Faculty of Engineering of the University of Porto

Development of a mixed reality platform to be used in surgery: needs assessment and case study

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Abstract

Mixed reality is a technology which allows the user to see and interact with both the physical and the virtual world simultaneously. Various applications of mixed reality have been implemented in the area of healthcare, particularly in surgical practice and training.

The several challenges in the operating room, namely the lack of communication in the surgical team, and mistakes made by the professionals, might be solved through the use of technology during the procedure.

In this dissertation, the importance and potential of mixed reality in surgery were investigated, through the research of some already existing applications, in a state-of-the-art analysis. Moreover, a national Delphi study was conducted in order to better understand the needs of the surgeons in the operating room. Participants have emphasized the importance of mixed reality in several surgical areas, as well as mixed reality's ability to improve the accuracy of the procedures.

Afterwards, a mixed reality tool was developed, using Microsoft HoloLens 2 and Unity, to be applied in the training of the anterior cruciate ligament reconstruction surgery. This application was evaluated by surgeons of *Unidade Local de Saúde de Santo António*, who performed a surgical simulation using a more traditional method (arthroscopy), followed by the mixed reality application; each section was repeated twice by the surgeons. The simulation times were measured, and they decreased, on average, in the second repetition of the simulation, which indicated that the surgeons were able to adapt to the technology being used. Finally, they answered a questionnaire related to the application's usefulness, and highlighted the potential these tools have in surgical training.

Keywords: Anterior Cruciate Ligament; Delphi Study; Extended Reality; Microsoft HoloLens 2; Surgical Training.

Resumo

A realidade mista é uma tecnologia que permite ao utilizador visualizar e interagir com o mundo real e virtual em simultâneo. Várias aplicações de realidade mista foram implementadas na área da saúde, em específico na prática e educação cirúrgica.

Os vários desafios existentes no bloco operatório, nomeadamente a falta de comunicação entre a equipa cirúrgica, e erros por parte dos profissionais, poderão ser resolvidos através do uso da tecnologia durante a cirurgia.

Nesta dissertação, a importância e o potencial da realidade mista na cirurgia foram investigados, através da pesquisa de algumas aplicações existentes, numa análise do estado da arte. Além disso, foi feito um estudo Delphi nacional, de forma a compreender melhor as necessidades dos cirurgiões no bloco operatório, onde os participantes enfatizaram a importância da realidade mista em várias áreas dentro da cirurgia, assim como a sua capacidade de melhorar a precisão dos procedimentos.

Por fim, foi desenvolvida uma ferramenta de realidade mista, com Microsoft HoloLens 2 e Unity, para ser aplicada ao treino cirúrgico de cirurgias de reconstrução do ligamento cruzado anterior. Esta aplicação foi avaliada por cirurgiões da Unidade Local de Saúde de Santo António, que fizeram uma simulação da cirurgia com um método mais tradicional (artroscopia), e, de seguida, experimentaram a aplicação de realidade mista, sendo que cada secção da simulação foi repetida duas vezes. Os tempos de simulação foram medidos. Os cirurgiões demoraram, em média, menos tempo a completar a segunda repetição, o que indica uma adaptação à tecnologia. Além disso, estes profissionais médicos preencheram um inquérito de usabilidade, onde destacaram o potencial das ferramentas de realidade mista para serem usadas no treino cirúrgico.

Palavras-chave: Ligamento Cruzado Anterior; Estudo Delphi; Realidade Estendida; Microsoft HoloLens 2; Educação Cirúrgica.

Contents

1. Introduction 1
1.1. Achievements 3
2. Theoretical Background 5
2.1. Delphi Method 5
2.2. Survey Implementation Strategies 7
2.2.1. Online Delphi (e-Delphi) 7
2.2.2. Welphi 8
2.2.3. Delphi Decision Aid 8
2.3. Extended Reality 9
2.3.1. Mixed Reality 9
2.3.2. Augmented Reality 9
2.3.3. Virtual Reality 10
2.3.4. Augmented Virtuality 10
2.4. Ethical Aspects and Regulations 10
2.5. Mixed Reality Tools 11
2.5.1. Microsoft HoloLens 2 11
2.5.2. Magic Leap 2 13
2.5.3. Meta Quest Pro and Meta Quest 3 14
2.5.4. Pico 4 16
2.6. Orthopedic Surgery and Mixed Reality 16
3. State of the Art 23
3.1. Research Process 23
3.2. Mixed Reality in Surgery 24
3.3. Mixed Reality in Surgical Training 32
3.4. Surgeon’s Problems in the Operating Room 34
3.4.1. Extended Reality as a Simulation Tool 35

4. Delphi Study 38
4.1. Characterization of the Experts 38
4.2. Questions 38
4.2.1. Round 1 39
4.2.2. Round 2 40
4.2.3. Round 3 41
4.3. Methods for the Analysis of the Results 41
4.4. Analysis of the Rounds 43
4.4.1. Round 1 43
4.4.2. Round 2 49
4.4.3. Round 3 53
4.4.4. Main Conclusions 56
5. Case Study 63
5.1. Preparation 63
5.2. Development 65
5.3. Questionnaire 79
5.4. Results 81
5.5. Discussion of the Results 87
6. Expectations and Hypothesis 92
7. Conclusions and Future Work 95
7.1. Limitations and Difficulties 95
7.2. Main Conclusions 95
7.3. Future Work 96
8. References 98
9. Appendixes 122
9.1. Gantt Diagram 122
9.2. IJUP's Abstract 123

9.3. State of the Art Summary 125

List of Figures

Figure 1 - Characteristics of the Delphi method. Adapted from: [6]. 5
Figure 2 - Microsoft HoloLens 2: Industrial Edition. From: [42]. 11
Figure 3 - Magic Leap 2 components. From: [57]. 13
Figure 4 - Physician using CommandEP with Magic Leap 2. From: [61]. 14
Figure 5 - Meta Quest Pro. From: [63]. 15
Figure 6 - Meta Quest 3. From: [66]. 15
Figure 7 - Pico 4. From: [68]. 16
Figure 8 - Cortical button used in the ACL reconstruction surgery. From: [84]. 18
Figure 9 - Pathfinder ACL guide. From: [88]. 19
Figure 10 - I.D.E.A.L. femoral tunnel location. From: [90]. 20
Figure 11 - Sawbone femur model. From: [92]. 20
Figure 12 - SYNBONE tibia model. From: [94]. 21
Figure 13 - Flow diagram illustrating literature research, exclusion process, and number of included studies in the review. 24
Figure 14 - C- Arm fluoroscopy. From: [120]. 29
Figure 15 - G-arm fluoroscopy. From: [126]. 30
Figure 16 - World Health Organization Surgical Safety Checklist. From: [142]. 34
Figure 17 - Soldamatic Augmented Training. From: [145]. 36
Figure 18 - Applications of MR in surgery assessed by the question: What are, in your opinion, the applications of MR in medicine, particularly surgery? 44
Figure 19 - Main benefits of MR in surgical procedures assessed by the question: What are the main benefits MR might offer to surgical procedures? 44
Figure 20 - Main limitations of MR in surgical procedures assessed by the question: What are the limitations or challenges you are able to identify regarding the implementation of MR in surgical procedures? 45
Figure 21 - Potential of MR to improve surgical procedures assessed by the question: Do you believe MR has the potential to improve the accuracy and efficiency of surgical procedures? Please explain. 46
Figure 22 - Use cases of MR in surgery assessed by the question: Are you aware of any examples of successful MR applications in surgery? Identify such cases. 47

Figure 23 - Surgical areas which could benefit from MR assessed by the question: What specific surgical areas might benefit the most from MR? 48
Figure 24 - Ethical concerns in the use of MR in surgery assessed by the question: What ethical concerns should be considered in the usage of MR in surgical procedures? 48
Figure 25 - Comparison of the usefulness of MR in surgery, in the rounds 2 and 3 of the Delphi study. 57
Figure 26 - Comparison of the applications of MR in surgery, in the rounds 2 and 3 of the Delphi study. 58
Figure 27 - Comparison of the benefits of MR in surgery, in the rounds 2 and 3 of the Delphi study. 59
Figure 28 - Comparison of the limitations in the implementation of MR in surgery, in the rounds 2 and 3 of the Delphi study. 60
Figure 29 - Comparison of the ethical considerations of MR in surgery, in the rounds 2 and 3 of the Delphi study. 61
Figure 30 - 3D model of the drill (from [171]). 66
Figure 31 - Windows Device Portal. 66
Figure 32 - Box to take photographs of the surgical motor. 67
Figure 33 - Hologram of the tibia (initially). 68
Figure 34 - Hologram of the femur (initially). 68
Figure 35 - Femur and tibia holograms (after adjusting). 69
Figure 36 - Hologram of the surgical motor (after adjusting). 69
Figure 37 – (a) Model of the femur; (b) Model of the tibia; (c) Model of the knee grafts; (d) Surgical motor and drill. 70
Figure 38 - Green target being hit by the motor. 71
Figure 39 - Motor after inserting the QR code in the drill. 72
Figure 40 - Holograms of the femur and motor after the final adjustments. 72
Figure 41 - Frame rate of the MR application with only the femur present, and after it disappeared, before the optimization (in between the black lines). 73
Figure 42 - Frame rate of the MR application with only the femur present, and after it disappeared, after the optimization (in between the black lines). 74
Figure 43 - Frame rate of the MR application with only the motor present (before the optimization). 74
Figure 44 - Frame rate of the MR application with only the motor present (after the optimization). 75

Figure 45 - Frame rate of the MR application with all the holograms present (before the optimization)..... 76
Figure 46 - Frame rate of the MR application with all the holograms present (after the optimization)..... 76
Figure 47 - GPU utilization of the MR application with only the motor present (from the black line onwards), before the optimization. 77
Figure 48 - GPU utilization of the MR application with only the motor present (from the black line onwards), after the optimization. 78
Figure 49 - GPU utilization of the MR application with all the holograms present, before the optimization. 78
Figure 50 - GPU utilization of the MR application with all the holograms, after the optimization, from the black line onwards. 79
Figure 51 – Complete model of the knee. 82
Figure 52 - Experimental apparatus with the arthroscopic camera. 82
Figure 53 - Experimental apparatus with the MR application (with the motor hitting the green dot in the femur). 83
Figure 54 - Answers related to the usability of the application. 86
Figure 55 - Answers related to the usefulness of the HoloLens 2. 87
Figure 56 - Prototype of a future ideation of the application. 90

List of Tables

Table 1 - Answers related to the usefulness of MR in surgery (round 2)..... 49
Table 2 - Answers related to the applications of MR in surgery (round 2)..... 50
Table 3 - Answers related to the benefits of MR in surgery (round 2)..... 50
Table 4 - Answers related to the limitations in the implementation of MR in surgery (round 2). 51
Table 5 - Answers related to the ethical considerations of MR in surgery (round 2). ... 52
Table 6 - Answers related to the usefulness of MR in surgery (round 3)..... 53
Table 7 - Answers related to the applications of MR in surgery (round 3)..... 54
Table 8 - Answers related to the benefits of MR in surgery (round 3)..... 54
Table 9 - Answers related to the limitations in the implementation of MR in surgery (round 3). 55
Table 10 - Answers related to the ethical considerations of MR in surgery (round 3). . 56
Table 11 - Surgeons' simulation times (for both iterations of each modality - arthroscopic camera and MR application)..... 84
Table 12 - Average and median of the simulation times. 85
Table 13 - Gantt diagram with the planification for the first semester..... 122
Table 14 - Gantt diagram with the planification of the second semester. 123
Table 15 - State of the art summary. 125

List of Abbreviations

3D	Three dimensional/Three dimensions
5G	Fifth Generation
ACL	Anterior Cruciate Ligament
AI	Artificial Intelligence
ALPPS	Associating Liver Partition and Portal Vein Ligation
A-PBNRR	Adaptive Physics-Based Non-Rigid Registration
AR	Augmented Reality
AV	Augmented Virtuality
CAC	Centro Académico Clínico
CBCT	Cone-Beam Computed Tomography
CPU	Central Processing Unit
CT	Computed Tomography
DICOM	Digital Imaging and Communications in Medicine
DL	Deep Learning
DMZ	Demilitarized Zone
FDA	Food and Drug Administration
FLR	Future Liver Remnant
GPU	Graphics Processing Unit
ICBAS	Instituto de Ciências Biomédicas Abel Salazar
I.D.E.A.L.	Isometric, Direct insertion, Eccentrically located, Anatomical, Low tension-flexion
IJUP	Investigação Jovem da Universidade do Porto
INEGI	Instituto de Ciência e Inovação em Engenharia Mecânica e Engenharia Industrial
IoMT	Internet of Medical Things
MR	Mixed Reality
MRI	Magnetic Resonance Imaging
MRTK	Mixed Reality Toolkit
ODI	Oswestry Disability Index
OR	Operating Room
PET-CT	Positron Emission Tomography-Computed Tomography

PQx	Planificación y Navegación Quirúrgica
rAC-GAN	Robust Auxiliary Classifier Generative Adversarial Network
RAM	Random Access Memory
RISP	Remote Interactive Surgery Platform
RT3D	Real-time 3D content
UI	User Interface
ULSSA	Unidade Local de Saúde de Santo António
UNet	Unity Networking
VAS	Visual Analog Scale
VR	Virtual Reality
XR	Extended Reality

1. Introduction

Developing a Mixed Reality (MR) platform for use in surgery is a complex and critical endeavor that requires careful planning, a deep understanding of the needs and challenges in the medical field, and rigorous testing. First, the goals of the MR platform should be clearly defined. Due to the project's time constraints, and since it will not be possible to follow all the phases in detail, three main situations will be explored: training, planning and intraoperative applications. To effectively address these areas and ensure the platform meets the real-world demands of surgeons, a Delphi study will be conducted. This method will gather expert consensus on the most pressing needs and optimal solutions, guiding the development process with informed and practical insights.

To design the questions of the Delphi study in the best possible way, a literature review will be carried out, analyzing the existing literature and the MR technologies used in surgery and identifying the gaps and opportunities in this field. From this survey, the weaknesses, needs, and challenges faced by the chosen experts should be understood. Data on the experts' preferences and expectations will be collected. With this, areas where MR technology can be integrated to improve efficiency and outcomes might be identified. Renato Magalhães, an engineering expert and co-supervisor of this dissertation, will play a pivotal role in selecting the experts to take part in this study. Moreover, Professor Lúcio Lara Santos will provide invaluable insights and guidance throughout the process, leveraging his extensive expertise in the field [1]. Even if it is not anticipated that they will be immediately needed in this project, it is imperative to proactively outline regulatory and ethical considerations. This involves comprehensive research into the regulatory requirements for medical devices and MR technology in surgery, along with a thoughtful examination of the ethical implications and patient data privacy concerns.

A comprehensive technological assessment will be carried out, with the objective of discerning the strengths and weaknesses of the hardware available for this project, the Microsoft HoloLens 2, in comparison to other market offerings, such as Magic Leap 2 and others. This assessment will also include the identification of essential software components, including 3D modeling, image recognition, as well as the certifications they have, and coding tools.

In the final phase of the project, the aim is to develop a prototype of the MR platform to demonstrate its viability. This potential digital health tool is thought to be developed using Unity and the Microsoft HoloLens 2 headset. The assistance of Bernardo Neto from INEGI (*Instituto de Ciência e Inovação em Engenharia Mecânica e Engenharia Industrial*) (Eng.) and Gilberto Silva from ICBAS (*Instituto de Ciências Biomédicas Abel Salazar*) will be invaluable here. Testing it with a small group of surgeons will be vital to obtain feedback and make or identify any necessary improvements. Collaboration with Adélio Vilaça (MD), an orthopedic surgeon, will be crucial during this stage. A better understanding of the tools involved will be needed. To achieve this, a combination of thorough research and checking with professionals will be done. Michel Audette, an Associate Professor from the Old Dominium University, will be able to provide insights and pertinent questions in the development of the platform. Moreover, INEGI will provide support with both the hardware and the software. Dulce Oliveira (Ph.D), the supervisor of this dissertation, will play a crucial role in coordinating these efforts. INEGI is an investigation center, located at the FEUP campus, with several investigation groups. It is over 35 years old, and it has over one hundred investigators [2]. Close collaboration with medical professionals is paramount to the development of an MR platform for surgical applications. Therefore, the partnership with the *Unidade Local de Saúde de Santo António* (ULSSA), a healthcare institution, is indispensable to successfully support this intricate project. The ULSSA is composed of four different institutions, the *Hospital Geral Santo António*, the *Hospital Magalhães Lemos*, the *Centro Materno-Infantil do Norte Albino Aroso*, and the *Centro de Genética Médica Jacinto de Magalhães*. The *Hospital de Santo António* has existed since 1799. ULSSA is a centralized hospital, and it values education and investigation deeply. The ULSSA and the ICBAS share the *Centro Académico Clínico* (CAC) [3], [4]. CAC has the goal to "make meaningful advances in investigation, and to improve medical education" [5].

This report is divided into 9 sections. The present section introduces the project, its achievements, and the main objectives. The "Theoretical Background" section provides essential context to the main tools being used in this project, namely the Delphi study and MR tools, as well as how they might be applied to orthopedic surgery. In the "State of the Art" section, a comprehensive review is presented to get a better understanding of the MR applications in surgery and surgical training. The "Delphi Study" section elaborates on the research conducted to develop the Delphi study, as well as methods to analyze the

experts' answers, the questions, and the main results and conclusions. In the "Case Study" section, the development process of the application, as well as the inquiry of satisfaction, and the main conclusions from the simulation are shared. The methods involved in conducting the state-of-the-art search, together with the Delphi study conceptualization and the prototype making are described within the "State of the Art", "Delphi Study" and "Case Study" sections, respectively. The initial Expectations and Hypothesis are explored in a dedicated section. In the "Conclusions and Future Work" section, the main conclusions are drawn, in addition to prospects of future developments, and the potential limitations of this dissertation. All of the sources are listed in the "References". Additionally, the planification of the process (Table 13 and Table 14), as well as the table used in the state-of-the-art review (Table 15), and an abstract submitted to a conference of young researchers are presented in "Appendixes" for reference.

