR Controller**	**Makerspace Controller**
Look Up	Mouse Up	Right Joystick Up	Pointer Hand Up	Fetoscope Up
Look Left	Mouse Left	Right Joystick Left	Pointer Hand Left	Fetoscope Left
Look Down	Mouse Down	Right Joystick Down	Pointer Hand Down	Fetoscope Down
Look Right	Mouse Right	Right Joystick Right	Pointer Hand Right	Fetoscope Right
Move Forward	Scroll Up/I	Left Joystick Up	Left Joystick Up	Fetoscope Push In (to womb)
Move Backward	Scroll Down/K	Left Joystick Down	Left Joystick Down	Fetoscope Pull Out (to womb)
Fire Laser	Left Mouse/-Foot Pedal	X Button/Foot Pedal	Trigger/Foot Pedal	Foot Pedal

in the game to match the discrepancy. The same function is called for keyboard and mouse events, but for the corresponding keypress to move forward or backward (defaulting to I and K).

The *FetoscopeRotation* script, attached to the pivot point where the trocar incision would be in a real laparoscopy, takes the yaw and pitch values from the fetoscope controller. These values are combined into a 3D vector with values (0, yaw, pitch). The in-game fetoscope is then rotated to match the same values. With respect to mouse and keyboard events, as well as gamepad controller input events, the yaw and pitch values are generated from the mouse axis X/Y (mouse position) and the right joystick on the controller, respectively. On VR controllers, the position of the virtual hand controls is handled by MRTK itself through its *PointerHandler* functions.

3.5.3.1 *Fetoscope Manipulation*

The movements of the virtual fetoscope are comprised of multiple components, each handling different degrees of freedom of the fetoscope camera. The fetoscope itself operates similarly to a ball-joint system, with the camera mounted on a cylindrical shaft that handles the forward/backward insertion movement. This shaft is, in turn, mounted on a rotating axle at the fetoscope's insertion point into the digital uterus. At the lowest level of the fetoscope object's hierarchy, a script for the fetoscope camera's pitch and yaw rotation are placed at the fetoscope's insertion point, which is effectively a fulcrum for the fetoscope's maneuvers. The shaft of the fetoscope is parented to this fulcrum, and holds a script managing the camera's forward and backward movement. The camera itself is mounted at the end of this shaft and manages its own roll rotation via an individual script. Each of these scripts contains alternative methods for each differing input method, being either a game controller, keyboard/mouse, or the custom haptic controller.

3.5.4 *Metrics Tracking Module*

The simulator metrics tracking module records the position of the virtual fetoscope in the virtual environment. The simulator outputs the fetoscope metrics for each frame of the application as it runs to a comma-separated value (`.csv`) file, along with the time elapsed since the application began. The metrics recorded by the VR scenario include: Head position/rotation (x/y/z values), aggregate heart rate, and right/left eye tracking (x/z values). Head position and rotation values refer to the location and rotation positions of the main camera, which are tracked according to the user's head position in real space. Units of these metrics are expressed in meters and degrees, respectively. The aggregate heart rate is also tracked using the HP Omnicept Headset and HP's software development kit [35], which natively provides an aggregate heart rate value in beats per minute (bpm). Eye tracking values are gathered via the Omnicept system as well, outputting the location of the user's eye focus on the headset's screen for each eye. The `.csv` file begins with a time stamp of the real world time and date, then prints the metrics of the fetoscope and the time elapsed in the game for each frame as it runs.

The time elapsed was recorded per frame, keeping track of how much time in milliseconds had passed since the virtual scene was started. Measurement of the time taken to complete a task offers a direct insight into the speed and proficiency with which an individual or system can execute a given set of actions. This metric is particularly valuable in scenarios where prompt and accurate task completion is critical, such as in medical procedures, emergency response, or industrial processes. Furthermore, tracking the time elapsed allows for comparison of performance between different individuals, interventions, or technologies, providing a standardized benchmark for evaluating efficacy. Furthermore, having timestamps recorded per frame allows for visibility of when any outstanding actions occur, such as loss of functionality of any part of the simulator, or of any noteworthy actions taken by participants that cause abnormal readings.

For head position, rotation, and eye-tracking data, these values per frame will be used to generate total path length, indicating positional variance and distance traveled from the initial position over the course of the simulator's usage. This can then be further analyzed to provide additional insight into the participant's movement behaviors while in the VR environment. The total path length of movement, both positionally and rotationally, provides data on how much the user is looking around and visually exploring the surrounding VR environment. As users feel more present in a VR environment, they are more likely to psychologically commit to the experience. This increased engagement leads to a greater willingness to interact with the virtual world, often through physical movements such as looking around [3].

Similarly, the aggregated heart rate metric is also used to provide insight into a user's sense of presence within VR. As immersive VR simulation emulates the setting of performing stressful tasks, such as surgery, the increased cognitive load and engagement needed to perform the task can lead to an elevated heart rate.

3.6 STUDY DESIGN

The study design focuses on having participants perform aim and laser tasks using different input devices while using the VR headset, with the purpose of answering the research question "How do different input devices affect usability, cognitive load, performance, and immersion when performing aim and laser laparoscopy tasks?" The main hypothesis of this work is that "input devices that better represent the laparoscopy procedure performed in VR will positively affect usability, cognitive load, performance, and immersion more than a non-immersive input device."

3.6.1 *Recruitment*

Recruitment was carried out primarily through the Discord messaging application, as well as through the recruitment of pamphlets in the SIRC building of Ontario Tech University in Oshawa, Ontario, Canada. Students, instructors, and health care professionals in the health sciences who are 18 years or older were considered eligible to participate in the study. Computer Science, Game Developers, and other professionals or students from STEAM areas are welcome to participate with the purpose of evaluating the usability component from a technical point of view. Further inclusion criteria required that participants are able to use non-immersive and/or immersive virtual reality in either seated or standing modes.

3.6.2 *Demographics*

The participant pool for this study included 13 adult participants, all of whom were university students with backgrounds in health sciences or information technologies. Six of the participants indicated they had a background in health sciences and the remaining indicated a background in game development. Seven students were male, six were female, and all participants were between the ages of 18 and 34 years. In the context of their previous VR experiences, 5 out of the 13 participants indicated any familiarity with VR, with two individuals spending less than 10 minutes, two spending less than 30 minutes, and one engaging in VR sessions lasting between 30 and 60 minutes. These experiences involved the use of VR devices, including Oculus Quest, Oculus Rift S, and HTC Vive. Furthermore, all participants reported having experience playing video games, 4 using personal computers, 5 using handheld consoles, and 4 using both console and handheld consoles. None of the participants had prior exposure to laparoscopy or other MIS procedures.

3.6.3 *Effect Size*

A statistical power analysis was performed using G*Power to determine the effect size of the study using the sample size. G*Power is a statistical software tool designed to calculate statistical power and perform sample size calculations [23]. This power analysis was done for the final set of data collected across the 4 experimental groups, as the final set is a better representation of the comparisons between the input device groups. Power analysis was performed as a post hoc test for ANOVA: Repeated measures between factors. The effect size f(U) of the parametric tests was calculated with SPSS's GLM Univariate tests to obtain a partial eta squared (np2̂) value of 0.778. With an error probability of 0.1, sample size of 13, 4 groups, and 7 measurements (4 of which were normally distributed, 3 which were not), G*Power returned a statistical power of 0.73. It is acknowledged that with a power of 0.73, the results of this study have only a 73% chance of correctly identifying an effect, leaving a 27% chance of missing it altogether. For non-parametric data, the correlation coefficient was obtained using the chi-squared values of the Kruskal-Wallis tests. With a chi-squared value of 3.714 and a sample size of 13, the correlation coefficient effect size is 0.53, lower than the effect size of the partial eta squared. A low-powered study is more susceptible to the influence of random variations in the data, making it difficult to distinguish true effects from noise. With lower statistical power comes an increased risk of Type II errors, also known as false negatives. In practical terms, this means that this research may fail to reject a null hypothesis when it is false, assuming that no effect exists even though an effect is present. Future research in this field should aim to achieve higher statistical power by increasing sample sizes.

3.6.4 *Study Session*

A consent form was provided to the participant at the beginning of the study, as the first step of the study process, as soon as they entered the GAMER lab to begin the study. Once the participants had given their consent (see Appendix 6.1), they were allowed to ask questions after being introduced to the study (see Appendix 6.4) and before proceeding with the study activities. The participants were additionally introduced to the location where the study took place, the GAMER laboratory in the SIRC building, North Campus, Oshawa. After completing all introductions, participants were assigned to an input device group to determine which input device they would be using to test with. The order of the conditions was balanced employing the Latin square to minimize carryover effects. The participants were then required to:

- Wear the VR headset and hold the VR controllers in either a seated or standing position for the immersive VR intervention or seated in front of their computer for non-immersive VR intervention.
- Once the application started, a researcher was present to teach the participant how to perform the aim and laser tasks.
- After giving the instructions, the participants were asked to: Within the virtual womb environment, traverse the area and locate the targets to be marked within the area. (2 minutes)
- Using the laser on the fetoscope, selectively mark each target identified with the laser until the target's color shifts from red to green.(2 minutes)
- The user repeats this process for each set of targets, completing all 3 sets in sequence. (5 minutes)
- Once the task had been completed, the participants were required to answer the System Usability Scale (SUS), NASA TLX, Virtual Reality Presence Questionnaire (VRPQ), and an open-ended questionnaire for them to describe their

experience during the trial (See Appendix 6.2), which took approximately 5-10 minutes.