1.1. Achievements

An abstract related to the contents of this dissertation was submitted and presented at IJUP (*Investigação Jovem da Universidade do Porto*) 2024, and the work was distinguished (see "IJUP's Abstract").

Moreover, an article is being written, provisionally titled "How useful is mixed reality in surgical treatment? - a Delphi Study", with the most relevant findings of the Delphi study.

2. Theoretical Background

This section aims to provide a theoretical background for this project. First, the Delphi method is discussed, and some online tools for applying this technique are presented. Afterwards, extended reality is defined, and mixed reality tools (which can be used in surgery) are introduced. Ethical considerations are discussed, and lastly, orthopedic surgery and the anterior cruciate ligament reconstruction surgery are introduced.

2.1. Delphi Method

The Delphi method is a structured process to gather information from an expert panel. This method consists of a survey with more than 2 rounds. In each of the rounds, the experts must give some sort of feedback or justification to their answers and are able to modify their answers in the following round, in order to reach consensus. The Delphi method is supposed to be anonymous, with the conductor of the study acting as a filter to preserve anonymity (Figure 1) [6].

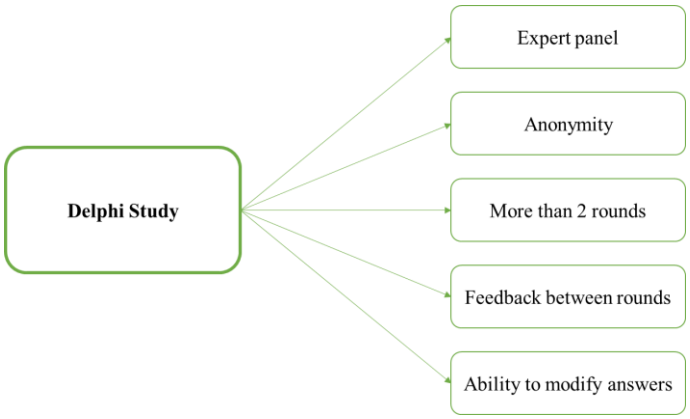

Figure 1 - Characteristics of the Delphi method. Adapted from: [6].

This process originated at the RAND Corporation (California), in the 1950s. Norman Crolee Dalkey and Olaf Helmer-Hirschberg are credited to having used this technique for the first time. Their research was published in 1963 [7].

The Delphi method might deal with more untraditional areas of knowledge. This tool uses opinions from the experts; however, it is worth noting that it is not an opinion poll but a

communication device for experts. The choice of experts is not random, although, in some cases, it might be [6].

The goal of a Delphi study might not always be to achieve consensus, but to establish different points of view, or to determine the degree of consensus in a certain topic. When the aim is to reach consensus, its level might be a predetermined percentage, for example, if the consensus level is 80%, this means that at least 80% of the participants must agree. It is important to explore disagreements, otherwise people with different opinions might quit (and, also, they might be right). Sometimes, there might be consensus only through peer pressure: this is something that should be avoided [1], [6].

There must be at least 2 rounds in each Delphi survey, in order to guarantee the existence of feedback. The first round could be, for instance, open-ended. Afterwards, the conductor of the study would summarize the findings, and create a questionnaire for the second round. The rounds will stop when consensus is reached, or when the experts' answers do not change anymore. It is not necessary for the same set of questions to be present in each round. Likert scale might also be used in Delphi studies. This type of scale is a rating system, and its responses generally range from "strongly agree" to "strongly disagree". Sometimes, numbers are assigned to the categories: 1 is equal to "strongly agree", and 5 to "strongly disagree" [6], [8], [9].

Anonymity is an important characteristic in Delphi studies. It guarantees that the responses are honest, since there is no way for influential people to pressure other experts. However, there might be a lack of accountability from the participants, and it might limit exploratory thinking [6].

The feedback provided by the experts may be a justification for their answers, or statistical feedback. The latter includes frequency distributions, for example, which are used to identify patterns of agreement. The advantage of distributions is that the outliers do not disappear in the average. This is crucial, because extreme opinions might constitute important views. This diversity of opinions guarantees that there are different points of view, and that the obvious is not overlooked. It is important to justify the different opinions, so that the researchers know where the experts are coming from [6].

The Delphi method has applications in healthcare, such as in forecasting developments in technology, and assisting the making of clinical guidelines [6].

All in all, Delphi studies must not be generalized, as they share some similarities, but also some differences. A typical Delphi survey will have a certain number of rounds, feedback between the rounds, opportunities for the experts to modify their answers, and anonymity. Nevertheless, Delphi studies may differ in panel sizes, composition and selection of experts, the design of the study, the number of rounds, the form of the feedback provided, and the treatment of consensus [6].

2.2. Survey Implementation Strategies

After designing the Delphi survey, it becomes crucial to decide on the method of survey administration (e.g., pencil-paper, email distribution, or via an online tool). Traditionally, a conventional Delphi procedure was administered using a "pen-paper" approach. However, contemporary Delphi practitioners predominantly opt for electronic methods. These electronic options encompass email distribution of surveys and comprehensive online tools that facilitate the entire Delphi process [10].

2.2.1. Online Delphi (e-Delphi)

As defined by J. Heed *et al*. (2022), the online Delphi method, also known as e-Delphi method, is a "structured process for assembling knowledge from a group of experts to achieve consensus on a specific theme" [11].

This technique allows for the study conductor to gather information coming from different parts of the world. However, possible limitations include inadequate Internet access and power supply in some regions of the globe. Nevertheless, the facilitated communication with the experts and the simplified statistical analysis of the results constitute some of the advantages of this method [11], [12].

The e-Delphi technique has been used in healthcare and clinical research [11], being applied throughout different online platforms.

There is also a software which shares the name of this method, the e-Delphi software [13].

2.2.2. Welphi

Welphi is a Portuguese online platform, used to implement the Delphi method. Researchers are able to conduct questionnaires and send the links via email to experts (who are able to answer in an anonymous way). A statistical summary of the answers is provided, in a user-friendly interface. This platform allows for an automation of the Delphi method [14].

This web application allows the experts to provide feedback, which is useful to reach a consensus. Participants are able to share their knowledge, and perhaps change someone else's mind. This might instigate a debate, where new ideas and perspectives flourish [14].

Welphi has 3 pricing plans, with the prices ranging from 40 euros per month, to 700 euros per month. The main difference is in the number of panelists allowed per process. There is also a 14-day free trial, and the ability to book a demo (meeting) with an employer of the platform, who shows how the application works [15]. This was the chosen platform to conduct the Delphi study of this dissertation.

2.2.3. Delphi Decision Aid

Delphi Decision Aid is a tool, developed by Scott Armstrong, used to apply the online Delphi method. With this free platform, users are allowed to anonymously survey a panel of experts, through a series of rounds [16].

Some of the functionalities of this platform include selecting experts, creating rounds and adding questions to each round. Experts should create an account in order to answer [17].

There are other survey tools, such as Surveylet and Mesydel. However, these tools do not present any pricing information on their websites; clients must contact them directly to obtain more data [18], [19]. Another tool which seemed interesting, but is currently unavailable (as of July 2024), is Global Futures Intelligence System. This is a platform where people are able to conduct real-time Delphi studies, meaning that at any time, a

new question might be added. The price for individual use is 99.95 dollars per year. The platform has other functionalities besides the Delphi study, such as writing reports on the problem at hand, as well as making comments, and being able to choose from 15 different global challenges [20].

2.3. Extended Reality

Extended reality (XR) is an umbrella term which includes mixed, augmented and virtual reality. As such, XR comprises solely virtual technologies, as well as "real-world" environments, enhanced by digital information [21], [22].

Fifth Generation (5G) technology is used in extended reality tools, since it provides a high Internet speed and moderate latency levels. This is important to avoid sickness during the use of this kind of device. Moreover, 5G allows for extended reality information to be in the cloud, therefore lowering the cost and weight of the used equipment [23], [24].

2.3.1. Mixed Reality

Mixed reality (MR) is a technology which allows the user to see the virtual and the real world simultaneously, with the possibility of interacting with both. This tool has the potential to be used in surgery, since the surgeon is capable of visualizing and interacting with three dimensional (3D) models which might be specific for each patient, while being able to see the physical world [25], [26].

2.3.2. Augmented Reality

Augmented reality (AR) enhances the real world. By overlapping digital objects into the physical world, the user's reality is therefore extended. AR has some applications in medicine, such as in anatomical education, or in the treatment of some phobias [27], [28].

2.3.3. Virtual Reality

Virtual reality (VR) uses software to create an artificial world, where the user has an immersive experience, and is able to manipulate 3D media generated by a computer. This technology uses sensory environments, such as sounds and images, which make the user believe they are in another reality. VR also has the potential to be used in clinical practice, with applications in medical education and simulation [29], [30], [31].

2.3.4. Augmented Virtuality

Augmented Virtuality (AV) is a seemingly lesser-known term, but it is characterized by the integration of real-world elements in the virtual world; however, unlike AR, it gives preference to the virtual contents, being mainly located in the virtual world. Users are able to interact with the real-world while seeing the virtual objects [32].

2.4. Ethical Aspects and Regulations

Medical devices should obey some regulations in order to be considered safe for the patients. In addition, there are some ethical concerns regarding these tools.

The Food and Drug Administration (FDA) has to authorize medical devices in the United States of America. This happens through the 510(k) clearance, Premarket Approval, or by granting a De Novo request [33].

Other potentially important standards include the IEC 60601 (a standard for safety and performance of medical electric gear); and the ISO-5 Cleanroom classification, which is needed by medical device companies, in order to ensure their products are secure, in a sterile environment [34], [35].

As for the ethical aspects, one should take into consideration privacy and patient confidentiality (with data encryption being one way to help with these concerns), security in the storage of files (for instance, videos of surgeries), and the consent in the use of

patient data. Even though there are some ethical concerns, the benefits of using MR tools during surgery could potentially outweigh the issues [36].

2.5. Mixed Reality Tools

There are several mixed reality tools, used for multiple purposes. Microsoft HoloLens 2 and Magic Leap 2, in particular, have applications in healthcare and surgery. For the purposes of this work, Microsoft HoloLens 2 will be used, since it is the available tool.

2.5.1. Microsoft HoloLens 2

Microsoft HoloLens 2 is an MR headset that costs 3500 dollars (or 3900 euros, if bought in Portugal). It allows for the completion of tasks by making less mistakes, and communicating remotely. Moreover, its Industrial Edition (Figure 2) can operate in regulated environments, since it is designated ISO Class 5.0 and it also is UL Class 1, Division 2 certified (the latter is more appropriate for industrial environments, since it refers to places where there might be volatile flammable liquids or gases). Microsoft HoloLens 2: Industrial Edition is a bit more expensive (4950 dollars); however, it has a larger warranty, and extra certifications [37], [38], [39], [40].

These glasses have see-through holographic lenses, sensors for depth, head and eye tracking, an 8 M pixel camera, microphone and speakers, voice commands, hand tracking, Wi-Fi and Bluetooth, a 43º horizontal field of view, and 2 to 3 hours of battery life [39], [41].

Figure 2 - Microsoft HoloLens 2: Industrial Edition. From: [42].

HoloLens 2 cannot be sterilized, so, if they were to be used during surgery, they could not be touched by the surgeons during the procedure. However, the device might be disinfected using a 70% isopropyl alcoholic solution to clean the hard surfaces, along with water. Also, the possibility of the surgeon giving voice commands during the operation helps mitigate this issue [39], [43], [44].

Microsoft offers some solutions to work together with this headset. Microsoft Dynamics 365 Remote Assist is used for people to collaborate in real time. This tool is mostly used in a workplace environment. Workers are able to assist each other with provided instructions. As for Microsoft Dynamics 365 Guides, they provide step-by-step holographic instructions to use at the workplace. This application assists employers in their learning process, thus improving productivity [45], [46].

There are HoloLens 2 tools more closely related to healthcare, specifically healthcare training, such as the Gig Immersive Learning Platform, which contains several applications. Medical students are able to study anatomy, visualize simulated patients, and see 3D holographic organs [47]. Another relevant platform is VSI HoloMedicine (by the developer apoQlar), which might be used to plan surgeries and in surgical training. Medical professionals and students are able to access 3D models, to have a better understanding of human anatomy [48].

Unity is a platform used for the creation of real-time 3D content (RT3D). This brand's values consist of putting users first and taking risks. Besides being used for the creation of RT3D solutions, it is also used for entertainment. This company is present in more than 45 locations across the globe, and applications made with Unity were downloaded more than 4 billion times per month in 2022 [49].

Unity can be used for the development of applications within Microsoft HoloLens 2. The programming languages employed are C++, for underlying runtime code, and C#, for the development scripting. There are toolkits to assist the development, such as the Mixed Reality Toolkit (MRTK). There are some core building blocks (available through the MRTK), namely the camera, gaze, gestures, text, hand and eye tracking, and voice input. Advanced features include tracking loss (to locate the device) and keyboard input. Using Unity and Visual Studio, the developer is able to emulate a device and test the application. There is, however, a low-code alternative: Microsoft Dynamics 365 Guides, which, as

mentioned before, provides visual information to its users, through instructions tethered to the spot where work is needed [46], [50].

2.5.2. Magic Leap 2

Magic Leap 2 (Figure 3) is an AR headset, with MR functionalities. Its price is approximately 4705 euros in Portugal. However, if bought at the United States of America, it can cost 3500 dollars [51], [52], [53].

This device has a 70º field of view, Wi-Fi and Bluetooth connectivity, a 12.6 M pixel camera, and several types of sensors, including inertial. Additionally, it can track the eyes and the gestures of the user. These glasses also have voice and keyboard inputs; the keyboard may be virtual, or connected by USB [54].

Magic Leap 2 is immersive and has an ergonomic design. The device can be worn with prescription glasses, thus making it suitable to use daily. It might be used for remote collaboration and assistance, workforce training, and 3D model visualization. These glasses might be used in the operating room and clinical environments, since they have the IEC 60601 certification (technical standards for the security of medical gear) [54], [55], [56].

Figure 3 - Magic Leap 2 components. From: [57].

Mixed Reality Capture is used to take 2D photos and videos of an in-device experience. Users are therefore able to show other people what they see when using the device, since it allows the capture of both the physical world and the holograms [51].

Magic Leap is working with Unity and the MRTK, thus making it easier for developers to build and port applications for Magic Leap 2. This lowers the costs of developing and minimizes the hardship of learning a new software stack [51].

SentiAR is a Magic Leap partner. Their product, CommandEP (Figure 4), creates 3D holographic models, to be used in minimally invasive procedures, namely cardiac ablation. In this way, physicians are able to see real-time data in their Magic Leap 2 glasses, and maintain sterility in the operating room, since a hands-free manipulation of the data is allowed. The initial prototype was built on Microsoft HoloLens; however, their most recent product is built on the Magic Leap 2 platform. The CommandEP received a second FDA 510(k) clearance in October 2023. This tool improves localization accuracy (up to 50%) and improves communication in the operating room, since the number of commands physicians have to give is lowered [58], [59], [60].

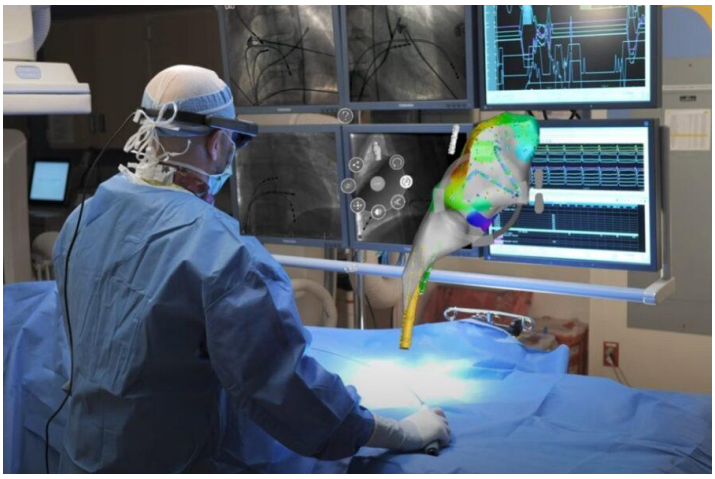

Figure 4 - Physician using CommandEP with Magic Leap 2. From: [61].

2.5.3. Meta Quest Pro and Meta Quest 3

Meta Quest Pro (Figure 5) is an MR headset from Meta. The price is 999.99 dollars (and up). This headset allows the user to interact with the real and the virtual world, with varying degrees of immersiveness. Users are able to collaborate with colleagues in real-time and are able to share their designs. The avatars used in calls and meetings mimic the person's facial expressions, in order for the experience to feel more real [62].

This headset is comfortable, since it has a type of lenses which reduce its weight, due to them being thin. It can be worn with glasses. Also, it offers 2 controllers, which are able to provide haptic feedback. The device comes with 256 GB storage, sensors, 12 GB of RAM (Random Access Memory), and it charges with a USB-C cable [62].

Figure 5 - Meta Quest Pro. From: [63].

Another MR headset from Meta, Meta Quest 3 (Figure 6), was launched in October of 2023. This is a less expensive headset, costing about 499.99 dollars, and it has MR functionalities and applications [64]. The main differences between Meta Quest Pro and Meta Quest 3 are in the comfort level (the Meta Quest Pro is said to be more comfortable), the performance (the Meta Quest 3 is faster and has a better Graphics Processing Unit, or GPU), the image quality (the Meta Quest Pro has a better dynamic range, but the Meta Quest 3 has a sharper image), and the price (the Meta Quest 3 is cheaper) [65].

Figure 6 - Meta Quest 3. From: [66].