- Once the questionnaires were completed, participants were asked to submit their data (see Appendix 6.5 of the data) and the researcher thanked them (see Appendix 6.3).

3.6.5 *Data Analysis*

Data collected from this study consists of two rounds of data collection. A preliminary set of data was collected using the simulation with consumer-level input devices, namely mouse and keyboard, gamepad controller, and HP Reverb Omnicept VR hand controllers. A second set of data was collected using the makerspace controller and analyzed in contrast to the three consumer-level input devices.

The raw data collected was originally in `.csv` format, with the following values being recorded for each frame of the simulation runtime: Head position/rotation ($x/y/z$ values), aggregate heart rate, right/left eye tracking (x/z values). The total length of the path for head position, rotation and eye tracking was calculated using Python's *NumPy* library. The `x/y/z` values of each frame were used as vector coordinates of a 3D point of each frame, and *NumPy*'s function to calculate distance between two points, using the values of each frame and that of the frame after it from the `.csv` data as endpoints. Then these distances were summed across all sequential frames for the duration of the simulation for each participant. The aggregate heart rate was averaged over the duration of the simulation experience per participant to determine whether there were significant differences in the heart rate values between the experimental groups.

The raw NASA Task Load Index (NASATLX) [69] scores were processed following a straightforward method that involved calculating the raw scores for each dimension (mental demand, physical demand, temporal demand, performance, effort and frustration) by summing up the participant's ratings for the corresponding items on a 20-point scale. These raw scores were then averaged across participants to obtain the mean scores for each dimension. The mean scores provided valuable insights into the perceived workload and stress experienced by users during a specific task or in a particular environment, allowing researchers to evaluate and improve the usability of the system and the user experience.

SUS [43] scores were processed by first reversing the appropriate elements, since elements 1, 3, 5, 7, and 9 were positively formulated, while elements 2, 4, 6, 8, and 10 were negatively formulated. The reversed scores were then calculated for each respondent. To calculate the SUS score for each respondent, the scores for all 10 items were summed and the total was multiplied by 2.5. The resulting scores, ranging from 0 to 100, indicated the perceived usability of the system or product of the respondents. The average SUS score was then computed by summing up all individual scores and dividing by the number of respondents. This average score served as an overall measure of the system's usability, with higher scores indicating better usability.

VRPQ [74] scores were processed on a 7-point scale, from "strongly disagree" to "strongly agree." The scores were then calculated by adding the ratings for each subscale: spatial presence, involvement, emotional involvement, realism, and physiological response. Additionally, a total VRPQ score was obtained by summing all 26 items.

These questionnaires were chosen as they are well established and widely used in the field of human-computer interaction and VR research. They have demonstrated validity and reliability through extensive use in various studies. Each of these questionnaires focuses on different aspects of the VR experience. NASA-TLX assesses cognitive and physical workload, SUS assesses system usability, and VRPQ measures the sense of presence and involvement in VR. Together, they provide a comprehensive assessment of the user's experience. Furthermore, all of these questionnaires use Likert scale response formats, which are relatively easy to quantify and compare between set of participants for data analysis.

Descriptive statistics, such as means and standard deviations, were calculated to summarize the data in all metrics. For each set of data, normality tests were first performed for each dependent variable to determine whether the data set for that variable indicated a normal distribution. For variables that showed a normal distribution, ANOVA tests were conducted to discern statistically significant comparisons between groups for each dependent variable. The Kruskal-Wallis non-parametric test was used to determine statistical significance between groups for variables that did not indicate normal distribution.

3.7 CHAPTER SUMMARY/TAKEWAYS

This chapter articulates the development of the aim-and-laser VR framework modeled after the FLA scenario of MIS. The simulator was developed using the Unity game engine for a VR headset and was designed to support multiple input device methods, including consumer-level devices such as a gamepad controller as well as custom makerspace devices intended to emulate the manipulation of surgical tools. The simulator was primarily focused on aim and laser maneuverability for laparoscopic procedures. This task scenario is a sufficient approximation of the FLA procedure as the main objectives of FLA are the maneuvering of the fetoscope and the selective laser coagulation. The movements of the fetoscope remain gesturally consistent with the real-life procedure, with elements such as the fetoscope's limited visiblity and movement reflected in the screen display in the virtual scenario. Likewise, the experience of using the fetoscope laser for selective laser coagulation is also properly reflected in the use of the foot pedal, and feedback to the user is delivered via an audio tone playing as well as the burn mark texture appearing at the laser's focal point. A user study where participants attempted the VR surgery scenario was conducted, and the data captured through surveys and simulator metrics tracked performance. The chapter also presents the materials and methods used for developing the simulator and conducting the user study. The laparoscopy simulator consists of a simulation module encompassing two 3D scenes through which the user performs the task simulation, a 3D User Interface module ensuring the inputs properly interact with the VR environment, and a metrics tracking module. The chapter concludes by discussing the different input devices that were tested to explore their effect on immersion during task performance.

4 RESULTS

4.1 OVERVIEW

This chapter presents a comprehensive analysis of the data collected during the experimental phase, offering insights into participants' interactions and experiences across various input device groups within the virtual environment. This section will include a detailed examination of the quantitative results obtained from the VR simulator participants, as well as their self-reported feedback. By delving into observed trends, significant differences, and patterns within each experimental group, this section aims to understand the impact of different input devices on user engagement, immersion, and task performance. The subsequent subsections will analyze trends and behaviors from the gathered data and obtain insight into what factors may have contributed to the results generated.

4.2 PRELIMINARY STUDY RESULTS

The preliminary results present data from six participants and are organized based on whether or not the data met the conditions of normality.

4.2.1 *Analysis of Normality*

The results of the Shapiro-Wilk normality test show that for HeadPos, HR, NASATLX, SUS and VRPQ, the p-value was greater than .05 indicating that the null hypothesis cannot be rejected, which means that the data do not have a normal distribution, thus requiring a non-paramatric analysis. For the HeadRot, REye, and LEye variables, the p-value was less than .05 indicating that the null hypothesis was rejected and therefore the data follow a normal distribution, thus requiring a parametric analysis.

4.2.2 *Parametric Analysis*

4.2.2.1 *Raw NASA TLX*

Scores for the NASA TLX raw scores indicate that keyboard+mouse had the lowest workload with a score of 1.83, followed by the gamepad and the VR controller tied with a score of 2.16 as shown in Figure 12. Standard deviation for NASATLX was 0.29. A one-way ANOVA revealed that there were no statistically significant differences in the SUS score between at least two groups (F(2) = 0.8, p = 0.527).

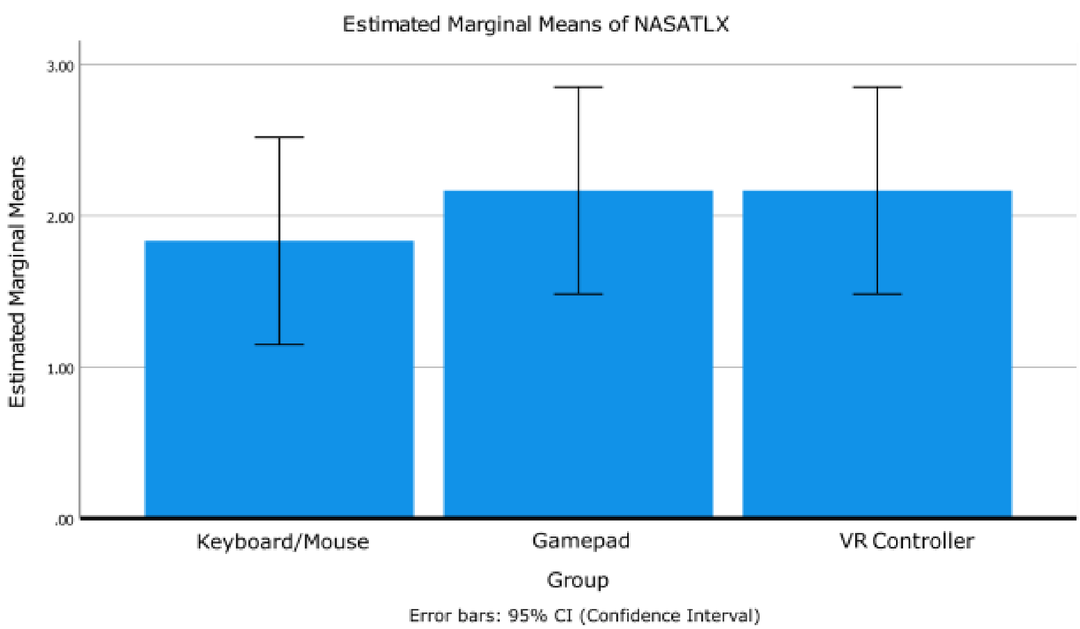


Figure 12: Group average box plot for raw NASA TLX

4.2.2.2 *SUS*

For the SUS questionnaire, the keyboard+mouse had the highest usability with a score of 81.25, followed by the VR controller with 78.75, and the gamepad with 77.5, as shown in Figure 13. Standard deviation for SUS was 13.5. A one-way ANOVA revealed that there were no statistically significant differences in the SUS score between at least two groups ($F(2) = 0.24$, $p = 0.976$).

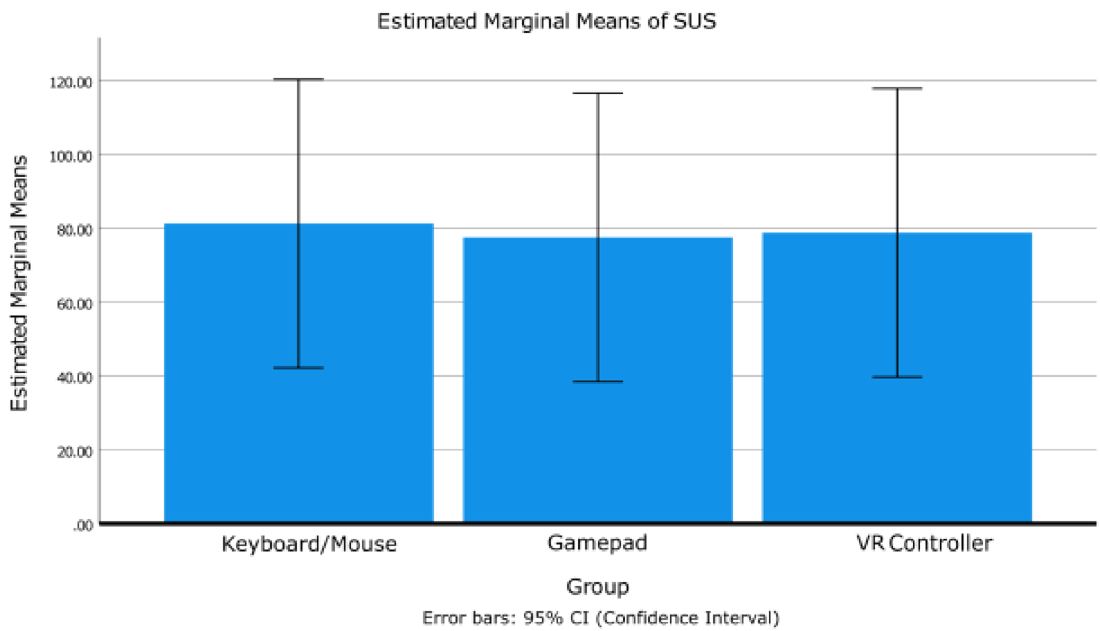


Figure 13: Group average scores for SUS, preliminary test

4.2.2.3 *VRPQ*

The results of the VRPQ indicate that the keyboard+mouse had the highest score with 84.5, followed by the VR controllers with 81.5, and the gamepad with 77.5 as shown in Figure 14. Standard deviation for the VRPQ was 6.43. A one-way ANOVA revealed that there were no statistically significant differences in the VRPQ score between at least two groups ($F(2) = 0.470$, $p = 0.664$).

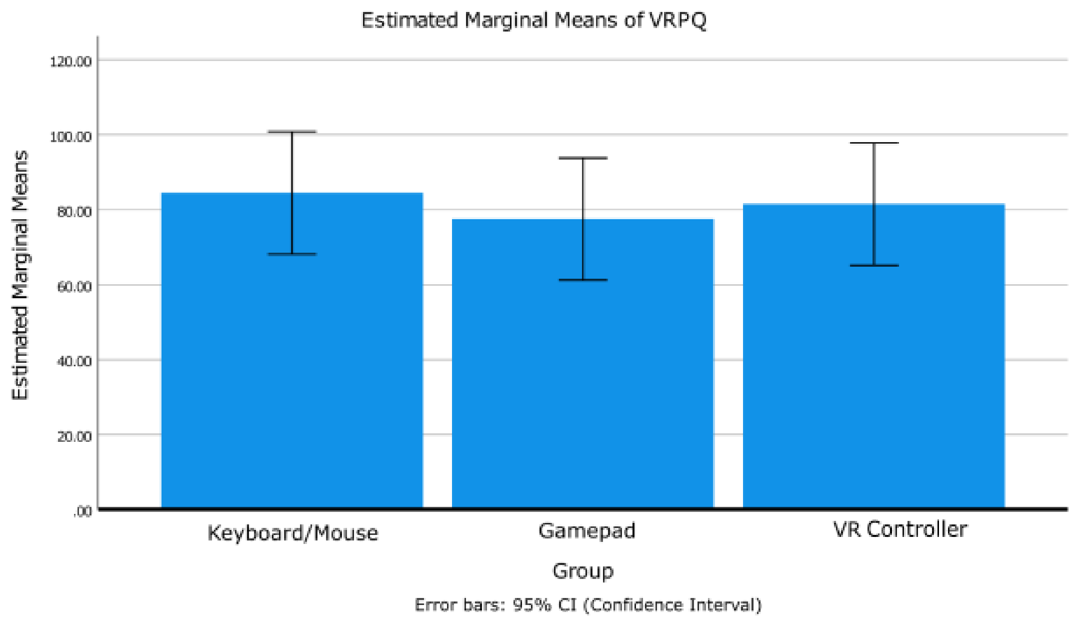


Figure 14: Group average scores for VRPQ, preliminary test

4.2.2.4 *Head Position and Heart Rate*

The average total path length for the head position was 11.47 units when on the keyboard and mouse, 3.16 units when on the gamepad and 3 units when using the VR hand controllers, with a standard deviation of 4.80 (Figure 18). The average heart rate recorded while running the simulator was 62.11 bpm for the keyboard and mouse, 34.59 bpm for the gamepad, and 71.43 bpm for VR controllers, with a standard deviation of 28.28 (Figure 21).

The results of the preliminary study did not reveal statistically significant differences between the three groups of input devices. A between-subjects analysis was conducted to compare the performance of the six participants in the study. Using SPSS, a multivariate analysis of variance was performed using the total path length of the head position, as well as the aggregated heart rate as dependent variables between three experimental groups as independent factors. Post-hoc using Tukey's HSD to determine which groups differed significantly from each other. A one-way ANOVA revealed that there was a difference approaching statistical significance in both head position and heart rate variables between at least two groups ($F(2) = 6.659$, $p = 0.079$), ($F(2) = 7.757$, $p = 0.065$). However, the Tukey HSD post-hoc test indicated that there was no significant statistical difference between the study groups ($p > 0.05$). This suggests that while there might be a significant overall difference between the groups, no significant differences were found in pairwise comparisons between the groups. Although Tukey's test comparing the keyboard and mouse group with the other two groups, as well as the gamepad group against the others, indicated a significance value approaching statistical significance ($p = 0.055$), the lack of statistical power in the other results indicates that this may be coincidental. Overall, the results suggest that there were no significant differences in Head Position and heart rate between the three experimental groups.

4.2.2.5 *Results Summary*

Overall, these results suggest that there are no significant differences between the groups on the NASA TLX, SUS, and VRPQ variables from the preliminary tests, with keyboard/mouse performance generally worse than gamepad performance on NASA TLX and VRPQ variables, and poorer than VR controllers on the SUS. As the standard deviation indicates the amount of variance from the mean average of an individual participant, the standard deviation metrics on these questionnaires indicate slight differences in self-reported scores between participants. However, standard deviations were rather large among gathered metrics, indicating that users' immersion may have differed between groups without a change in perception of the simulation's usability.

4.2.3 *Non-parametric Analysis*

4.2.3.1 *Head Rotation and eye tracking*

Head Rotation and eye tracking (Reye, Leye) did not have a normal distribution and the analysis of variance for these variables was performed with the Kruskal-

Wallis test. The average total path length for head rotation was 38.75 units on the keyboard and mouse, while the gamepad averaged 7.63 units, and the VR hand controllers averaged only 6.56 units (Figure 20). The average total path length of the eye movement was 161.03 units on the keyboard and mouse, while only 61 units on the gamepad and 59.88 units on the VR hand controllers (Figure 19). Non-parametric tests were performed for the Head Rotation and eye tracking (Reye, Leye) variables. All three variables indicated a p-value greater than 0.05, retaining the null hypothesis. No statistically significant differences were found between the experimental groups for these variables.

4.3 MAIN STUDY

The main study consisted of a second round of data collection that included the makerspace controller. This second round of tests consisted of a total of 13 participants, including the results of the 6 participants in the preliminary round. Half of these participants were students in a health sciences related program and the other half were from a computer science or IT background.

4.3.1 *Analysis of Normality*

The HeadPos metric, NASA TLX, SUS and VRPQ are normally distributed ($p > 0.05$), unlike HeadRot, HR, and eye tracking metrics, which did not meet this condition.