2.5.4. Pico 4

Pico 4 (Figure 7) are VR glasses, which will have MR applications. These glasses have a balanced design, since the weight is distributed equally in the front and back. Besides, they are comfortable to wear, with a cushion on their back. This headset has a battery of 5300 mAh, and a refresh rate of 90 Hz, which makes for good image quality, with 2K pixels of resolution per eye, and a 105º field of view. It also has 2 controllers, and costs around 430 euros [67], [68].

Figure 7 - Pico 4. From: [68].

2.6. Orthopedic Surgery and Mixed Reality

Orthopedic surgery handles musculoskeletal problems, such as trauma, tumors, deformities and injuries in the spine and other associated structures, and the extremities of the body [69]. In this project, the anterior cruciate ligament reconstruction surgery will be discussed in specific.

Initially, it was discussed for an MR tool to be applied to the Gamma Nail technique, used for the treatment of trochanteric fractures. However, it was decided to change the surgery to the Anterior Cruciate Ligament (ACL) reconstruction surgery. This procedure is planned in advance [70], which allows the acquisition of a 3D model from the patient's

Magnetic Resonance Imaging (MRI) in advance [71]. If needed, a C-Arm could be used intraoperatively to obtain X-ray [72].

The ACL is a ligament localized in the middle of the knee, which crosses with another ligament (the posterior cruciate ligament). It plays a crucial role in stabilizing the knee joints, and it links the thighbone to the shinbone [73], [74].

Therefore, tearing the ACL might cause the knee to become unstable. The patient is thus unable to perform some more demanding physical activities, and might be more at risk of other lesions, such as in the menisci and cartilage [75].

This injury is prevalent in players of a good deal of sports, such as skiing, handball, tennis, dancing, but mainly football. It is a very common type of injury in the knee, which might occur if the patient extends their lower leg too much in a forward direction, or, alternatively, if the patient's lower leg and knee twist [75], [76], [77].

An ACL injury, if not very severe, may heal with some physiotherapy, without the need for surgery. However, if there is a full tear, then it cannot heal on its own, and the patient needs to undergo an ACL reconstruction surgery [78].

The ACL reconstruction surgery, if performed immediately after the injury, could increase the pain in the post-operative period, as well as the risk of articular stiffness. The knee should be able to regain muscle mass and mobility. As such, the patient should wait and engage in physiotherapy for 2 to 6 weeks before the surgery [75].

The ACL reconstruction surgery has the goal to place a graft in the patient's knee, which replaces their ACL. Two tunnels are done: one in the tibia, and one in the femur. Usually, the grafts used in replacing the ACL are from the knee region (autografts), such as the semitendinosus and the gracilis, which are introduced during surgery in the tunnels mentioned above, and later attached to the bone. There are other types of grafts, such as the ones which come from cadavers (allografts), from animals (xenografts), and synthetic grafts. However, the most common are the autografts [75], [79].

The surgery is usually done with arthroscopic techniques. Its main steps include graft selection, harvest, and preparation; tibial and femoral tunnel placement, as well as the graft placement and fixation; and wound closure [79].

An incision is made, and the arthroscopic camera is inserted. The torn ACL is removed, and the new ACL is placed. Afterwards, a guide wire is inserted, in order to assist before

drilling the bones, which is done with a surgical motor. After consulting with an orthopedic surgeon, the surgical motors which are used the most at ULSSA are from BBraun and Stryker. The graft is then pulled through the upper hole with a wire, and then then it is fixated [75], [79], [80], [81], [82].

As for the graft fixation, this is usually done using a cortical (or suture) button, which is biocompatible; therefore, it does not need to be removed and a patient is still able to do MRI scans. This button is used to fixate the soft tissue of the graft to the bone. It is a flat plate with holes where the suture goes through (Figure 8) [75], [83], [84].

Figure 8 - Cortical button used in the ACL reconstruction surgery. From: [84].

This medical procedure has some associated risks that a patient should consider. For instance, their knee might still not be as it was before the procedure. Moreover, the replacement graft might cause some pain. There is also a risk of the area being infected [85].

Besides risks, there are also some errors that might result from this surgery. Graft failure originates in errors in the tunnel placement, tensioning, graft selection or fixation methods. What most influences the outcome of the surgery is the placement of the femoral tunnel, which is the cause of 80% of ACL surgery failure [79], [86].

The best possible location of both the femoral and the tibial tunnel has been estimated. As for the tibial tunnel, this should be located, according to Patel *et al.* (2017), aligned with the anterior horn of the lateral meniscus, as well as 9 millimeters posterior to the

intermeniscal ligament, and around 7-10 millimeters anterior to the insertion of the posterior cruciate ligament [87].

The femoral tunnel, on the other hand, according to Patel *et al.* (2017), should be placed "between 9 and 10 o'clock on the lateral wall of a right knee with the knee flexed to 90º", and it should be left 1-2 millimeters of bone between the back wall of the femur and the tunnel, and around 7-9 millimeters between the medial aspect of the ACL and the lateral aspect posterior cruciate ligament. In this article, they used a Pathfinder ACL guide (Figure 9) to assist in finding this position, which uses a combination between placing the tunnel using a transtibial technique (where the patient's anatomy is better visualized, but there is more instability, which leads to potential failure), and an anteromedial portal technique (where there is less risk of instability, but it is more technically demanding) [87].

Figure 9 - Pathfinder ACL guide. From: [88].

There is more than one way to estimate the position of the femoral tunnel. The one considered in the case study of this dissertation was described by Pearle *et al.* (2015), where they claim that the ideal position of the femoral tunnel should be "within the anatomical footprint of the ACL", and that a "more eccentric femoral tunnel position" should be preferable over a central or posterior one. This is called the I.D.E.A.L. (Isometric, Direct insertion, Eccentrically located, Anatomical, Low tension-flexion) position (Figure 10) [89].

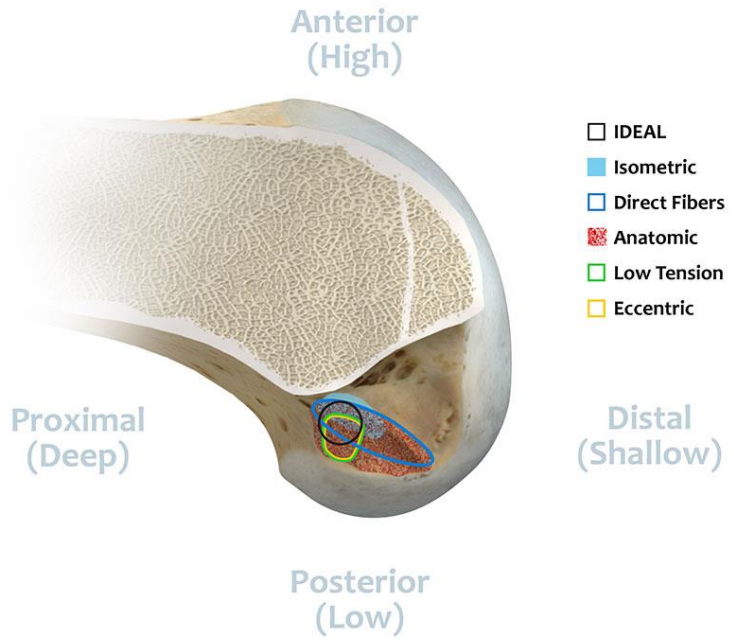

Figure 10 - I.D.E.A.L. femoral tunnel location. From: [90].

Sawbones are used in orthopedic training, since they are 3D models of bones. The bones come in various sizes and a wide range of materials and could be used as an alternative to cadaveric bones. For instance, the femur model seen in Figure 11 costs 18.25 dollars [91], [92].

Figure 11 - Sawbone femur model. From: [92].

Another brand which makes anatomical models of bones is SYNBONE. SYNBONE's models are used for orthopedic surgical education, and they simulate a real bone, with an inner core of polyurethane foam, and an outer shell which is harder. The tibia model in Figure 12 costs 17.10 dollars, for example [93], [94].

Figure 12 - SYNBONE tibia model. From: [94].

Both Sawbones and SYNBONE's models have different mechanical properties, that try to simulate the bone as best as possible. For instance, for the human skull, SYNBONE models have a Young's modulus which matches the bone more closely; however, the Sawbones' models have a Young's modulus which is similar to a cranial bone with higher porosity [95].

In orthopedic surgery, MR might introduce novel ways to visualize and interact with anatomical structures, surgical procedures, and patient data.

In preoperative planning, MR might be beneficial at creating detailed 3D reconstructions of patient anatomy from medical imaging data. Surgeons might leverage this capability to visualize and plan procedures with heightened precision, ultimately enhancing overall surgical accuracy. Transitioning to intraoperative guidance, MR offers real-time overlay of digital information onto the surgical field, with the potential of aiding surgeons in navigation and decision-making. This dynamic platform might enable the visualization of critical structures and optimal implant placements. Moving beyond the operating room, in medical education and training, orthopedic trainees might find value in immersive simulations within a risk-free virtual environment. MR might be beneficial for interactive learning experiences, having the potential to provide realistic surgical scenarios that contribute significantly to skills development.

Regarding the described surgery, MR could be useful in assisting the surgeons with the tunnel placement, through an MR application which would help with its position, as well as allowing the surgeon to visualize holograms of both the bones and the surgical motor and drill.

3. State of the Art

In this section, the main goal was to investigate the current state of mixed reality technology in the context of surgical applications, including extended reality. The state-of-the-art review will be divided in 4 subsections, each dedicated to distinct aspects: one reporting the methods used for the research, one of each investigating MR in surgery, another exploring MR in surgical training, and the last one examining possible problems in the surgical practice and how technology could potentially improve them.

3.1. Research Process

For the state-of-the-art analysis, a comprehensive search query across two prominent databases, PubMed and Scopus was conducted. The query was structured as follows: "mixed reality" AND ("surgery" OR "surgical procedures" OR "surgical training" OR "surgical education" OR "surgeons") AND ("operation" OR "operating room"). This query underwent refinement following a prior search, which yielded a limited number of results with the following: ("Mixed reality" OR "Augmented Reality" OR "Virtual Reality ") AND "Delphi Study" AND "Surgical procedures". Forty-three articles from PubMed and 70 articles from Scopus were collected, forming a total of 113 articles. These selections adhered to specific filters, including language (only English and Portuguese articles were included), publication year (spanning from 2018 to 2023, thus encompassing the past five years), and accessibility (limited to open-access articles).

The review process was improved by adopting the Rayyan platform [96]. Rayyan offers effective tools for streamlining the organization of articles in a review, improving its efficiency. It expedites the initial screening of abstracts and titles through a semi-automated process, coupled with a user-friendly interface [97]. With the assistance of this platform, a duplicate detection process was conducted, identifying a total of 36 duplicated articles. The aspects evaluated were the following: technologies used, indicators, results, application, pros, cons, and future works, which were registered in a table, present in the Appendixes section - Table 15. After a careful read of all the abstracts, methods, and conclusions, 42 articles were excluded, for a number of different reasons: one was related

to veterinary medicine, another was non-surgical related (being about Origami), 14 were reviews, one was not related to a headset, one was a duplicate which was not found previously in the duplicate detection, 2 were not related to MR, and 22 were excluded due to being about an application similar to other articles included (namely the use of a headset to visualize 3D model of a patient's anatomy). All in all, a total of 35 articles were considered for this section. Figure 13 shows the search strategy and list of excluded articles.

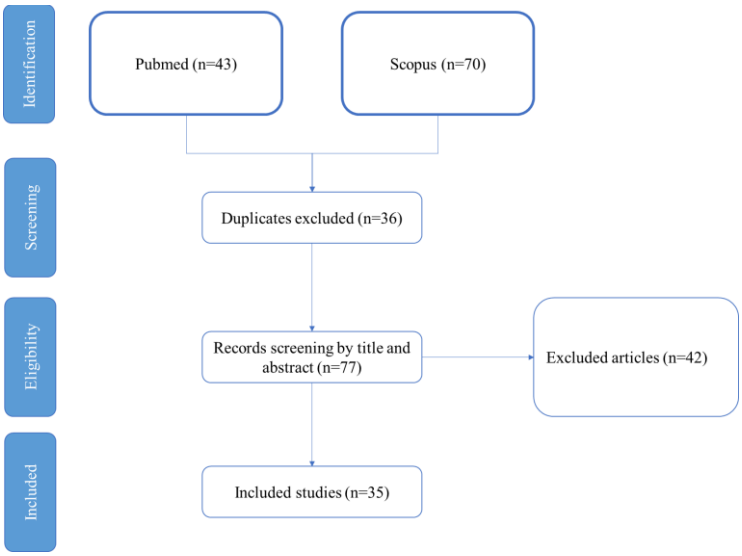

Figure 13 - Flow diagram illustrating literature research, exclusion process, and number of included studies in the review.

3.2. Mixed Reality in Surgery

Mixed reality has the potential to be used in surgery. Some applications, particularly with Microsoft HoloLens or Microsoft HoloLens 2, have been developed by several investigators. These tools might be used in various kinds of surgery.

3D models of the organs might be visualized with MR, namely Microsoft HoloLens. For instance, in 2020, Cartucho *et al.* developed an MR tool, using Unity networking, with

the purpose of viewing multimodal imaging data [25]. To code this tool, Unity 3D and Visual Studio were used, as well as the toolkit HoloToolkit. Besides having 2 virtual screens displaying tissue morphology, captured intraoperatively, this platform also allows surgeons to visualize a 3D organ model (brain or liver), and volumetric imaging preoperative data [25].

MR could be used in order to have a better understanding of anatomy during surgery. For example, Microsoft HoloLens 2 were used in rectal cancer surgery as a tool for pelvic anatomy visualization, and to see the position of the cancer as a hologram, obtained through positron emission tomography-computed tomography (PET-CT). Hayashi *et al.* (2023) reported that these intraoperative holograms were found to be a safe and useful tool in this context [98].

A comparison between the understanding of anatomy with MRI versus 3D models was performed by Pelanis *et al.* (2020). In this study, the surgeons were presented with MRI with segmented lesions, as well as 3D models of the liver anatomy (visualized in Microsoft HoloLens). The accuracy was similar in both cases; slightly larger in the MRI case, since the specialists had access to multiple angles; however, in one of the segments, it was much larger in the 3D model case. Generally, the visualization of anatomy with HoloLens was considered a useful tool [99].

The use of 3D models is also useful for surgical navigation. In Fidan *et al.* (2023), the surgeons used a hologram of the patient's liver, during surgery, in order to have a better understanding of where the metastases were located, thus assisting in the decision-making process. This 3D model was generated by the Visible Patient software and visualized in a Microsoft HoloLens headset [100].

In order to transform DICOM (Digital Imaging and Communications in Medicine) data from Computed Tomography (CT) or MRI into 3D holograms, the CarnaLife Holo system software was used by Wierzbicki *et al.* (2022). The surgeons wore a Microsoft HoloLens 2 headset in liver and pancreatic tumor surgery. HoloLens 1 was also tested, but it was considered to be heavier and with a smaller field of view. The sterility was maintained, since voice commands and hand gestures were given to the Microsoft HoloLens 2 glasses [101].

The TM-MIS 1.0 software was used in Zhu *et al.* (2022) to convert DICOM data from CT images into 3D holograms of the patient's anatomy, namely their liver, blood vessels

and tumor. These data were visualized by the surgeon with the help of Microsoft HoloLens glasses. The study was able to compare two groups of patients: in one of the groups, the surgeons performed the procedure with the assistance of the MR headset; in the other group, no MR was used. It was discovered that the first group had less postoperative complications, as well as a shorter operation time and less bleeding volume. However, some limitations were found, namely the difficulty in fusing the 3D anatomical holograms into the patients' liver, due to the respiratory movements of the patients [102].

Through CT data, Liao *et al.* (2018) were able to guide the placement of the needle, which means MR has applications in surgical navigation. A comparison trial was performed between CT-guided surgery and MR-guided surgery. The error of the system when using the MR tool was smaller, and the precision was higher. The field of view was considered to be a limitation, since it might be too small. However, Liao *et al.* (2018) used Microsoft HoloLens; this limitation might be mitigated when using Microsoft HoloLens 2, which has a larger field of view [43], [103].

DICOM data from cone-beam computed tomography (CBCT) images were converted into 3D data with the assistance of the 3D Slicer software, in order to be able to visualize the tip of an endoscope, in real-time, during surgery, with the help of markers. Lysenko *et al.* (2022) emphasized the individualized diagnosis and treatment which comes with the use of MR in surgery, thus improving its quality and accuracy [104].

CT data were also converted into 3D images by Ito *et al.* (2021). In this case, 2 headsets were used: the Windows Mixed Reality Headset, for VR surgical simulation, and the Microsoft HoloLens, for MR surgical navigation. The importance of using web applications was emphasized, since they can be assessed anywhere on the globe. Moreover, it is important to note that XR tools do not guarantee that the surgery will go well; the surgeon has to be able to deal with unexpected complications [105].

MR tools have applications in orthopedic surgery, for instance, in talocalcaneal coalition resection [106]. 3D models were superimposed with the patient's anatomical structures, allowing for a clear visualization within the surgery, with an effective system. Zhang *et al.* (2023) felt relevant to note that MR headsets are an aid to the surgeons and are not meant to replace their experiences [106].

For the trajectory planning of corridor screws in pelvic fracture reduction, a system with automatic registration was used in Li *et al.* (2023). To achieve this, data from CT scans

were segmented with the Mimics software and transformed into 3D models. In order to do the registration automatically, the CT scan had to contain a reference. In this case, the reference was a screw connected with a tracker and attached to the bone. This allowed for the automatic calculation of the coordinates with a high precision [107].

A preliminary study was conducted on the usability of Microsoft HoloLens 2, with Dynamics 365 Remote Assistance, by Veloso *et al.* (2021). Even though only the requirements were identified, it was concluded it could be beneficial to use this tool during arthroscopies, for remote technical support from the manufacturers. In this way, the technicians would not have to be displaced to the surgical site, thus reducing the risk of infections and CO_2 emissions [108].

MR might also be used in the extraction of maxillary mesiodens. Plastic *et al.* (2023) used a Microsoft HoloLens headset to visualize CT data, obtained preoperatively, as a 3D hologram. This was done by using an application named CarnaLife Holo, by MedApp. The procedure was considered to be safe and more accurate, without postoperative complications. One of the limitations of this study was the high weight of the HoloLens. However, HoloLens 2 present an improved weight distribution [109].

3D printing might be combined with MR tools. In total knee arthroplasty, 3D printed solid models may be used as a reference during surgery (a technique called “volume amplification method" by Su *et al.* (2022)); then, the surgeon is able to see the 3D data in an MR display. This is done to prevent registration problems, which happen with MR (registration errors occur when the virtual objects appear in the wrong position in relation to the real-world). In this type of surgery, MR headsets, such as HoloLens 2, are used for surgical navigation and surgical planning (in a way where it is possible to predict mistakes and solving them beforehand) [110], [111].

MR technology was used in the treatment of an intertrochanteric fracture in a patient’s femur, in combination with 3D printing, to solve the registration problem [112]. Surgery using these tools was considered more individualized and precise. Using 3D models during surgery provided safe and accurate results, and patients presented a good recovery [112].

MR was also combined with 3D printing in Sugahara *et al.* (2021) for the making of 3D models in the resection of maxillary tumor. An MR application was developed for the Microsoft HoloLens, using Unity and Visual Studio Community. The usage of this tool

decreased the time of the surgery, and, since it was possible to have a better visualization of the anatomical structures, the surgery was considered safer [113].

Besides being combined with 3D printing, MR might be integrated into other existing technologies, such as robotic surgery. In Iqbal *et al.* (2021), the User Interface (UI) of a surgical robot was transmitted and visualized in Microsoft HoloLens during surgery [114].

Another application of MR in maxillofacial surgery, specifically tumor resection, was reported in Pepe *et al.* (2019), who developed an application with a marker-less registration approach of the PET-CT data. To achieve this, they had to combine MR with a computer vision algorithm. To evaluate the results, a survey based on the ISO-9241/110 norm was conducted, and the surgeons agreed that the tool was comfortable [115].

Four registration methods were explored in Drakopoulos *et al.* (2020), and the one with higher accuracy was selected: the adaptive physics-based non-rigid registration (A-PBNRR). This method was combined with MR in Microsoft HoloLens, and deep learning (DL). The technique was considered to be beneficial for image-guided neurosurgery [116].

MR also has utility in screw placement. For instance, in lumbar pedicle screws implantation, MR might be used in order to diminish the number of times C-arm fluoroscopy is done (this is a unit used in orthopedic procedures, to show images in real-time – Figure 14), thus reducing the harm made to surgeons, since it lowers the intraoperative C-arm X-ray irradiation. In Gu *et al.* (2020), a total of 50 procedures of lumbar pedicle screws placement were done: 25 of each without MR, and 25 with MR (using HoloLens 2). Although there was a small number of procedures, and a short follow-up time, the group using MR obtained better results, as the patients presented less bleeding, a lower surgery time, and more success in doing the first threading [117], [118]. As for Li *et al.* (2021), an MR system was combined with 3D printing, in order to insert the pedicle screws into the 3D-printed lumbar model, with the help of the MR navigation device. Afterwards, the position of the vertebrae was determined. Using this tool, no extra X-ray was necessary during the operation. This case study shredded light in some limitations of using MR systems, such as a potential visual discomfort, and a difficulty in simulating soft tissues [119].

Figure 14 - C- Arm fluoroscopy. From: [120].

MR might be used for estimating the pose of the C-arm, using a marker-based approach [121]. In Hosseinian *et al.* (2019), the importance of correcting the distortion in X-ray images is emphasized, since it can cause inconsistencies in perspective invariants (necessary for the pose estimation), and thus affect the accuracy of the algorithm [121].

By combining MR technology with C-arm fluoroscopy in Wei *et al.* (2019), the surgeons were able to accurately perform percutaneous kyphoplasty. Two groups of operations were considered in this study. The first group used Microsoft HoloLens combined with C-arm fluoroscopy to visualize a 3D model; the second group only used C-arm fluoroscopy. The MR group presented lower X-ray irradiation results, and the needle insertion was considered to be accurate. The mixture of both techniques allowed for the hologram, obtained through CT data, to be combined with the patient [122].

A surgical simulation combining MR and 3D printing, based on the patient's CT data, was performed by Koch *et al.* (2022). This was done to assess if flow disruptions during surgery lead to performance failures within the surgical team, during a simulated vertebroplasty. The operating room was fully equipped, including a C-arm, with simulated X-ray images [123].

A simulated operating room was also used in Stefan *et al.* (2023), to adapt the universal framework of intraoperative performance to spine surgery. This simulation was done with MR and physical tools, including a C-arm, with radiation-free X-ray images, due to their simulated nature [124].

MR technology might be combined with G-arm fluoroscopy (Figure 15). In Liu *et al.* (2021), the surgery completed with Microsoft HoloLens 2 was considered to be easier. The MR tool reduced the surgery time and the exposure to radiation (still necessary, since

procedures performed with MR had to be confirmed with fluoroscopy, such as needle insertion and positioning the working sheath). However, the usage of this headset increased eye fatigue, when used for more than half an hour. Still, it was considered that the learning curve for residents could be reduced by using MR tools [125].

Figure 15 - G-arm fluoroscopy. From: [126].

Besides being used by the surgeons, MR could be useful for the nonsurgical staff. In Kos *et al.* (2023), the use of MR within the nonsurgical team members in neurosurgery was evaluated. To achieve this, the surgeon used Microsoft HoloLens 2 glasses, from which the holographic 3D models were streamed to a monitor, in order for the rest of the team to observe. Most of the team found that MR did not lead to flow disruptions, and they found it useful in improving their understanding of the pathology dimensions and the spatial orientation [127].

MR was used for telemedical simulation, in combination with DL and 5G technology. In Tai *et al.* (2022), a system based on the Internet of Medical Things (IoMT) and the Digital-Twin paradigm used a DL model, Robust Auxiliary Classifier Generative Adversarial Network (rAC-GAN) in the prediction of lung cancer; and MR was used in remote diagnosis and surgical planning, while the surgeon wore the headset. This technique served as a tool for telemedical simulation [128].

An MR system was used for tele-consent during pediatric surgery in Yun *et al.* (2022). The patients' caregivers, while in the waiting room, wore the XREAL glasses (formerly NREAL [129]), which were communicating with a medical computer cart through a video

call. The surgeon was able to explain the procedure, and, if it was necessary, the surgical plan could be adapted in real-time. This tool was found useful, through the analysis of questionnaires given to both the caregivers and the surgeons [130].

MR technology was used for multiple purposes in Gao *et al.* (2019), including orthopedic surgery. The MR headset was combined with 3D printing for the reconstruction of 3D models; and also, with artificial intelligence (AI), for the intelligent detection of lesions, and later displaying them with an MR headset. Moreover, it was used for surgical training, and it was considered to shorten the training time for medical students [131].

PQx, or Planificación y Navegación Quirúrgica, is a Spanish company, which uses headsets of AR and VR during surgery, for surgical navigation. Their main product is called VEGA Surgical Navigator. This is used by the surgeon as a guiding tool, during resections and osteotomies. The company also combines 3D printing with their services [132], [133].

3.3. Mixed Reality in Surgical Training

MR tools were used in training medical doctors during the Covid-19 pandemics, since it would have been impossible to achieve the training process otherwise. In Simone *et al.* (2021), surgeons used an MR headset while performing laparotomic and laparoscopic oncological surgeries. This type of equipment was considered to be "low-cost" by the authors of this article. The visual information of the surgeons' headset was shared, so that nurses and trainees could see their point of view, through other MR devices, as well as their phones and computers. In this way, MR headsets allowed for the sharing of real-time multimedia contents [134].

Another case of XR being used during the pandemic for training purposes was in Wisotzky *et al.* (2023), where a scalable solution for educating professionals during cochlear implants is shown. This type of surgery is conducted with the assistance of a digital surgical microscope, thus making training a hard process, since it is not possible that, during a course, all trainees take a look into the binoculars. With the help of AR, this process becomes more feasible. In this article, an AR-based 3D surgical video system was developed. The microscope presented an XR interface, in a way that the surgeon's point of view was video and audio streamed to the trainees, via head mounted displays, or a YouTube stream. On the other hand, the trainees could remotely ask questions during the procedure to the surgical team. A tool which was found valuable among the trainees was the ability to annotate the live images, with drawings, arrows, and text. Moreover, this platform has the potential to improve international collaboration in regard to surgical education [135].

A platform called SYNAPSE VINCENT was developed to be used in rectal cancer surgery, particularly in lateral lymph node dissection [136]. This provides a surgical simulation tool, which might be used by both experienced and non-experienced surgeons, where the medical professional is able to see 3D images of the paths of the external and internal iliac arteriovenous systems, as well as the swollen lymph nodes. It was considered that, for younger surgeons, they could become more familiarized with the procedure and the anatomy more quickly, thus making a good learning curve [136].

An MR platform was created by Kalbas *et al.* (2023) for surgical telementoring. This system, called "Remote Interactive Surgery Platform", or RISP, provides a tool for

surgeons to be able to communicate with a remote consultant via voice. This consultant can see the surgeon's field of view, leave 3D annotations, and display other medical images in a floating window for the surgeon to see. The surgeon is able to interact with the holograms through hand gestures and voice commands. The surgery is therefore streamed in real-time [137].

Microsoft HoloLens might be used as a simulation tool for surgical training. In Caligiana *et al.* (2020), the authors used MR combined with 3D printing to simulate the intricate process of cutting a virtual bone. Microsoft HoloLens was used for visualization of the objects, and Leap Motion was used to track the user's hands and their precise finger movements, as well as the "cutting" motion. To enhance the connection between the physical and virtual components, Vuforia's tools were employed to associate the 3D-printed bone with its virtual counterpart. The virtual cuts were almost instantaneous, so the application was considered helpful for the doctors [138].

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3.4. Surgeon's Problems in the Operating Room

There are some issues and challenges present in the operating room, which might be potentially helped with technology.

It is crucial to ensure that documentation and records are kept accurately, since it makes communication between professionals easier, and it assists in the tracking of the progress of the patient. Video and audio recordings, as well as images captured during surgeries might be a way to achieve this accurate tracking [139].

Infections on the surgical site are a problem to patients undergoing surgery. To avoid this issue, the operating room should be a sterile and hygienic place. Moreover, the surgeons (and the rest of the team) should keep their hands disinfected [140].

To lower the chances of human errors, which may result in completing surgery on the wrong site, or in unintentionally retaining foreign objects on the patient's body, the implementation of surgical checklists, such as the Surgical Safety Checklist from the World Health Organization (Figure 16), might be helpful [139], [141].

Figure 16 - World Health Organization Surgical Safety Checklist. From: [142].

There might be occasions where it is important for surgeons to be able to communicate with other professionals outside the operating room, for example, in cases where there is equipment malfunction, and the patient needs to be moved to another room. Because of this issue, it is crucial to have devices where surgeons are able to communicate in real-time with another surgical team [139].

3.4.1. Extended Reality as a Simulation Tool

In surgery, simulation might be used as a powerful tool to teach students. Since it involves working in a controlled environment, students will feel more confident when they operate on an actual patient. Moreover, errors do not bring such terrible consequences, and students have the opportunity to correct them accordingly. Simulation allows students to repeat the movements as long as they need to, making them able to improve their professional competences [143].

Microsoft HoloLens 2 can be, and were already used in a multitude of surgical simulations. These glasses might bridge a need gap, and provide a simulating environment which could be used for students to grow as professionals. Moreover, even if eyestrain is a potential symptom caused by this type of headset, it appears less frequently in HoloLens 2, when compared to VR simulators [144].

Extended reality, namely augmented reality, has also been used for other applications other than surgical, which could be adapted to this dissertation, nonetheless. For example, the Soldamatic Augmented Training (Figure 17) is a product that uses augmented reality in welding training. This system is composed of a simulation machine, a helmet, and professional welding torches and gloves. It allows for personalized training. The tip of the torch has 2 different components: a circle, to indicate the rotation of the tool, and an arrow, to indicate the proximity to the target. These components appear when the user looks at the small QR codes present at the tip of the torch [145].

Figure 17 - Soldamatic Augmented Training. From: [145].

All in all, MR has a myriad of applications in surgery. Most of them are related to surgical planning, intraoperative applications, such as surgical navigation, simulation, and surgical training. The most common application was the use of 3D models of the anatomy of the patient, using CT data and visualized with Microsoft HoloLens 1 or 2. Some challenges were the registration issue, specifically with soft tissues. This could be solved by combining MR with other techniques, such as 3D printing, or by developing automatic registration approaches. Some articles reported the importance of having a control group, and a big number of participants. The comfort of the surgeons during the procedure is key; the headsets should be light and should not cause eye fatigue. MR could also be combined with AI techniques, such as DL, and with robotic surgery. This technology presents a lot of benefits, such as increased accuracy and safety, and a better learning curve for medical students. It might also reduce the radiation dosage in procedures with a C-arm. Some studies would benefit from a long-term follow-up. The cost-effectiveness was also discussed in some articles, which found MR not to be an expensive technology. This all seems promising for the implementation of MR in surgical applications, whether it be in the training, planning or navigation phase.

4. Delphi Study

In this section, a nationwide Delphi study with the goal of assessing surgeons' needs in the operating room will be developed. The rounds have been conceptualized and analyzed together with Renato Magalhães (Eng.). The types of questions were about the professional, the existing problems in surgery, the potential of MR in the operating room, and the ethical concerns which might exist, and the benefits and limitations in the implementation of MR in surgery. The state-of-the-art research for this project, along with a systematic review involving Renato Magalhães, has informed the development of these questions. Moreover, several methods for analyzing the results were investigated, in order to understand which ones might be the most adequate for this study in particular. This questionnaire has helped to gain a better understanding of the Delphi method's phases, as well as its structure.

4.1. Characterization of the Experts

In this Delphi study, the participants were chosen based on their experience with immersive technologies in surgery. Twenty-two doctors were selected, who had previously worked with immersive digital health tools of any kind, such as robotic surgery, VR or AR headsets, 3D laparoscopy, among others, applied in the surgical area, with at least one year of experience, from several Portuguese hospitals.

4.2. Questions

The main question of a Delphi survey is crucial for the experts' understanding of the entire survey. Thus, for this study in particular, the main goal was to evaluate the usefulness of MR tools in surgical treatment.

4.2.1. Round 1

The first round was comprised of open-ended questions, in order to assess the surgeons' input in MR. It consisted of 5 different sections: the first one was about the expert; the second was related to MR in surgery; the third pertained to the potential of MR in the improvement of surgical procedures; the fourth was connected to the ethical and safety concerns; and, lastly, additional comments were requested to the experts.

This survey was first sent to 3 doctors, so they could offer their opinion on its structure, and the clarity of the questions. Some changes were required. The final questionnaire presents as follows:

1. **Section 1: Information about the participant**
   - 1.1. Job title of the participant;
   - 1.2. Years of professional experience in surgical treatment;
   - 1.3. Years of professional experience in immersive technologies applied to surgery;
2. **Section 2: MR and surgery**
   - 2.1. What are, in your opinion, the applications of MR in medicine, particularly surgery?
   - 2.2. What are the main benefits MR might offer to surgical procedures?
   - 2.3. What are the limitations or challenges you are able to identify regarding the implementation of MR in surgical procedures?
3. **Section 3: Potential of MR in the improvement of surgical procedures**
   - 3.1. Do you believe MR has the potential to improve the accuracy and efficiency of surgical procedures? Please explain.
   - 3.2. Are you aware of any examples of successful MR applications in surgery? Identify such cases.
   - 3.3. What specific surgical areas might benefit the most from MR?
4. **Section 4: Ethical and safety concerns**
   - 4.1. What ethical concerns should be considered in the usage of MR in surgical procedures?
   - 4.2. Do you think that the patient's privacy might be affected by the use of immersive technologies, when applied to surgery?
   - 4.3. Do you think that the patient's safety might change during the surgical procedure with MR tools?

5. **Section 5: Additional comments**
   5.1. Which other aspects should be discussed?

4.2.2. Round 2

The questions in this round were adapted from the answers given by the experts in the previous round. In round 2, the experts were asked to sort a series of statements, divided into 5 areas. The questions were as follows:

1. **Section 1: Usefulness of MR (the following statements should be sorted)**
   1.1. MR is more useful in surgical navigation and in getting a more accurate surgical orientation.
   1.2. MR is more useful in the training and optimized teaching.
   1.3. MR is more useful in surgical planning with the integration of the patients' data.
2. **Section 2: Applications of MR (the following statements should be sorted)**
   2.1. The main applications of MR are surgical orientation and navigation.
   2.2. The main applications of MR are education and surgical training.
   2.3. The main application of MR is surgical planning.
   2.4. The main application of MR is integration with other surgical systems, such as robotics.
3. **Section 3: Benefits of MR in surgery (the following statements should be sorted)**
   3.1. The main benefits of MR are the accuracy and the improvement of results.
   3.2. The main benefit of MR is the safety.
   3.3. The main benefits of MR are the efficiency and the optimization.
   3.4. The main benefits of MR are communication and collaboration.
4. **Section 4: Limitations in the implementation of MR in surgery (the following statements should be sorted)**
   4.1. The main limitations in the implementation of MR in surgery are related to the technology.
   4.2. The main limitations in the implementation of MR in surgery are related to the people (in its adoption).
   4.3. The main limitations in the implementation of MR in surgery are the costs and investment.