4.3.2 *Parametric tests*

The makerspace controller is now the input device with the highest raw NASA TLX score of 2.33, the lowest SUS score of 74.64, and the highest VRPQ score of 89.85 as shown in Figure 15, Figure 16, and Figure 17, respectively. Inferential statistics indicated a significant difference between groups in questionnaire score-dependent variables (F (3,6) = 100.57, p < 0.001).

4.3.2.1 *Raw NASA TLX*

A one-way ANOVA revealed that there was no statistically significant difference in the NASA TLX score between at least two groups (F(3) = 2.385], p = 0.137). The introduction of the makerspace controller group did not show significant differences in contrast to the other three experimental groups.

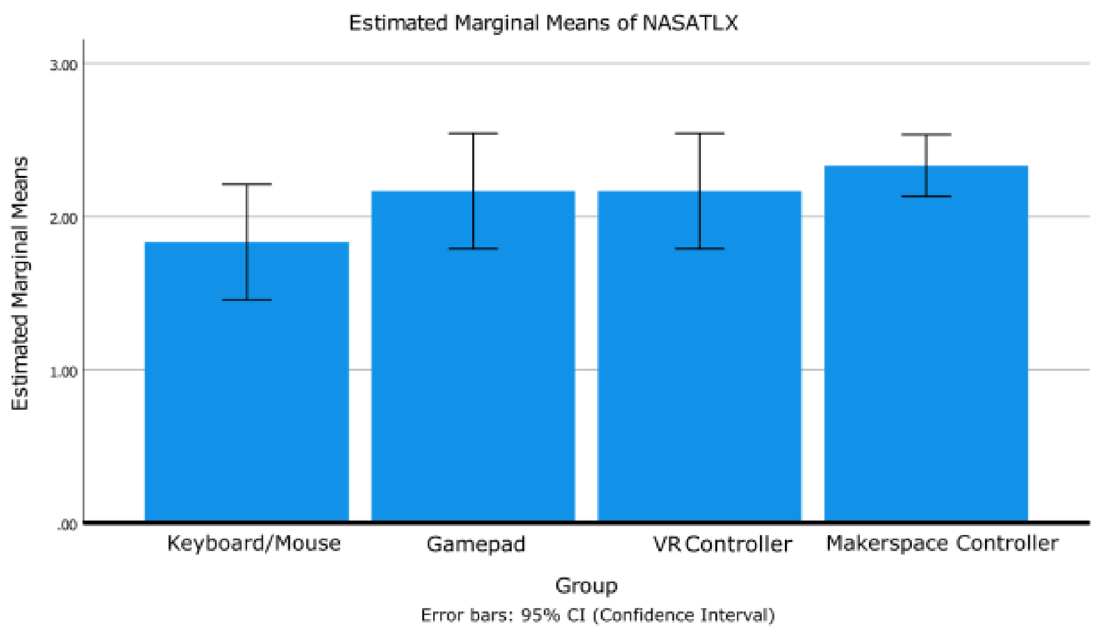


Figure 15: Group average scores for NASA TLX, main study

4.3.2.2 *SUS*

A one-way ANOVA revealed that there were no statistically significant differences in the SUS score between at least two groups (F(3) = 0.140], p = 9.33).

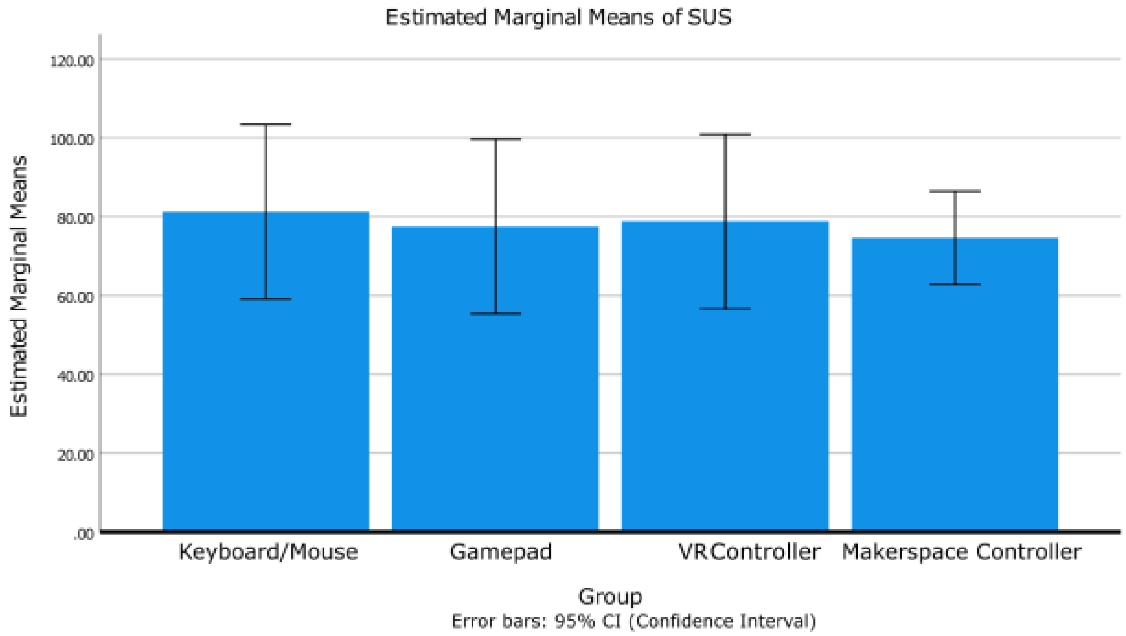


Figure 16: Group average scores for SUS, main study

4.3.2.3 *VRPQ*

A one-way ANOVA revealed that there were no statistically significant differences in the VRPQ score between at least two groups ($F(3) = 1.98$, $p = 0.188$).

4.3.3 *Head Position*

A one-way ANOVA revealed that there was a statistically significant difference in the HeadPos score between at least two groups ($F(3) = 10.505]$, $p = 0.003$), with mean averages shown in Figure 18. Post hoc tests were performed using the Tukey HSD method. The Tukey HSD test allows pairwise comparisons between the experimental groups to determine which specific group(s) differ significantly from each other. There are significant differences in the HeadPos variable between groups, as determined by the Tukey HSD test. The averages on the keyboard and mouse were significantly different from those on the gamepad ($p < 0.05$) for

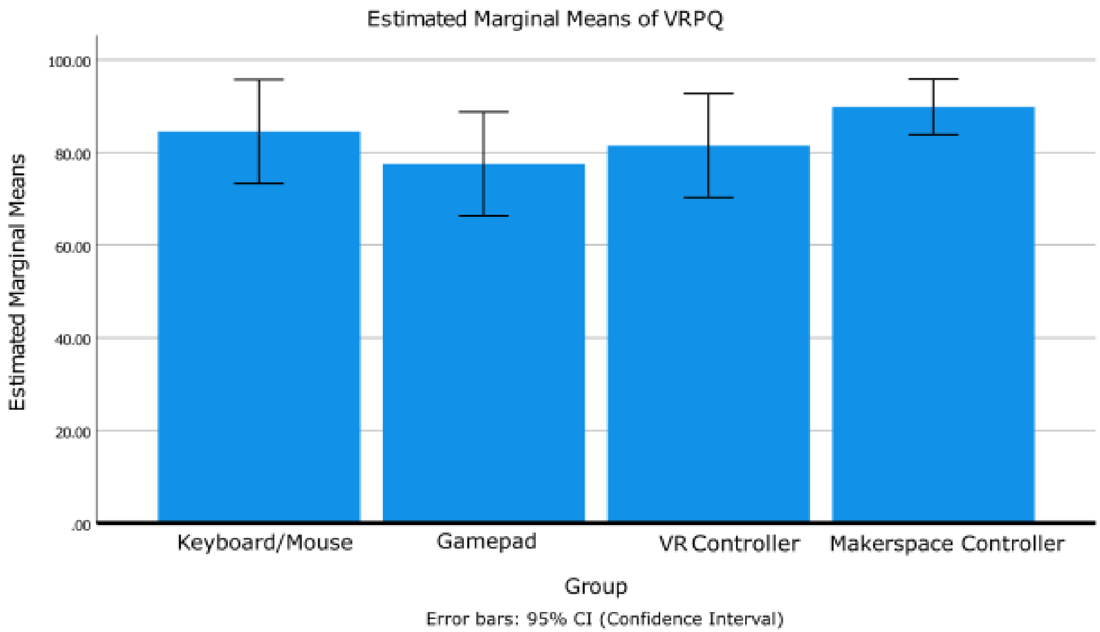


Figure 17: Group average scores for VRPQ, main study

the HeadPos variable. No other comparisons for the HeadPos variable reached significance at the alpha = .05 level.

4.3.4 *Non-parametric tests*

Non-parametric tests were also performed for the Head Rotation, Reye, Leye, and Heart Rate variables. The test results showed that the distribution of the variables HeadRot and HR is not the same across all groups, due to the Kruskal-Wallis tests showing a p-value < 0.05. However, the eye-tracking variable Reye and Leye showed a p-value of 0.65, retaining the null hypothesis. Figure 19 shows mean averages for eye position, while Figure 20 shows mean averages for Head Rotation and Figure 21 shows mean averages for Heart Rate.