4.4. The main limitation in the implementation of MR in surgery is the regulatory area.

4.5. The main limitation in the implementation of MR in surgery is data protection.

5. **Section 5: Ethical considerations (the following statements should be sorted)**

5.1. The patients' privacy and confidentiality are the main ethical issues to consider.

5.2. Responsibility and regulation are the main ethical issues to consider.

5.3. The safety in the procedures and the patients' protection are the main ethical issues to consider.

5.4. The patients' informed consent is the main ethical issue to consider.

4.2.3. Round 3

Given the results obtained in Round 2, another round was realized, with the same questions as the previous round. In this third round, the participants were given the chance to visualize the percentages of the previous round, and change their position, in order to reach a collective consensus on the topic.

The Delphi study of this dissertation was completed after 3 rounds. A consensus letter with the main conclusions is thought to be drafted in the near future; however, this is not necessary for a complete Delphi study [146].

4.3. Methods for the Analysis of the Results

The method of analyzing a Delphi study's results depends on the study design. However, feedback might be of 2 main types: qualitative, where the experts write justifications of their answers, and quantitative. The latter form involves statistical and numerical feedback. Statistical feedback uses medians together with minima and maxima, usually, as well as quartiles and interquartile range. This type of feedback may also include means, accompanied by standard deviations. Frequency distributions (numerical and graphical) are used in some Delphi surveys, as a way of identifying patterns, and to assure that information is not lost, since outliers and opposing points of view are taken into consideration, instead of being averaged [6].

All in all, the method of analysis will highly depend on the study design and the type of questions. For instance, if the questions are open-ended, then the feedback will most likely be qualitative; however, if the questions are multiple-choice or with a Likert scale, then the feedback might be numerical or statistical.

There have been several robotic surgeries performed in Portugal, which indicates a good omen in the implementation of new technologies in healthcare. For instance, in ULSSA, a surgical robot arrived in May of 2023, and several surgeries have been performed with its assistance since then. In *Centro Hospitalar Universitário São João*, the first robotic surgery was accomplished in February of 2023, and it is estimated that the equipment is able to perform 846 surgeries every year. About 6000 surgical robots exist worldwide. The first robot to have been used in the Portuguese National Health Service is in Curry Cabral Hospital, in Lisbon, since 2019 [147], [148], [149].

In Portugal, there are several surgical specialties which a surgeon might choose from. According to *Ordem dos Médicos* [150], the surgical specialties are vascular surgery, cardiac surgery, cardiothoracic surgery, general surgery, oral and maxillofacial surgery, pediatric surgery, reconstructive and esthetic plastic surgery, thoracic surgery, stomatology and neurosurgery. Furthermore, other surgical specialties include otolaryngology, trauma and orthopedic surgery, urology and academic surgery [151], as well as oncologic surgery, hepato-pancreato-biliary surgery, and ocular surgery [152], [153], [154].

As for the consensus level, there was found to be some inconsistencies among different Delphi studies, with different authors defining the consensus level at different percentages. This percentage might vary from as low as 51% to as high as 100% (when all the experts agree on a certain topic) [155]. After some research and pondering what would be best for this study, since a “perfect” score is usually unattainable [156], the consensus level was defined to be 70%, as is seen in Cascella *et al.* (2021) and Vogel *et al.* (2019) [146], [157].

The chosen methods for the analysis of this Delphi study are described in the following section.

4.4. Analysis of the Rounds

In this section, a description of the achieved round analysis will be provided.

4.4.1. Round 1

After all the answers had been collected in an Excel [158] file, they were analyzed together with the co-supervisor of this dissertation and divided into areas of interest. Following a PRISMA-like [159] approach, the areas were discussed, as well as the answers in each area, and a consensus was reached between both investigators, through the assistance of Professor Lúcio Lara Santos. The second round was then conceptualized, being divided into 5 main areas. The goal, besides reaching consensus between the experts, was to streamline the questionnaire, in order to reduce the number of areas being discussed by the experts. To achieve this, only the main areas of interest (those which had a higher percentage of answers from the participants) were addressed.

The results will be presented in the following graphs, obtained with the assistance of the Python programming language [160], using the environment Spyder, with the Matplotlib and the NumPy libraries [161], [162], [163], [164].

In each of the graphs, the number of answers is the total number of answers in each of the areas (some answers are in more than one area); and the number inside the bubbles is the percentage of participants whose answer(s) corresponded to that area of interest.

The experts identified six areas of interest regarding the applications of MR in medicine, particularly in surgery, as seen in Figure 18.

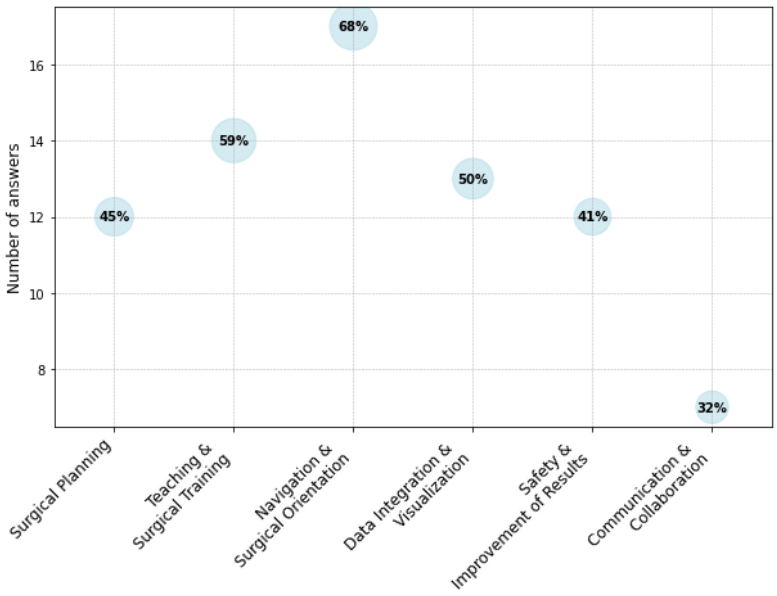

Figure 18 - Applications of MR in surgery assessed by the question: What are, in your opinion, the applications of MR in medicine, particularly surgery?

As for the main benefits of MR in surgical procedures, 4 areas were identified (Figure 19).

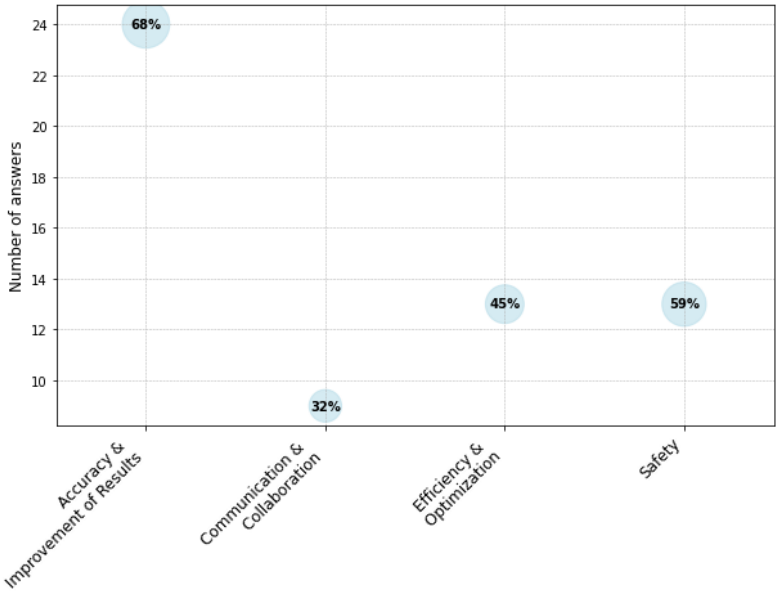

Figure 19 - Main benefits of MR in surgical procedures assessed by the question: What are the main benefits MR might offer to surgical procedures?

In Figure 20, the main limitations in implementing MR in surgical procedures were identified by the experts, divided into 6 areas.

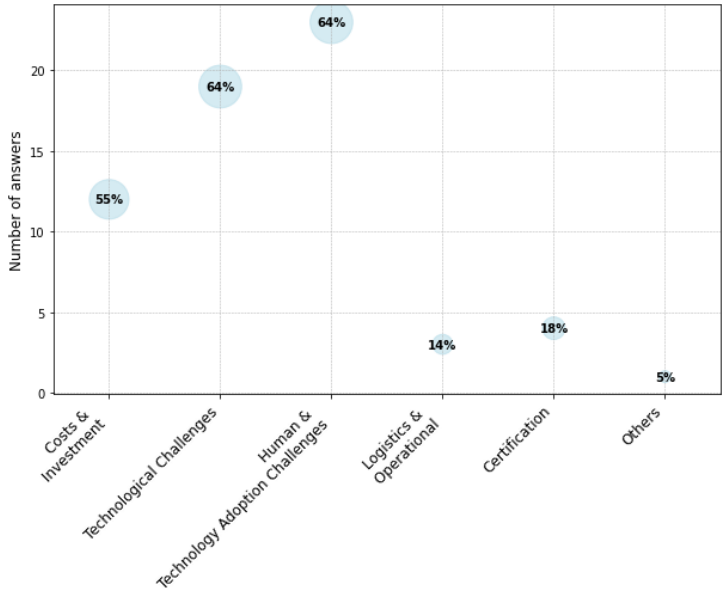

Figure 20 - Main limitations of MR in surgical procedures assessed by the question: What are the limitations or challenges you are able to identify regarding the implementation of MR in surgical procedures?

Experts were asked to evaluate whether MR had the potential to improve surgical procedures, and they all agreed it could. Their answers were divided into 2 main areas, as seen in Figure 21.

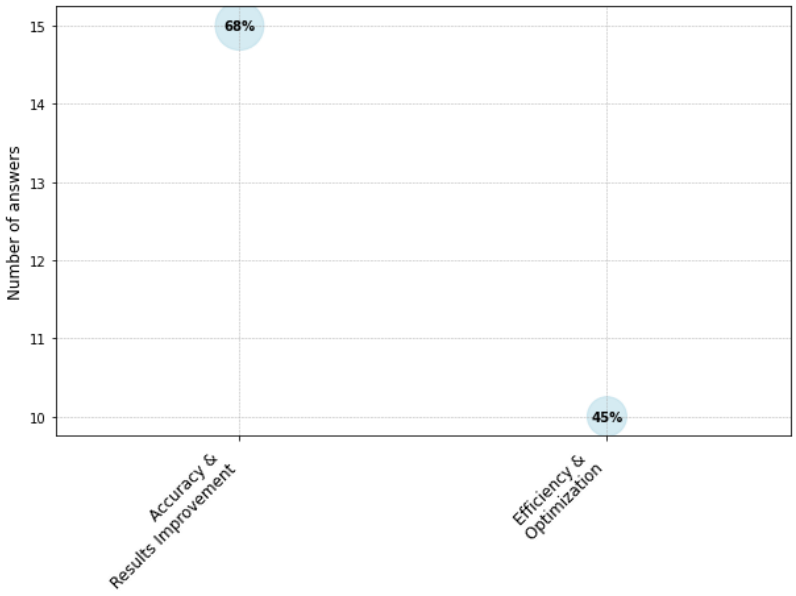

Figure 21 - Potential of MR to improve surgical procedures assessed by the question: Do you believe MR has the potential to improve the accuracy and efficiency of surgical procedures? Please explain.

When asked if they were aware of any use cases of MR being successfully applied to surgery, 73% of the experts said they knew at least one case, with 6 experts being aware of 3 use cases, 8 experts being aware of 2 use cases, and 2 experts being aware of 1 use case (Figure 22).

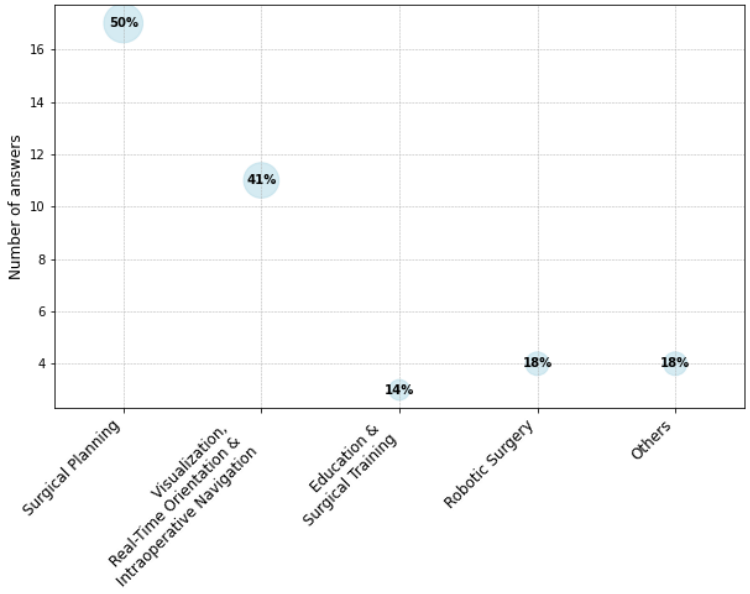

Figure 22 - Use cases of MR in surgery assessed by the question: Are you aware of any examples of successful MR applications in surgery? Identify such cases.

Eight different surgical areas which could potentially benefit from the application of MR were identified by the experts, as it can be visualized in Figure 23.

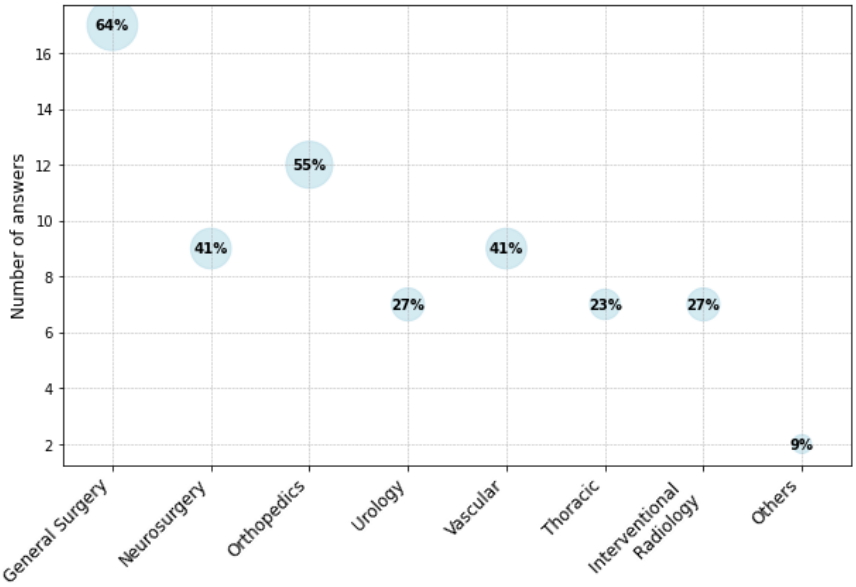

Figure 23 - Surgical areas which could benefit from MR assessed by the question: What specific surgical areas might benefit the most from MR?

Six areas of potential ethical concerns were identified by the experts, with privacy and patient confidentiality gathering the most responses (Figure 24).

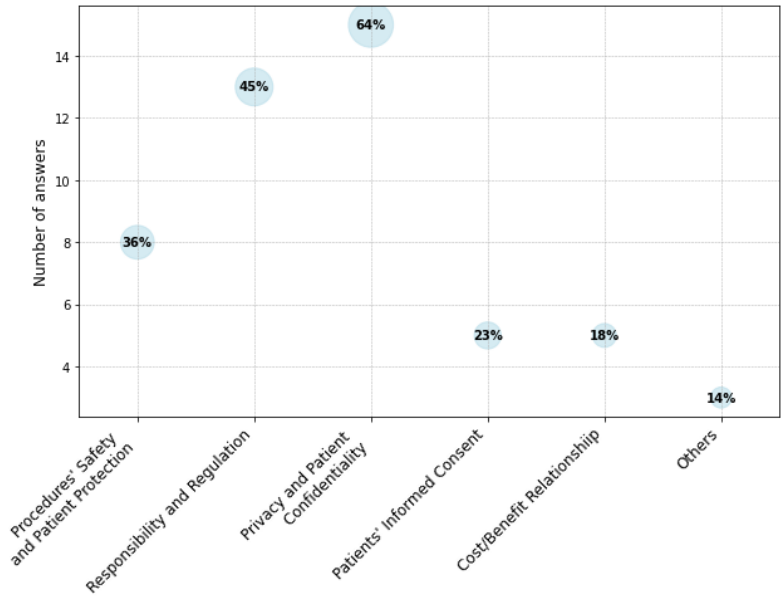

Figure 24 - Ethical concerns in the use of MR in surgery assessed by the question: What ethical concerns should be considered in the usage of MR in surgical procedures?

In the question “Do you think that the patient’s privacy might be affected by the use of immersive technologies, when applied to surgery?”, half of the experts thought that there were no concerns regarding the patients’ privacy; however, the other half argued that there might be issues with data privacy.

Regarding the patients’ safety, in the question “Do you think that the patient’s safety might change during the surgical procedure with MR tools?”, 9% of the participants argued there would be no changes, and 91% agreed it would be changed, either positively or negatively.

The last question (“Which other aspects should be discussed?”) did not provide any new insights.

4.4.2. Round 2

In the first section, “Usefulness of MR”, 64% of the experts agreed that the biggest utility of MR is in surgical navigation. The order of the 3 answers was surgical navigation, followed by surgical planning, and lastly, surgical teaching and training (Table 1).

Table 1 - Answers related to the usefulness of MR in surgery (round 2).

	1st	**2nd**	**3rd**
Surgical Navigation	**64%**	18%	18%
Surgical Teaching and Training	14%	27%	**59%**
Surgical Planning	23%	**55%**	23%

As for the section "Applications of MR", 59% of the participants thought that the biggest application of MR in surgery was surgical orientation and navigation, followed by surgical planning, integrating MR with other surgical systems, and lastly, education and surgical training (Table 2).

Table 2 - Answers related to the applications of MR in surgery (round 2).

	1st	**2nd**	**3rd**	**4th**
Surgical Orientation and Navigation	**59%**	18%	14%	9%
Education and Surgical Training	14%	14%	32%	**41%**
Surgical Planning	23%	**36%**	18%	23%
Integration of MR with other Surgical Systems	5%	32%	**41%**	23%

In the third section, "Benefits of MR in surgery", 64% of the participants believed accuracy and results' improvement were the biggest benefit, followed by safety, efficiency and optimization, and lastly, communication and collaboration (Table 3).

Table 3 - Answers related to the benefits of MR in surgery (round 2).

	1st	**2nd**	**3rd**	**4th**
Accuracy and Results Improvement	**64%**	23%	9%	5%
Safety	18%	**50%**	23%	9%
Efficiency and Optimization	14%	23%	**36%**	27%
Communication and Collaboration	5%	5%	36%	**55%**

The main limitation in the implementation of MR in surgery, according to 64% of the experts, is its cost, followed by technology-related, people-related, the regulatory area, and, lastly, data protection (Table 4).

Table 4 - Answers related to the limitations in the implementation of MR in surgery (round 2).

	1st	**2nd**	**3rd**	**4th**	**5th**
Technology-related	23%	**36%**	14%	14%	14%
People-related	5%	32%	**41%**	14%	9%
Costs and Investments	**64%**	5%	14%	9%	9%
Regulatory Area	9%	23%	18%	**45%**	5%
Data Protection	0%	5%	18%	18%	**59%**

As for the last section, “Ethical considerations”, 55% of the participants agreed that the safety in the procedures and patients’ protection were the main ethical issues, followed by responsibility and regulation, the patients’ privacy and confidentiality, and, finally, the patients’ informed consent (Table 5).

Table 5 - Answers related to the ethical considerations of MR in surgery (round 2).

	1st	**2nd**	**3rd**	**4th**
Patients’ Privacy and Confidentiality	5%	23%	**36%**	36%
Responsibility and Regulation	27%	**45%**	18%	9%
Safety in the Procedures and Patients’ Protection	**55%**	18%	14%	14%
Patients’ Informed Consent	14%	14%	32%	**41%**

4.4.3. Round 3

For round 3, since the questions were the same as the previous round, they will be compared section by section. Unfortunately, in this round, only 20 experts answered (91% of the participants). The consensus level was rated as the following: if the statement which appeared in the first place for most experts had a percentage higher than 70%, then the consensus was reached. Following this definition, the consensus level was reached in all of the sections.

In the first section, "Usefulness of MR", 75% of the experts agreed that the biggest utility of MR is in surgical navigation, with an increase of 11% compared with the second round. The order of the 3 answers remained the same (Table 6).

Table 6 - Answers related to the usefulness of MR in surgery (round 3).

	1st	**2nd**	**3rd**
Surgical Navigation	**75%**	5%	20%
Surgical Teaching and Training	10%	20%	**70%**
Surgical Planning	10%	**75%**	15%

As for the section “Applications of MR”, the order of the answers stayed the same as well; however, instead of 59% of the experts answering that the biggest application of MR in surgery was surgical orientation and navigation, this time, 80% of the experts agreed on that, thus having a 21% increase (Table 7).

Table 7 - Answers related to the applications of MR in surgery (round 3).

	1st	**2nd**	**3rd**	**4th**
Surgical Orientation and Navigation	**80%**	10%	5%	5%
Education and Surgical Training	10%	15%	40%	**35%**
Surgical Planning	10%	**50%**	10%	30%
Integration of MR with other Surgical Systems	0%	25%	**55%**	20%

In the third section, “Benefits of MR in surgery”, 75% of the participants believed accuracy and results’ improvement were the biggest benefit (11% increase in relation to the second round). The order of the answers remained the same (Table 8).

Table 8 - Answers related to the benefits of MR in surgery (round 3).

	1st	**2nd**	**3rd**	**4th**
Accuracy and Results Improvement	**75%**	15%	10%	0%
Safety	15%	**70%**	5%	10%
Efficiency and Optimization	10%	10%	**55%**	25%
Communication and Collaboration	0%	5%	35%	**60%**

The main limitation in the implementation of MR in surgery, according to 75% of the experts, is its cost, with an 11% increase when compared to the previous round. Once again, the order of the answers remained the same (Table 9).

Table 9 - Answers related to the limitations in the implementation of MR in surgery (round 3).

	1st	**2nd**	**3rd**	**4th**	**5th**
Technology-related	20%	**50%**	15%	10%	5%
People-related	0%	25%	**65%**	10%	0%
Costs and Investments	**75%**	10%	10%	0%	5%
Regulatory Area	5%	15%	5%	**70%**	5%
Data Protection	0%	0%	10%	15%	**75%**

As for the last section, “Ethical considerations”, 70% of the participants agreed that the safety in the procedures and patients’ protection were the main ethical issues. Even though this section had the lowest percentage of consensus, there was a 15% increase in the agreement of experts, when compared to the second round. The order of the other statements remained the same (Table 10).

Table 10 - Answers related to the ethical considerations of MR in surgery (round 3).

	1st	**2nd**	**3rd**	**4th**
Patients’ Privacy and Confidentiality	5%	20%	**40%**	35%
Responsibility and Regulation	20%	**55%**	20%	5%
Safety in the Procedures and Patients’ Protection	**70%**	15%	5%	10%
Patients’ Informed Consent	10%	10%	35%	**45%**

4.4.4. Main Conclusions

Since the differences in the results between the rounds 2 and 3 of the Delphi study were in the percentages of each statement, and not in their order, a comparison of both rounds was made in the following graphs.

In Figure 25, one can see that the statement most experts chose to place in first place was the surgical navigation, which is mostly blue in the graph; surgical planning appears in second (mostly in green); and, thirdly comes surgical teaching and training, mostly in red. There is some difference in the percentages, as it is visualized more clearly in the graph.

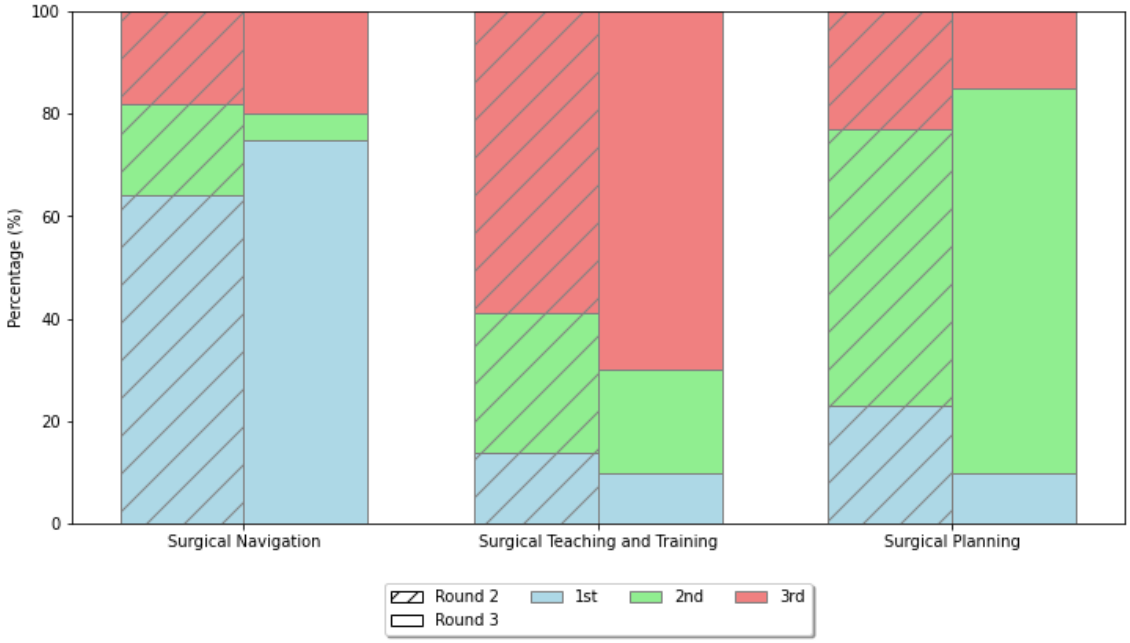

Figure 25 - Comparison of the usefulness of MR in surgery, in the rounds 2 and 3 of the Delphi study.

In Figure 26, there are 4 statements; the last one is mostly in a yellow color. Surgical navigation and orientation were considered the main applications of MR in surgery in both rounds, with a clear increase in its percentage in round 3.

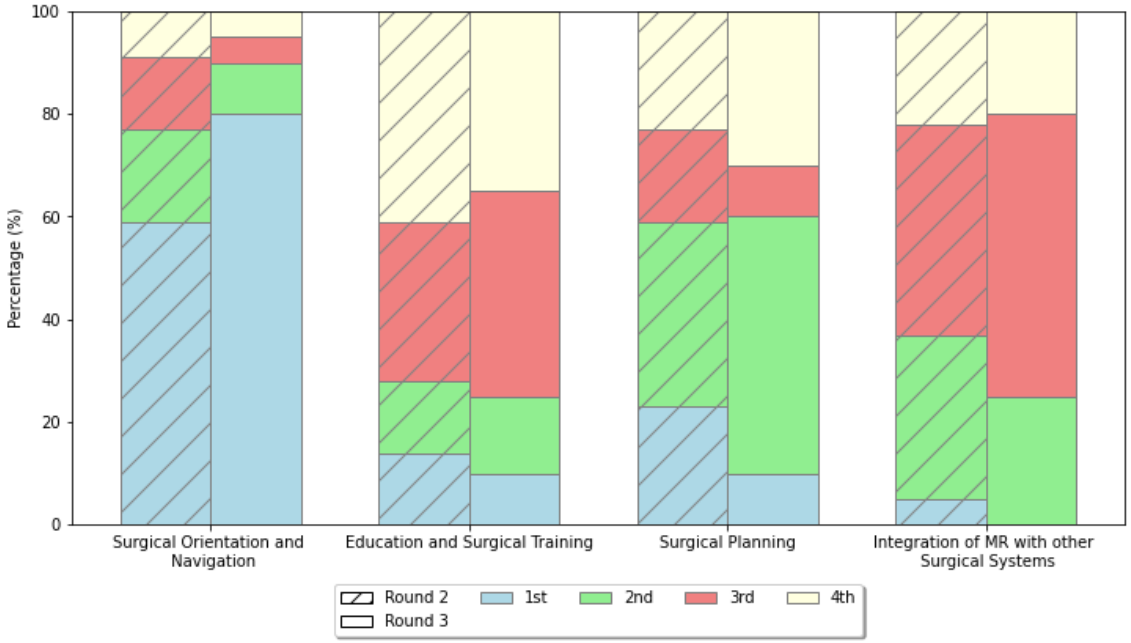

Figure 26 - Comparison of the applications of MR in surgery, in the rounds 2 and 3 of the Delphi study.

The main benefits of MR in surgery were related to the accuracy and results improvement in both rounds, as is seen in Figure 27.

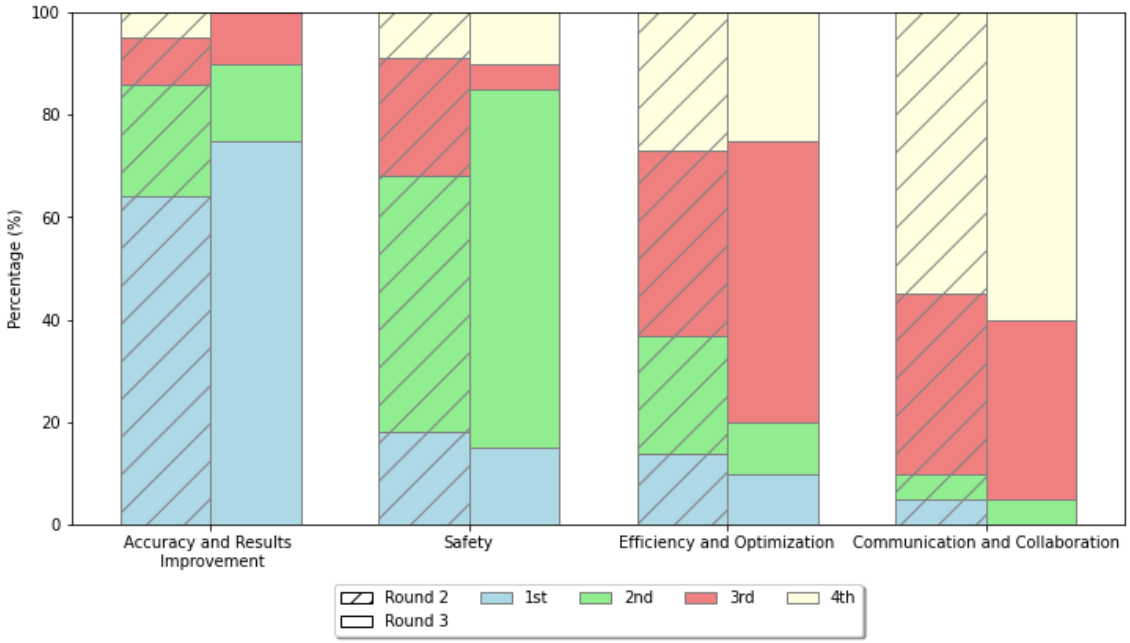

Figure 27 - Comparison of the benefits of MR in surgery, in the rounds 2 and 3 of the Delphi study.

In Figure 28, one can visualize that the main limitations in the implementation of MR in surgery are mostly related with its costs and investment; the least important issue was considered to be data protection (as seen in grey).

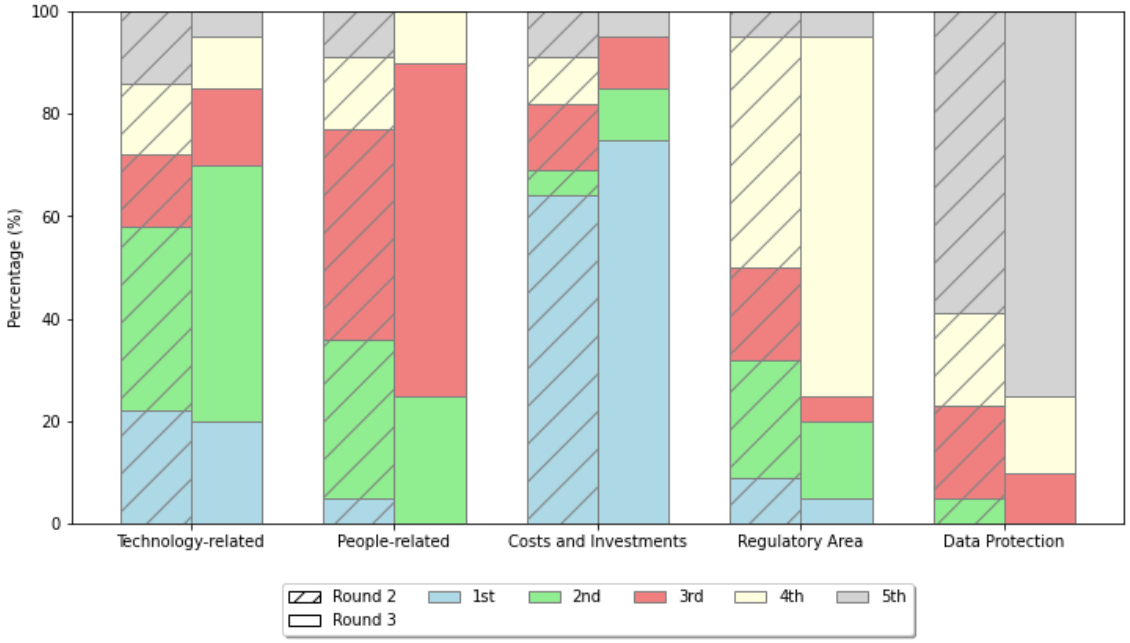

Figure 28 - Comparison of the limitations in the implementation of MR in surgery, in the rounds 2 and 3 of the Delphi study.

In Figure 29, one can see that the safety in the procedures and patients' protection was considered by the experts to be the main ethical consideration in the implementation of MR in surgery.

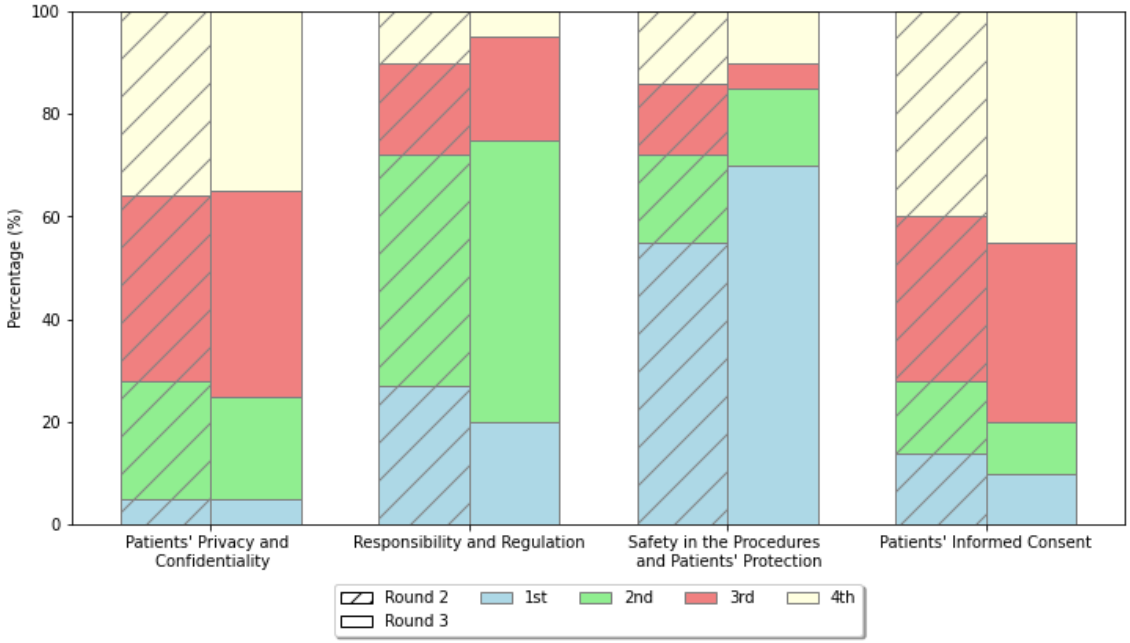

Figure 29 - Comparison of the ethical considerations of MR in surgery, in the rounds 2 and 3 of the Delphi study.