Specifically, the independent samples Kruskal-Wallis test revealed that for Head-Rot, the group on VR controller had significantly different values compared to the groups on the other three devices.

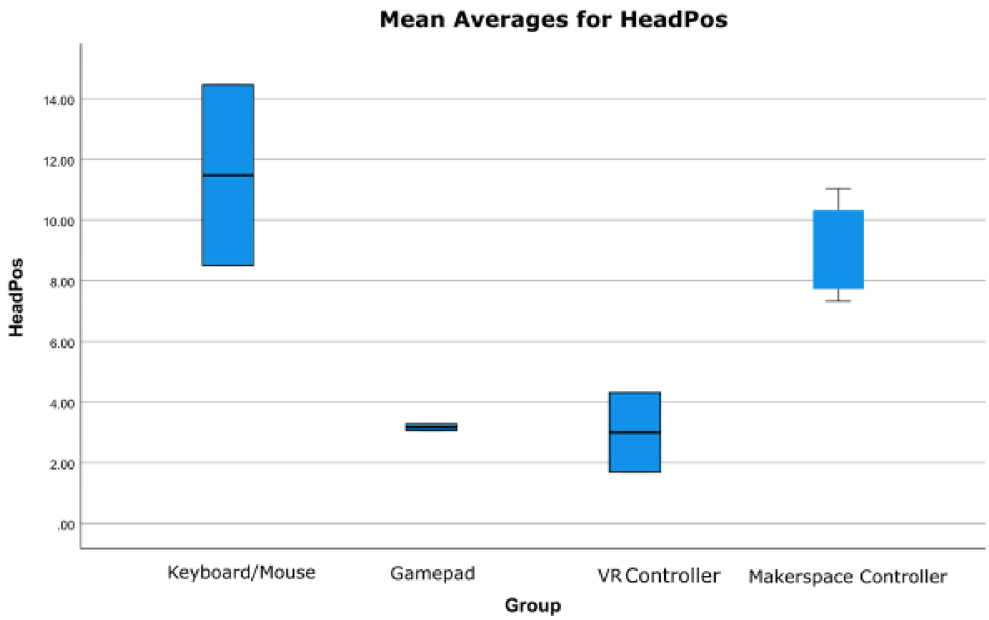


Figure 18: Mean average scores for HeadPos by group, main study

Regarding the HR variable, the keyboard and mouse group had significantly different values compared to the makerspace haptic controller group.

4.4 DISCUSSION

4.4.1 *Metrics*

The metrics collected are indicative of both cognitive involvement and motor skills, which in turn are factors that can impact the research goals of this thesis. The HeadPos and HeadRot variables, which track a user's variance of head position and rotation, are indicative of a user's ability to control their head movements and orientation in the VR environment. Variance in head position and rotation is closely tied to motor skills, particularly fine motor skills, as users must make precise movements to control their viewpoint within the VR space. This can affect the ability to perform tasks effectively. As mentioned previously in Chapter 3,

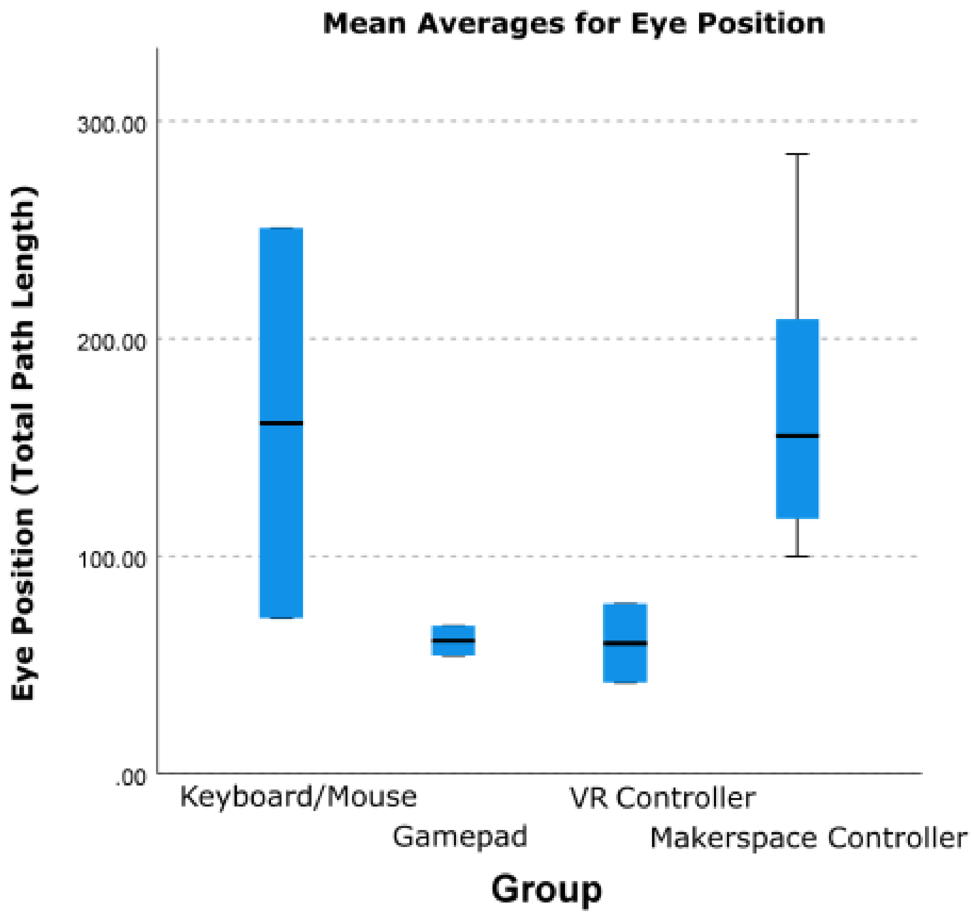


Figure 19: Mean average scores for SUS by group, main study

these metrics were collected as indicators of physiological interest and willingness to explore the immediate surroundings, which is a factor in user immersion [3].

Heart rate and eye tracking data can provide insight into a user's cognitive metrics. As key variables for understanding cognitive skills, eye tracking data reveal where users focus their attention during the task, while heart rate reflects the user's emotional and cognitive engagement. Efficient eye movements and attention allocation are critical for cognitive performance, while an elevated heart rate can indicate an increased cognitive load or emotional response to VR experience, which can affect task performance. Similarly to the HeadPos and HeadRot variables, eye tracking data is a valuable physiological indicator of increased engagement with the virtual environment. Heart rate is also used as a correlative metric to evaluate

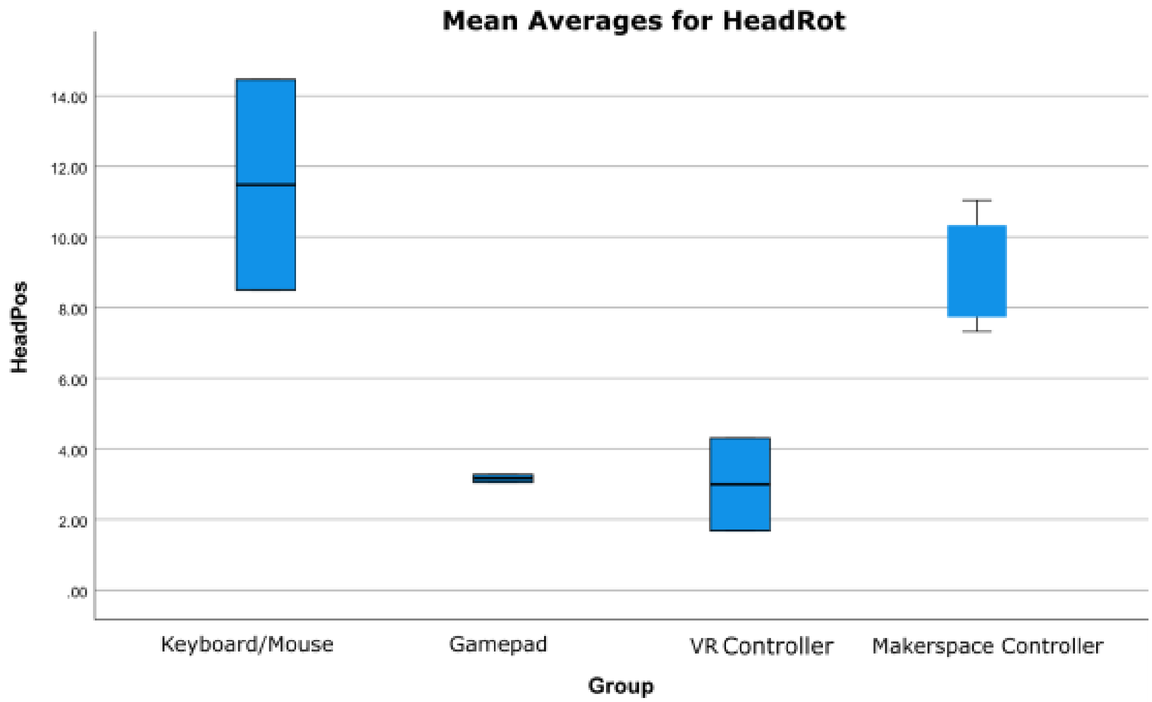


Figure 20: Mean average scores for HeadRot by group, main study

cognitive workload alongside questionnaires such as NASA TLX in usability studies [24].

The results of the univariate ANOVA analysis indicated that the mean scores in HeadPos were significantly different between the different groups. This means that the differences in head movement between the groups were not random and were therefore affected by the choice of interface. The keyboard and mouse had the lowest mean score, and the custom controller had the highest mean score. This can be attributed to the increased immersion with the custom-made controller due to its closer representation of the laparoscopy task, having the physical fetoscope handle, as well as a model of a human belly. The novelty of the custom-made controller is also a factor that leads participants to want to look around the virtual environment more closely. Self-reported feedback from participants supports this reasoning, with multiple participants saying that they enjoyed the simulator with

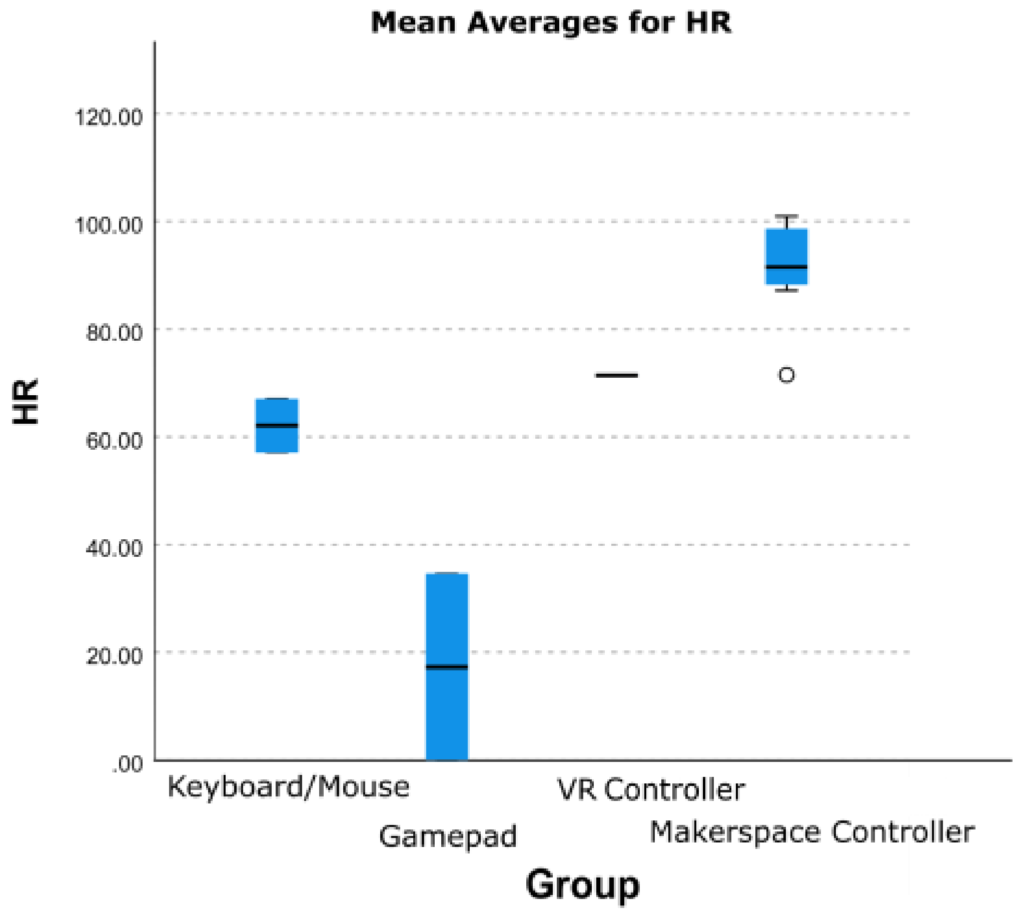


Figure 21: Mean average scores for HR by group, main study

the custom-made controller and expressing interest during the study with respect to the virtual environment. Two participants directly mentioned the immersiveness of the simulation with the makerspace controller through self-reported feedback: "The simulation was both engaging and immersive" and "The clinic made the task feel real." The makerspace controller group also had significantly higher HR scores than the other three experimental groups. The increase in the mean heart rate for the HR variable is a positive indicator of increased immersion [19], as is the high mean score for the variation in head position. The unique novelty of the makerspace controller's design, coupled with its potential for offering a more intricate and versatile interaction with the virtual environment, may have triggered participants' curiosity and engagement. However, this additional curiosity is built upon the fact that the participants did not have prior experience with the device, and likely had very limited experience with VR simulation as a whole. Therefore, the unfamiliarity of the makerspace controller could have prompted participants to explore a wider range of unfamiliar actions and manipulations, demanding an increased cognitive load. This, in turn, may have led to increased physiological responses, such as elevated heart rate, as well as greater variation in head position, indicating an immersive experience. This is further supported by self-reported feedback post-study, with a participant saying "the hardware can be (...) finicky" and another saying "simulation will improve once the calibration of the device is refined".

With regard to head rotation, VR controllers showed significantly lower scores compared to both keyboard/mouse and makerspace laparoscope controller, and gamepad and VR controllers had significantly lower scores for REye and LEye compared to keyboard/mouse and makerspace controller. This means that participants moved their heads and eyes much less while using the VR controllers compared to the other experimental groups, keeping themselves more steady during task operation. This reduced total path length for head rotation and eye movement could be due to a need to reduce sensory conflict on an unfamiliar input system [31]. Self-reported background information for all three consumer-level device groups indicated some familiarity with PC gaming for most participants (10 out of 13 participants), and only one participant indicated previous experience with VR gaming. Furthermore, participants in the VR controller group indicated prior experience only in PC and mobile games. This background indicates that VR controllers would be a less familiar input system than keyboard and mouse, which supports the reasoning that the increased stability was done to combat this sensory conflict, consciously or subconsciously.

4.4.2 *Usability, Cognitive Load, and Presence*

The SUS, NASATLX, and VRPQ questionnaires primarily measure the usability, cognitive workload, and presence experienced by users. These measures provide direct self-reported insights into cognitive skills and task performance. A higher cognitive workload, as indicated by NASATLX, may suggest that the task is cognitively demanding, potentially affecting performance. The VRPQ can provide information on the sense of presence and participation, which can also influence the performance of the task. The SUS is an indicator of a system's usability, as well as a user's comfort level while interacting with the system.

The overall multivariate test showed a significant effect between groups for the post-study questionnaires. A univariate ANOVA did not show significant differences between the groups for the NASA TLX, SUS, and VRPQ questionnaires. These findings confirm the null hypothesis, which states that the input device did not have a statistically significant impact on the participants' self-reported experience in VR simulation in terms of mental load, usability, and presence in VR. However, null results do not necessarily mean that there are no differences to be found between the tested device types; instead, they indicate that no significant differences were observed in this particular sample. Potential explanations for the null findings include the relatively small sample size of 13 and the specific choice of input devices used in this study. Furthermore, while the small sample size limits statistical power, noticeable differences can be observed in questionnaire scoring between the group of participants. Specifically, the keyboard and mouse had significantly higher scores on NASA TLX than all but the makerspace controller, indicating higher preferences for the keyboard and mouse among consumer retail devices. Since participants within the keyboard and mouse group had indicated relatively high prior experience with PC gaming (at least several hours a week on PC), this can be attributed to prior familiarity with the WASD control scheme. The makerspace controller group had significantly lower scores in SUS compared to all other groups, which is attributed to unfamiliarity with the input gestures using the fetoscope controller. Due to the custom-made nature of the fetoscope controller, no participants would have prior experience with such an input device. During the study sessions, it was observed that some participants were initially uncertain of how to hold the fetoscope, frequently changing their positions on the fingers for the first few targets until a comfortable position was found. There were also multiple responses from within the makerspace controller group with feedback on the accuracy with which the virtual fetoscope responded to input via the makerspace controller. No other significant pairwise differences were observed on the dependent variables.

Although no statistically significant differences were shown when distinguishing between the results of participants from different academic backgrounds, the SUS showed lower average scores from health science students than from game development students. Differences in average scores between demographic groups were negligible for the NASA TLX and VRPQ questionnaires, indicating that the simulator provided less usability, but approximately the same cognitive load and presence, to health science students compared to the game development students.

4.4.3 *Further Observations*

Demographically, the health science students had less prior experience with video games, VR or otherwise, than game development students. Health science students also showed greater uncertainty with the initial operation of the VR headset during the study sessions, which correlates with a greater variance in head position and rotation due to unfamiliarity with the use of HMD. However, while inferential statistics showed that there was a significant difference between the groups in questionnaire scores, no significant notion of difference was found based on the academic background of the subjects. It should be noted that participants of all academic backgrounds had no previous experience with laparoscopy and very limited experience with VR; therefore, it should not be considered that they had prior knowledge of the procedure or simulation tasks.