All in all, surgical orientation and navigation was found to be the main usefulness and application of MR in surgery; MR is thought to improve the accuracy and the results of a given surgical procedure; a possible limitation for the implementation of this kind of technology in surgery would be its cost, and developers should consider the safety in the procedures and patients' protection above all (as seen in Raza *et al.* (2022), the main ethical issues were also related to the patients and the regulatory area). All of the sections reached consensus among the experts: the highest percentage, 80%, was reached in the main applications of MR in surgery; and the lowest percentage, 70%, was obtained in the ethical considerations in implementing an MR system in surgery [165].

5. Case Study

In this section, both the development process and the results of the case study will be discussed in greater detail.

5.1. Preparation

For the case study, a Unity-based platform was developed. It was thought to work with the Microsoft HoloLens 2 headset, since it was the available hardware. Its purpose is to be used in the training of the ACL reconstruction surgery.

In order for this platform to be fully developed and tested, familiarity with the existing tools was gained. To achieve this, Unity tutorials were watched, as well as experimenting with Microsoft HoloLens 2 and its functionalities. The assistance of the professionals in ULSSA, ICBAS and INEGI was crucial. In addition, the state-of-the art review, as well as the Delphi study and the consulting with the doctors in ULSSA was very valuable for the requirement gathering and development process. For the testing part, a "real-world" scenario was used, using bone models, an arthroscopic camera for comparison, and Microsoft HoloLens 2.

To achieve this, some initial main goals were drafted:

- Experiencing an operating room environment for the familiarization with the surgical technique, the understanding of the surgeons' needs, as well as crucial steps in this type of surgery, where MR could potentially be an asset;
- Design and development of a functional MR application prototype adapted for this kind of surgery, to act as a digital health tool. One of the possibilities will be to use this technology in surgical planning, in a way to simulate the trajectory of the drill, before drilling the bone.
- Validation of the prototype in Sawbones or SYNBONE's models, to test and improve the system before applying it in other contexts, such as a simulated operating room.

- Evaluation of the developed prototype in a simulated operating room environment: the prototype will be evaluated in conditions that bear a closer resemblance to an actual operating room, possibly on cadaveric parts. This stage will allow the system's effectiveness to be evaluated in more complex and variable conditions.

A Gamma Nail Technique surgery (applied to the treatment of a trochanteric fracture) was watched on the 4th of January 2024, since, originally, the MR application was thought to be used in this kind of surgery, and it was later changed to the ACL reconstruction surgery. In any case, a female 88-year-old patient was subjected to surgery using the Gamma Nail Technique in the ULSSA, following a fracture on her femoral neck after an accident. First, the patient was prepared on the orthopedic operating table. Afterwards, she was anesthetized. The "time out" [166] phase then took place, where everyone in the room had to state their names and job titles, the patient's name, as well as the expected duration time and the expected blood loss. The surgical team consisted of 2 surgeons, an anesthesiologist, and nurses. The surgery was expected to last 30 minutes. Upon talking with a nurse, she stated that is usually the average time of said surgeries, expect in cases where there are complications, such as when fracture reduction needs to be performed. In this case, the surgery's duration can go up to an hour and a half.

There were no complications. The operation started at 6:34 PM, and ended at 7:03 PM, within the predicted timeline. There was a table with several instruments. All of them are reusable and sterilized, except for the screws, which are stored in individual boxes and only used once.

The surgeon inserted the first guide wire after manually feeling the bone and visualizing the X-ray image of its position. This had to be done twice, since on the first attempt, the wire was not in a central enough position. Only then do they drill the bone. During the insertion of the second guide wire, more than one attempt was made, to subsequently insert the second nail. Since it is done by trial and error, the process could benefit from some automation.

Although the case study will be applied to the ACL reconstruction surgery training and not the Gamma Nail Technique, MR could still be useful in the wire insertion phase.

During surgery, about 65 X-ray images were obtained through the C-arm. The stages where most images were captured were when the surgeon had to place the wires and

assess the drill direction. Everyone in the room had to wear a lead apron because of the radiation exposure. The total radiation dose was 5.45 mGy, with a total exposure time of 0.41 seconds. This is not a high amount [167]; however, it could still be reduced, if less attempts at inserting the screws were made. If applied to this kind of surgery, the MR tool could help indirectly reduce the radiation exposure, since with the use of holograms, less X-ray images would have to be obtained.

It would have been inspiring to watch an ACL reconstruction surgery to have a better understanding of the technique; however, this was not possible. Nevertheless, by studying the literature and having several meetings with Adélio Vilaça (MD), the steps which constitute the surgery became clear.

The second and the third goals were also completed. However, the application could not be tested in cadaveric parts yet, but it would be interesting in the future to do so, since it would be a step closer to testing in actual patients.

5.2. Development

The application was developed using Unity Hub, after obtaining a student license, and Visual Studio, with C# as the coding language [50], [168], [169]. A series of Unity tutorials were watched, to gain some familiarity with the tools [170].

First, a 3D model of a drill was obtained from [171] (Figure 30), in order to create an application where the user could visualize and manipulate this hologram. The computer had to be paired with the Microsoft HoloLens 2, and, in Unity, the ObjectManipulator script, as well as the BoxCollider, were added to the motor.

Figure 30 - 3D model of the drill (from [171]).

Through the Windows Device Portal [172] (Figure 31), it was possible to see live on the computer what was happening in the headset, which made the testing process easier. Moreover, this allowed for the download of videos and photographs from the HoloLens 2.

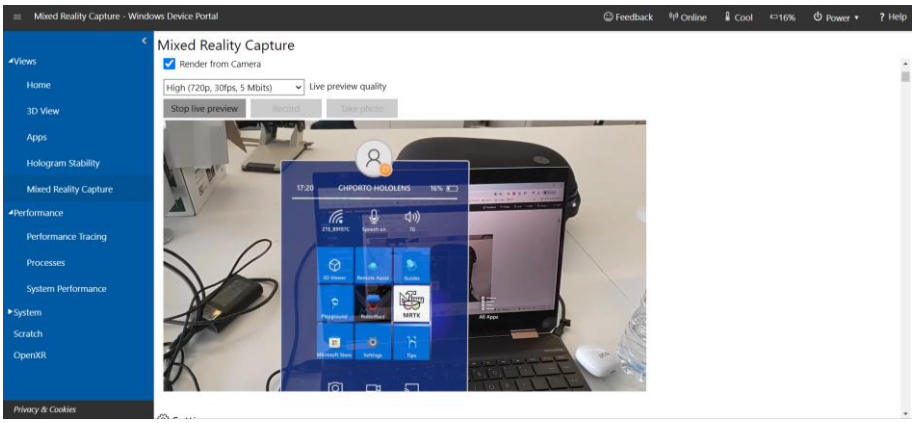

Figure 31 - Windows Device Portal.

Then, a surgical motor was digitalized, through the process of obtaining 600 photos, and passing them to Meshroom [173], and Blender software [174]. This process was assisted by Gilberto Silva (Technical Coordinator). The motor was placed inside a box, open on one of the sides only, and on top of a circle (Figure 32). The circle was moved in small distances at a time, pre-defined, in order to take 600 photos, without moving the motor directly. Those images were compounded and passed to Meshroom, where the 3D model of the object was created by Gilberto Silva (Technical Coordinator). Then, with his

assistance, the model was “cleaned” in Blender, and exported to .obj file extension. This 3D surgical motor model was inserted in Unity, where the same scripts were applied as the drill. 3D models of a femur and a tibia were supplied by Dulce Oliveira (Ph.D). These models were also inserted in Unity.

Figure 32 - Box to take photographs of the surgical motor.

To anchor the virtual objects to the physical ones, 3 QR codes needed to be generated: one for the femur, another for the surgical motor, and, lastly, one for the tibia, using the website QR Code Generator [175]. The option used was “text” (FEMUR01, MOTOR01, and TIBIA01, respectively). These QR codes were printed, and they were squares with 10 cm side, in order to be better detected by the Microsoft HoloLens 2 [176].

In order to have a better understanding of QR codes as anchors, a project from GitHub was cloned (authored by Joost van Schaik [177]). After extensive reading on the project’s documentation [178], the project was adapted to fit the needs of this dissertation – the models of the original project were replaced with the surgical motor, the tibia, and the femur, and they had to be scaled and positioned in a different way. The scale and positions were adjusted manually, in a trial-and-error process. The tibia and the femur were initially placed slightly to the left of the QR code (since the QR code was thought to be positioned

in the right side of the “real” bones), and the surgical motor was placed on top of the QR code.

Initially, the models of the bones looked small and out of place, as one can see in Figure 33 and Figure 34. The hologram of the femur had to be rotated, since it was placed perpendicularly (and not parallel) to the QR code. It is to be noted that the hologram of the tibia was initially green; however, the color was adjusted in Blender.

Figure 33 - Hologram of the tibia (initially).

Figure 34 - Hologram of the femur (initially).

After adjusting, the 3 models looked visually better (Figure 35 and Figure 36); however, the models of the bones had to later be mirrored in Blender, since they belonged to the opposite leg.

Figure 35 - Femur and tibia holograms (after adjusting).

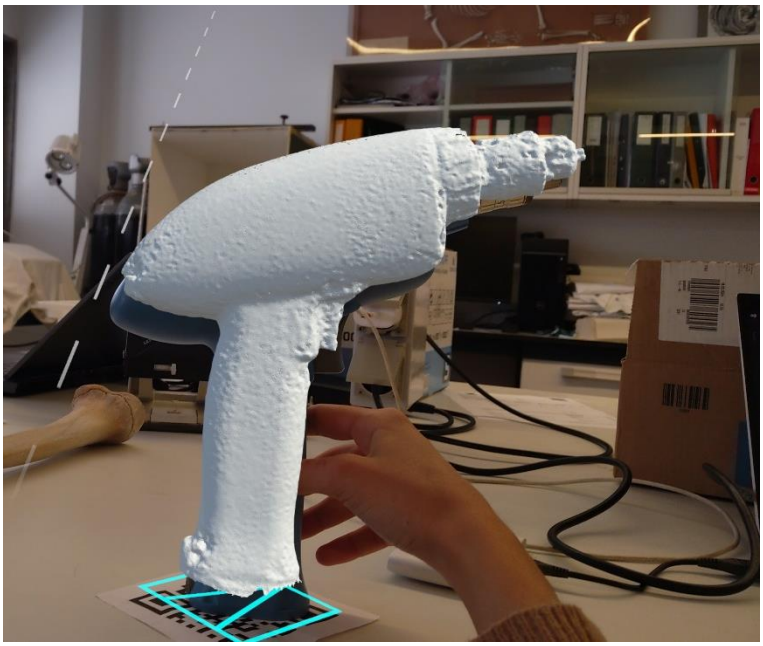

Figure 36 - Hologram of the surgical motor (after adjusting).

In a second phase of this case study, Gilberto Silva (Technical Coordinator) prepared a physical model of the right knee, by connecting the femur and the tibia models and simulating the grafts (Figure 37). Afterwards, the QR codes were attached to the bones directly; therefore, the positions and rotations of the holograms had to be adjusted again

in Unity. As for the surgical motor, a QR code was also attached to it, and a new script was created, allowing a continuous read of the QR code of the motor, and a continuous adjusting of the position, without the need for a “reset” button.

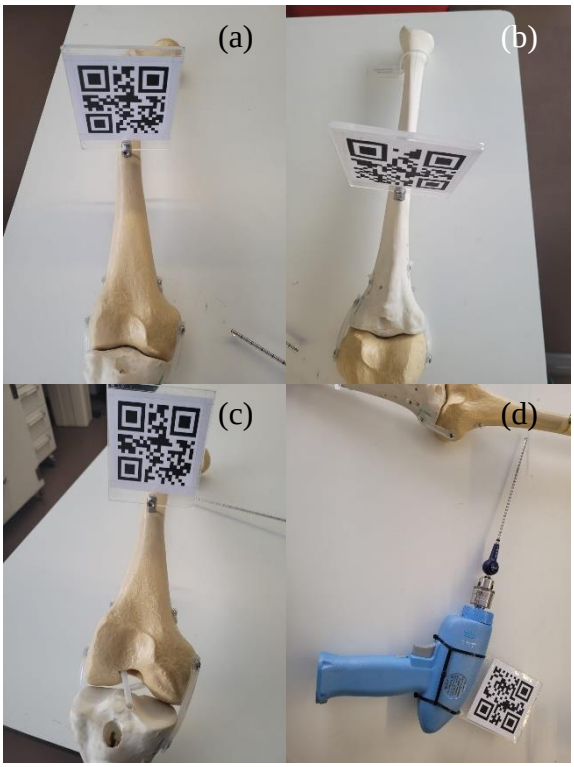

Figure 37 – (a) Model of the femur; (b) Model of the tibia; (c) Model of the knee grafts; (d) Surgical motor and drill.

In a third phase, as per the suggestion of Adélio Vilaça (MD), a green target was added to the femur model in Blender, symbolizing the coordinates of the femoral tunnel, as seen in Pearle *et al.* (2015). A cylinder was added to the tip of the surgical motor, to simulate the surgical drill. The goal of this would be for the doctors to hit the green dot with the tip of the surgical drill (Figure 38).

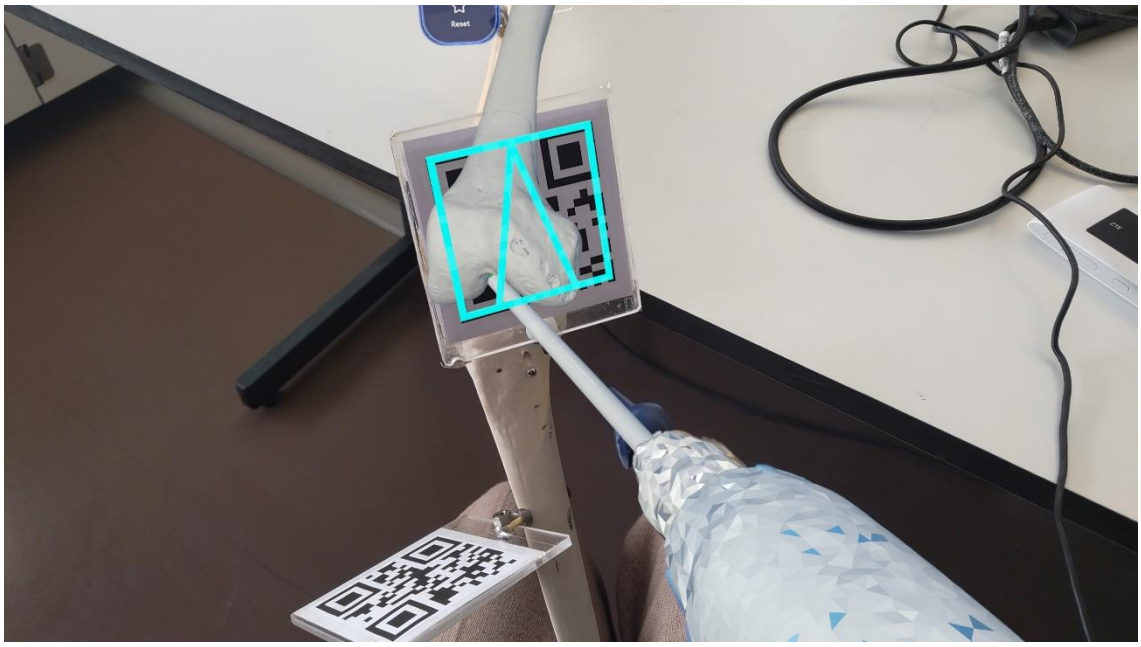

Figure 38 - Green target being hit by the motor.

The QR code of the motor had to be placed in the drill itself (Figure 39), because, otherwise, the surgeon would have to be constantly looking to the blue part of the motor and losing track of the drill. The hologram of the motor had its position adjusted in Unity. In this way, the surgeon could be looking at the tip of the drill and the hologram of the motor would still appear in the right position. However, this would not work in an actual surgery, since there would be drilling of the bone (and the drill would spin). A possible solution would be to use computer vision to do an object recognition of the motor, thus eliminating the need for a QR code in the first place.

Figure 39 - Motor after inserting the QR code in the drill.

Moreover, the hologram of the tibia is not in the final application, due to partially covering the field of vision of the surgeon (since the goal of the application was only to guide the femoral tunnel, not the tibial one). This was done following a suggestion from Adélio Vilaça (MD).

Finally, the holograms of the motor and the femur were readjusted to overlay the real objects in a more precise manner (Figure 40).

Figure 40 - Holograms of the femur and motor after the final adjustments.

As one can notice, the holograms of the motor in the Figure 36 and Figure 38 are not the same; the latter has less quality than the former. Using Blender, the number of triangles of the motor's mesh was reduced from 306462 to 12190, in order to try and optimize the application. The number of triangles of the femur model is extremely high (1184972

triangles, it should be lower than 100000 [179]); however, when reducing this number, the femur's quality decreased immensely. Since the femur had to be in good condition in order to better visualize the position of the femoral tunnel, this number was not reduced. A comparison of the frame rates (number of times a certain application is able to render an image per second [180]) of the application prior to these changes, and after them, was made. It is to be noted that the final application did not have the hologram of the tibia, which might also reduce its complexity and response times. The frame rate's graphs were obtained through the Windows Device Portal, in the "System Performance" tab.