4.4.3.1 *Limitations*

It is important to note certain limitations of the study. For example, the sample size of 13 for this study was small, which may limit whether these results may apply to other populations on a larger scale. Due to the complexity of the test setup area, which involves a custom controller device and VR devices as well as a laptop, the study required in-person testing. This restriction added significant difficulty in gathering recruitment participants willing to physically travel to the testing location to participate. Furthermore, the different types and levels of prior familiarity with VR systems and/or digital games received by each group are not fully controlled. Future research should take these limitations into account to build on these findings and expand on their implications.

4.5 CHAPTER SUMMARY/TAKEWAYS

This chapter presents a comprehensive analysis of data collected during the user study, providing information on participant interactions and experiences between various groups of input devices within the virtual environment. The data collected were analyzed to obtain information on possible trends and behaviors that could show how the study groups based on input devices differed from each other. A statistical power analysis was conducted using G*Power to determine the effect size of the study using the sample size. The effect size f(U) was calculated using SPSS GLM Univariate tests to obtain a partial eta squared (np2) value of 0.778. The data collected were analyzed as two different sets: i) a preliminary study that was conducted using only commercially available input devices, with statistically significant differences between six participants in the study, including the total path length, the NASA TLX raw score, and the SUS score; and ii) analysis that included the custom-made haptic controller, showed different differences from the other experimental groups in terms of statistical significance.

The results showed that the custom-made controller had the highest mean score for head position variance and heart rate, indicating increased immersion, while the VR controller group showed significantly lower scores in head and eye movement compared to the other groups. However, there were no significant differences in questionnaire scores between input devices and the study found that previous experience with video games or VR did not significantly affect performance. The conclusion of this chapter also included some limitations of the study that can be potentially addressed in future work.

5 CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORK

5.1 OVERVIEW

This chapter presents the conclusions, recommendations, and future work drawn from the research process of answering the research question "How do different input devices affect usability, cognitive load, performance, and immersion when performing aim and laser laparoscopy tasks?"

5.2 CONCLUSIONS

This master's thesis presented the development and evaluation of a VR simulator utilizing the Unity game engine and the HP Reverb 2 Omnicept Edition headset for laparoscopic fetoscopic surgery simulation with four different input devices, including a mouse+keyboard, gamepad, VR controller, and makerspace controller representing a real laparaocope housed in a 3D printed womb. To answer the research question, self-reported questionnaires of usability, cognitive load, and presence, in addition to the incorporation of eye tracking technology, were used to enhance the user experience, providing a deeper understanding of interactions within the virtual environment. The simulator's design featured two virtual spaces for providing proper visual representation, including the operating room and the uterus, with an abstract and simplified task board used for laparoscopy training.

The study involved two rounds of data collection with a total of 13 participants of Health Sciences and computer science backgrounds. To answer the research questions, the study investigated the impact of custom-made input devices on immersion, usability, cognitive load, and performance during aim and laser tasks within the VR simulator. Due to the small sample size, our preliminary findings, which require further research, indicated that custom-made devices positively influenced these aspects compared to non-immersive input devices like keyboards and mice. Furthermore, the makerspace device significantly affected participants' cognitive load, suggesting potential implications for future VR simulator designs in medical education and training. Therefore, it can be concluded that the original hypothesis of "Input devices that better replicate the task being performed will positively affect usability, cognitive load, performance, and immersion more than a non-immersive input device" is confirmed.

From the development process, it can be concluded that IVR integration for non-immersive digital simulators is a viable solution to heighten immersiveness while operating medical simulators. As the process involved in the development of this simulation used the Unity game engine to handle the virtual environment, it can also be concluded that Unity is a viable platform for developing mid-end laparoscopic task simulations. It is also important to note as a takeaway that, while designing simulations for training, the input devices selected may influence the execution and usability of the overall system.

The contributions of this thesis extend beyond technical aspects, addressing economic sustainability in VR simulation. Using consumer-level hardware and makerspace devices, this research contributes to understanding the effects of consumer-level input devices and their impacts on laparoscopic simulation that could be used to inform improvements and further applications in other procedures. The review of the literature supports the adoption of virtual reality in medical simulation, emphasizing the need for further exploration of the impact of user interfaces on user experience and task completion. Ultimately, this thesis sets the stage for the wider adoption of cost-effective VR simulations in medical education, marking a potential shift in the landscape of MIS training and promoting diversity in access to medical education resources.

In conclusion, user input devices that are more representative of medical instruments, in this case the laparoscope, have a positive effect on presence and usability, while increasing cognitive load as participants become familiar with the controls and manipulations that require them to use a laparoscope and a pedal instead of a keyboard, mouse, gamepad, or VR controller for the first time. By better understanding how multiple user input devices impact the user experience and the task being performed, this thesis serves as a source of information to inform decision-making when developing VR simulators that rely on traditional user interfaces. For example, when being limited to using keyboard, mouse, gamepads, or VR controllers, efforts should be made to capture and replicate tools as accurately as possible. Furthermore, with current advances in 3D printing, cost-effective add-ons to gamepads, and VR controllers are possible to further increase realism and task representation.

5.3 RECOMMENDATIONS

Based on the user study and the development of the VR simulation, the following recommendations from lessons learned are shared:

- Increase the sample size: One of the main limitations of this study is the ability to obtain a large sample size to establish strong statistical power. The difficulty of obtaining participants in person during the summer months of the academic year was a main contributing factor to this limitation. Although this study recruited 13 participants between factors, future research could target a larger sample size to increase generalizability of the results and yield more statistically significant results.
- Variation of Laparoscopic Scenarios: While the current study simulated only one virtual laparoscopic scenario, future studies could include other medical scenarios to provide more information on the impact of input devices on different types of tasks. This would also allow medical simulation to accommodate a wider range of MIS procedures for training.
- Alternative input devices: The results of this study suggest that custom-made input devices optimized for the task at hand can significantly improve the

user experience. Future work could examine the use of alternative input devices, such as other makerspace prototypes or hand tracking motion controllers such as the LeapMotion, to further improve the novelty, realism, and accuracy of medical simulations. Longitudinal studies: Additional studies that evaluate the repeated engagement of a user with the simulation over longer periods of time, such as an academic semester or a year, can provide insight into metrics such as skill retention or interest in self-practice.

- Skill transfer studies: This study focused on the impact of immersion and user experience within the virtual environment. However, as an educational aid, another factor that determines the efficacy of digital simulation is task performance. Further research can explore task performance as a metric to confirm the validity of the construct.
- Cross-disciplinary collaborations: Further collaboration among experts in computer science, game development, and medical education can help ensure the development of robust and effective VR simulators for medical training.

The above recommendations acknowledge the limitations of the study and build on the insights gained over the course of this thesis. The effectiveness of VR simulators in future work can be improved by further exploring the design elements and strengths of VR as an interactive medium. As the fidelity and capabilities of VR as a vessel for interactive media grow, research on its impact on human factors must grow proportionally to maximize the user benefits VR can enrich our lives with.

5.4 FUTURE WORK

This project's exploration of VR simulation and immersion for MIS has revealed promising avenues for advancement and refinement. As previously mentioned in the previous Recommendations section, future work should focus on understanding how varied input devices, such as hand controllers, haptic gloves, or other emerging technologies, influence the immersive experience for surgical trainees.

In addition to exploring the subjective perception of immersion, future research efforts can elaborate further on gathering and analyzing quantitative metrics on human immersion. Conducting controlled experiments to measure objective indicators of immersion, such as presence, embodiment, or task performance metrics influenced by input devices, would enrich our understanding of their impact. Physiological indicators such as cognitive load and electrocardigram (ECG) metrics can be used to gain further insight into how immersion in VR is understood.

As the process involved in the development of this simulation used the Unity game engine to handle the virtual environment, it can also be concluded that Unity is a viable platform for developing mid-end laparoscopic task simulations. Further development of digital MIS simulations can continue to use Unity or similar digital game engines to develop medical simulation software. It is also important to note as a takeaway that, when designing training simulations, the input devices selected can influence the execution of tasks and usability of the overall system. As digital MIS simulations become more ubiquitous, further research on custom-made input devices can help fill the gap in research on how hardware can impact immersion in a VR experience.

Design-wise, more research could also focus on developing user-centric design principles for input devices in VR simulations. Investigating user preferences, ergonomic considerations, and the intuitive nature of different devices among consumer and custom hardware would help optimize the immersive experience, facilitating the seamless integration of technology into surgical training curricula. The continued incorporation of custom user interfaces will further contribute to reducing costs, promoting accessibility, and democratizing medical education, especially in underserved or remote communities.

6 APPENDICES

6.1 appendix:consent form

Title of Research Study: Virtual reality aim and laser framework usability assessment

You are invited to participate in a research study entitled Virtual reality (VR) aim and laser framework usability assessment. This study has been reviewed by the University of Ontario Institute of Technology Research Ethics Board [**17127**] and originally approved on [Feb 17, 2023].
Please read this consent form carefully, and feel free to ask the Researcher any questions that you might have about the study. If you have any questions about your rights as a participant in this study, please contact the Research Ethics Coordinator at 905 721 8668 ext. 3693 or researchethics@uoit.ca.

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Purpose and Procedure:
Virtual reality (VR) is becoming widely adopted due to recent affordability, thus making a consumer-level technology that is disrupting how education, training, entertainment, and health care is done. However, VR solutions typically present one-size-fits-all interactions that fail to account for the variability of users with respect to their ergonomics. For example, average arm length may pose interaction challenges to users with shorter or longer arms resulting in difficulties associated with completing the tasks that can negatively affect immersion, presence, and usability.

This Thesis study focuses on understanding how upper limb ergonomics may affect task completion and usability, engagement and immersion as part of the user experience.

Procedures:

The study will take place in-person in one session. You will;
i) complete this consent form for 5 minutes,
v) put on the head-mounted display equipment and undergo an introduction to the experiment and tasks

6.2 APPENDIX: QUESTIONNAIRES

SUS: System Usability Scale

Questionnaires

1) I think that I would like to use this interaction mode again	1: Strongly Disagree 2: 3: 4: 5: Strongly Agree
2) I found the interaction unnecessarily complex	
3) I thought the interaction mode was easy to use.	
4) I think that I would need the support of a technical person to be able to use this interaction mode	
5) I found the various functions in the interaction mode well integrated	
6) I thought there was too much inconsistency in this interaction mode	
7) I would imagine that most people would learn to use this interaction mode very quickly	
8) I found the interaction mode very cumbersome to use	
9) I felt very confident using the interaction mode.	
10) I needed to learn a lot of things before I could get going with this interaction mode	

NASA TLX: Task Load Index

1. How mentally demanding was the task?	1: Very Low 2: 3: 4: 5: Very High
2. How physically demanding was the task?	
3. How hurried or rushed was the pace of the task?	
4. How successful were you in accomplishing what you were asked to do?	
5. How hard did you have to work to	

6.3 appendix: thank you script

Appendix 4: Thank you script

We thank you for volunteering your time to help with this study. If you have any further queries or observations arising from this study, please feel free to write to us by email.

Have a great day!

6.4 appendix: instructions

Instruction Script:

Welcome:	Welcome to the test scene! You will be seated during the study. Please ensure you have sufficient space to move your arms and if you are in a chair with wheels or that swivels, please lock this on your chair or do your best to refrain from swivelling/moving the chair position. For this study, you will be required to aim and fire a laser from your position to the targeted zone in front of you. At any point, if you wish to stop please take the headset off. If you wish to continue, you will have to start the user study from the beginning. If you are ready to start, please hold the trigger button on your controller for 3 seconds.
Study Instructions	For this study you will be performing aim and laser tasks using 4 different random input devices. The interaction will require you to aim and mark points of interest in the virtual environment. Each task will take 2 to 5 minutes. After completing each aim and laser task, you will complete the provided questionnaires followed by general questions about your experience. Answering these questionnaires will take 5-10 minutes to complete after each aim and laser interaction technique. If you have any questions, please ask the researcher now.
Questionnaire introduction:	Questionnaire time! Please feel free to remove the headset and complete the questionnaires on the provided laptop until you are ready to continue.
Conclusion and Thank you	You've reached the end of the study session. We thank you for volunteering your time to help with this study. If you have any further queries or observations arising from this study, please

6.5 APPENDIX: SUBMISSION OF DATA

Once you have completed the study, please go to this link to our Google form to submit your data.

https://forms.gle/nDSdkfa2BLEhWTmD6

Please follow the instructions on this link to submit.

6.6 appendix: review summary (aggregations)

Table 4: Review Summary (Aggregations)

Authors	Study	Methods	Conclusions
[37]	Virtual Reality as an Affirmative Spin-Off to Laparoscopic Training: An Updated Review	Literature review on three databases, including MEDLINE, EMBASE, and Cochrane Library.	VR simulators are an effective training modality for laparoscopy training, with promising outcomes.
[45]	Immersive Virtual Reality for Surgical Training: A Systematic Review	Literature search was performed on MEDLINE, EMBASE, CENTRAL, Web of Science, and PsycInfo	Immersive VR incorporation into surgical training programs supported by high-quality, albeit heterogeneous, studies demonstrating improved procedural times, task completion, and accuracy, positive user ratings, and cost-effectiveness.

[55]	Virtual Reality Applications in Medicine During the COVID-19 Pandemic: Systematic Review	Systematic search of the literature on the PsycINFO, Web of Science, and MEDLINE databases	Virtual reality has been applied frequently in medicine during the COVID-19 pandemic, with positive effects for the treatment of several health conditions and for medical education and training. Some barriers need to be overcome for the broader adoption of virtual reality in the health care panorama.
[4]	Virtual reality adoption during the COVID-19 pandemic: A uses and gratifications perspective	Surveyed 298 Amazon Mechanical Turk users during the fall of 2020 on VR usage	Pandemic's perceived impacts influenced the likelihood of acquiring VR for education, tourism, and work

6.7 APPENDIX: REVIEW SUMMARY (STUDIES)

Table 5: Review Summary (Studies)

Study	Simulator	Participants	Assessment	Results
Understanding VR Simulation				
[32]	RobotiX Mentor VR Simulator	11 novice surgeons, 11 experienced surgeons	Guided Vaginal Cuff Closure module	The experienced surgeons significantly outperformed the novice surgeons on 6 of the 18 metrics.
[62]	virtual immersive operating room simulator (VIORS)	27 novices, 13 intermediates, and 5 experts	Laparoscopic cholecystectomy procedure	The participants gave positive feedback on the realism and procedural training capabilities of VIORS, and the results showed that the simulator was effective in distinguishing between participants with varying skill levels.
High-End MIS Simulators				

[27]	Lapsim virtual reality simulator, Simball box trainer	20 participants all regarded as novices	Two sets of laparoscopic tasks on the Simball trainer, with the non-control group undergoing a practice course on the Lapsim simulator in between	The group that practiced on the LapSim had a faster learning rate compared to the control group, with an overall faster completion time on three of the four Simball tasks after the training course
[59]	screenspace virtual reality simulator for urologic surgery	10 clinicians without prior experience with the simulator	Virtual surgery in the urinary tract	The system scored adequately on usability, 4.4 to 4.6 out of 5
Mid-End MIS Simulators				
[39]	SmartSIM, low-cost VR simulator	Unknown	MIS training workshops at a Pakistani hospital	SmartSIM demonstrated higher degrees of usefulness for MIS skill training compared to box trainers and commercial simulators such as LapSim

[33]	Highly immersive virtual reality laparoscopy simulation: development and future aspects	16 participants being surgical staff	regular VR vs IVR laparoscopy	no significant performance difference, but heightened immersion
[57]	low-cost virtual reality surgical simulator for surgical oncology	Surgical trainees (unknown number)	VR prototype simulation vs traditional training	No results
[30]	LapSim simulator with Holopointer augmentation	10 novice trainees	Virtual cholecystectomy	significantly improved economy of movement and reduced error rates, as well as an overall improved user performance
[36]	Hybrid fetoscopic skills trainer	8 participants (2 experts, 2 intermediate, and 4 novices)	Fetal laser ablation (Solomon technique)	A median score of 3.50 out of 5 for all aspects
Low-End MIS Simulators				

[2]	SIMISGEST-VR	30 participants	Grip and placement tasks, target manipulation, diathermy	Averages of 3-5 on all categories (likert questionnaire out of 5)
[75]	box trainers	18 junior doctors	General practice	Participants used an individualized approach to training at home, mixing their at-home training on the box trainers with more formal practice at the simulation center
[78]	Haptic versus non-haptic virtual reality simulators	36 residents without any previous laparoscopic experience	General skill test	Haptic virtual reality simulators reduce the time to reach proficiency compared to non-haptic simulators.}
[12]	low-cost laparoscopic trainer named "Lap-Pack"	8 surgeon trainees	FLS tasks, Lap-pack vs Inovus Pyxus HD	Confirmed validity of Lap-pack from questionnaire feedback

[16])	Lap-Tab box trainer validity study	74 medical students and novice OBGYN	laparoscopic peg transfer task before/after 3 weeks of self-study	laparoscopic trainer boxes are just as effective in developing skills in medical students as simulation centers
[22]	laparoscopic box-trainer dataset, IFCL.LBT100	N/A	Dataset for image recognition during FLS peg transfer tasks	Testing confirmed the image recognition worked for 3 different trainees
[76]	a low-cost, space-efficient, portable box trainer that allows for the breakdown of complex tasks	10 participants, of faculty and trainees	FLS training tasks, rated by survey	Majority indicated favorably to the box trainer's ease of use and realism.
Task Representation				

[20]	LapSim laparoscopic simulator	Participants (n = 63) were grouped based on their level of experience into three categories: 16% were residents, 46% were specialists, and 38% were consultants.	Peg transfer, salpingectomy by extra-uterine pregnancy	Statistically significant result (p \textless 0.001), confirming face validity
[40]	VR simulator prototype designed specifically for training core manual skills in laparoscopic pediatric hernia repair.	36 pediatric surgeons	Hernia suturing task	Overall simulation realism was rated an average of 3.08 (out of 5), good content validity, with scores of 3.61, 3.64, and 3.89
[78]	haptic versus non-haptic virtual reality simulators	36 residents without any previous laparoscopic experience	General skill test	Haptic virtual reality simulators reduce the time to reach proficiency compared to non-haptic simulators.

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