In Figure 41, one can see that the frame rate falls linearly after only the hologram of the femur appears; and it increases linearly after it disappears in the MR application. The same happens after the optimization (Figure 42), since the femur did not actually go through the optimization process.

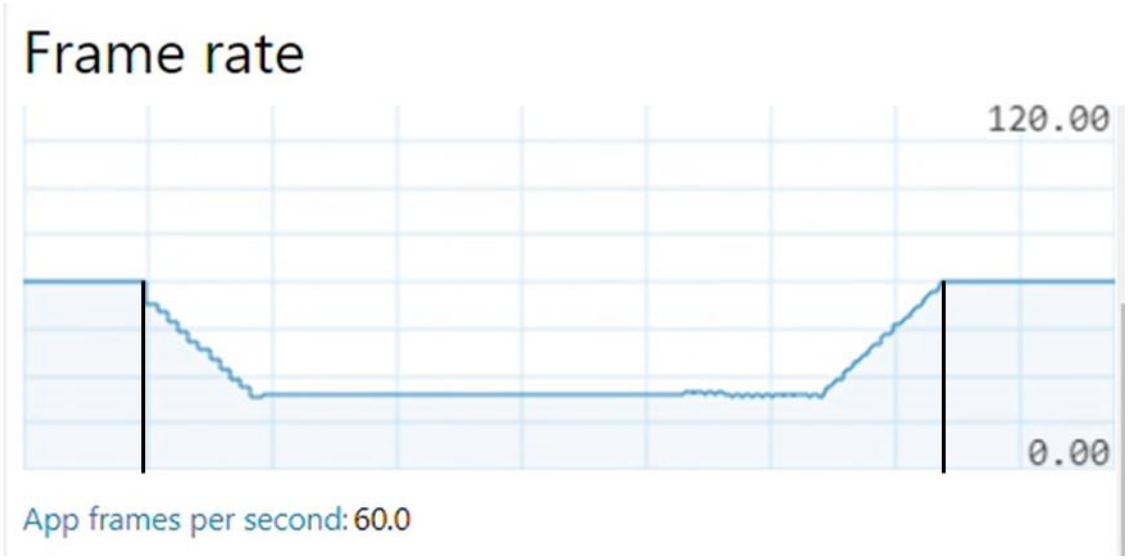

Figure 41 - Frame rate of the MR application with only the femur present, and after it disappeared, before the optimization (in between the black lines).

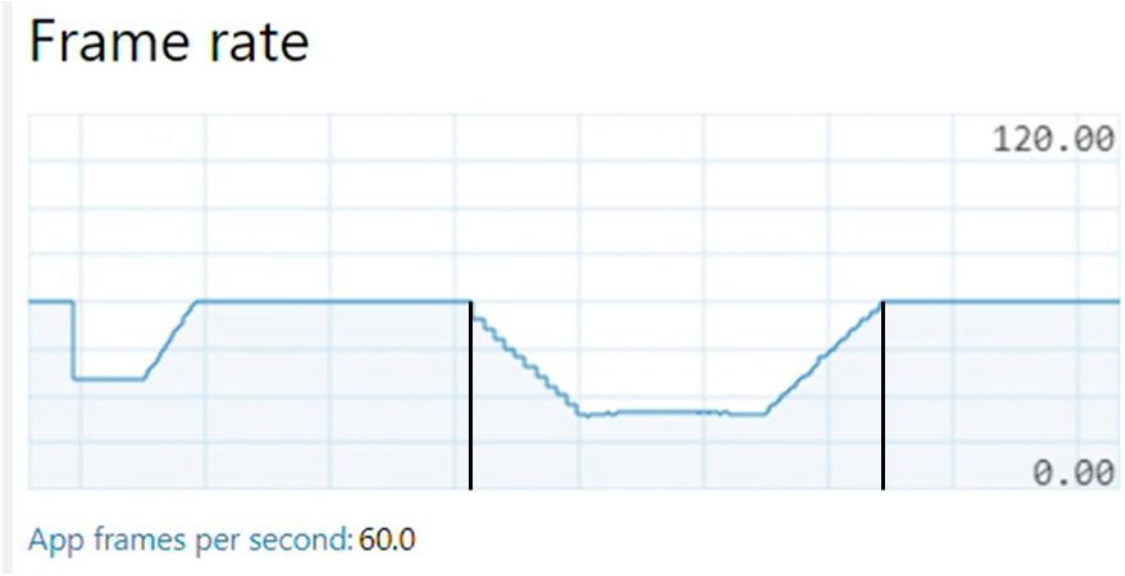

Figure 42 - Frame rate of the MR application with only the femur present, and after it disappeared, after the optimization (in between the black lines).

Before the optimization (Figure 43), the frame rate of the application when only the motor appeared was not constant and it did not look steady. Afterwards (Figure 44), it is a much more constant graph, and the frame rate is closer to 60 frames per second (in the first graph, the value read is 60 frames per second, but only because there is a slight delay between the graph and the value read, since the graph is showing up in real time in Windows Device Portal). This means that reducing the number of triangles of the motor made the application have a better frame rate.

Figure 43 - Frame rate of the MR application with only the motor present (before the optimization).

Figure 44 - Frame rate of the MR application with only the motor present (after the optimization).

The following graphs (Figure 45 and Figure 46) consist of when the application was showing all the holograms (3 in the first case, and 2 in the second case). By analyzing the previous graphs, it is noticeable that the replacement of the motor hologram did indeed improve the frame rate of the application (the closer to 60 frames per second, the better, since it improves hologram stability and tracking [180]); however, when all holograms were present, the frame rate remained approximately the same in both cases, as it did when only the femur was present. In conclusion, the hologram of the femur should have been replaced as well, for better results.

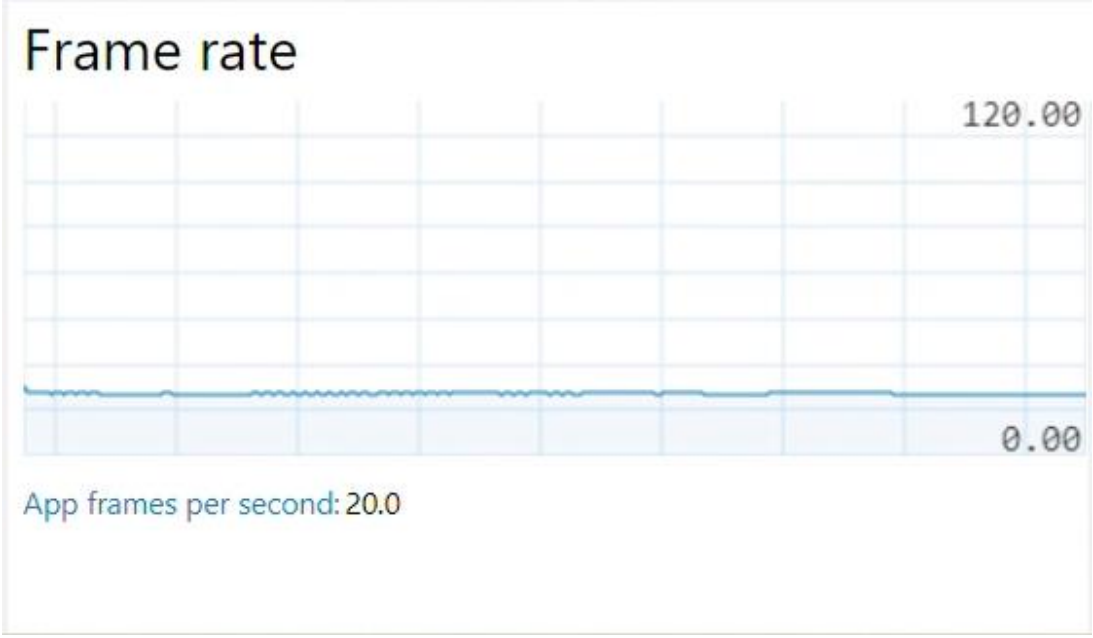

Figure 45 - Frame rate of the MR application with all the holograms present (before the optimization).

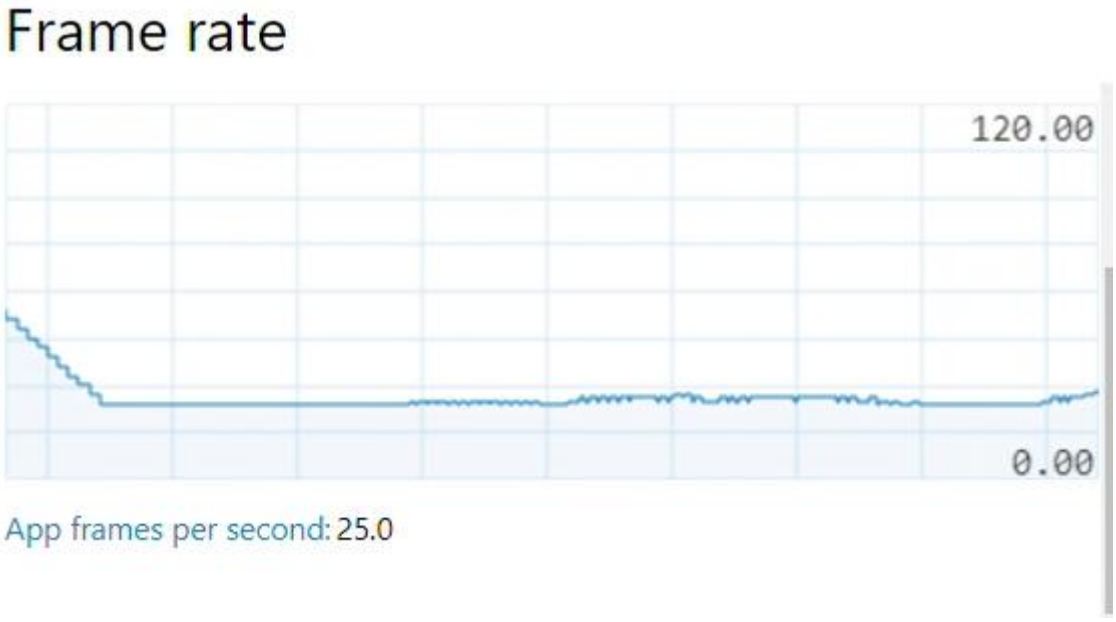

Figure 46 - Frame rate of the MR application with all the holograms present (after the optimization).

The CPU (Central Processing Unit) utilization was also compared, and it did not differ much between both applications. However, the behavior was similar: once the application was opened, the CPU utilization increased to 90%, and afterwards, it decreased and

remained approximately constant, around 35 to 50%. The CPU is the main part of digital computer systems, and its function is to recover and select the orders from the main memory [181].

As for GPU, it plays a key role in rendering the graphics of an application. It started off with the primary function to accelerate computer graphics; however, nowadays, it is also used to solve computing problems [182].

Some applications are CPU bounded and others are GPU bounded. Since the number of triangles in the mesh was reduced, and that increased the frame rate, then it is likely that this application is GPU bounded, which means that, probably, the execution of the application is mostly being run on the GPU. In this case, improving the polygon count, as was accomplished, would likely improve the GPU [180], [183].

Therefore, the GPU was also compared before and after the optimization. The biggest difference between both applications was when the motor was alone in the scene: before the optimization, the GPU utilization was nearly 100% (Figure 47); after the optimization, it decreased, until it achieved approximately 40% (Figure 48). The GPU did not differ when only the femur was present, or when both the motor and the femur were seen (Figure 49 and Figure 50), which means that it was indeed the improvement of the polygon count of the motor that improved the GPU utilization, and it would have been interesting to reduce the number of triangles on the bone's mesh, in order for the application to be further optimized.

Figure 47 - GPU utilization of the MR application with only the motor present (from the black line onwards), before the optimization.

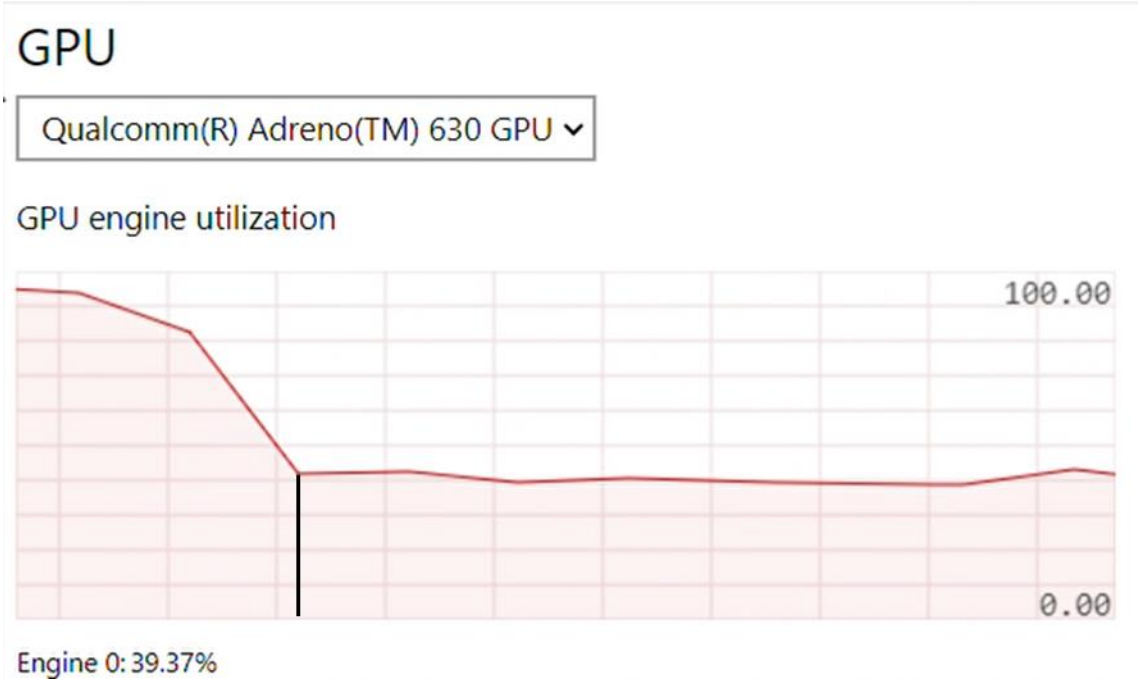

Figure 48 - GPU utilization of the MR application with only the motor present (from the black line onwards), after the optimization.

Figure 49 - GPU utilization of the MR application with all the holograms present, before the optimization.

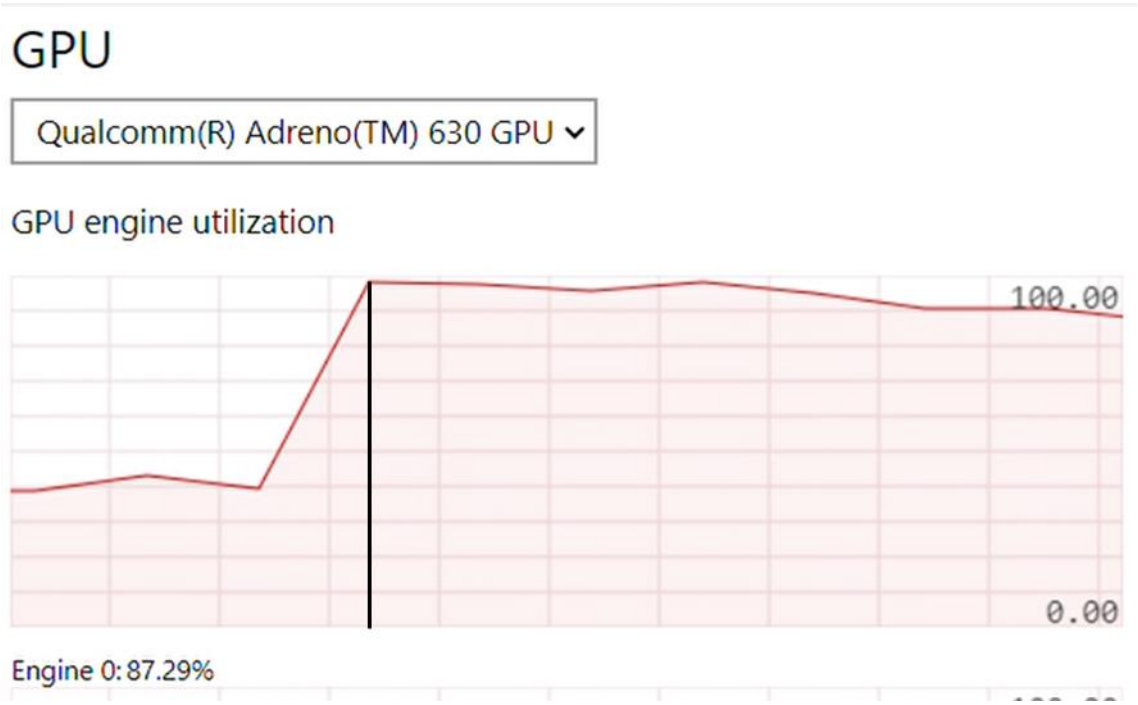

Figure 50 - GPU utilization of the MR application with all the holograms, after the optimization, from the black line onwards.

5.3. Questionnaire

For this case study to be validated, an informative questionnaire had to be created. This questionnaire was inserted in Microsoft Forms [184], which allows to share the form in a QR code, in order for the surgeons to answer the questions. This questionnaire was divided into 4 sections.

The first section had questions related to the technology itself. The first 3 questions were yes/no questions, and the fourth was an open-ended question. The questions of this section were adapted from literature [185].

As for the second section, it was adapted from the NASA Task Load Index [186]. A 5-point Likert scale was used, with the values “strongly disagree”, “disagree”, “neutral”, “agree” and “strongly agree”, in order for the experts to rate the statements [9].

The third section was related to the equipment used, the Microsoft HoloLens 2. This section also used the Likert scale, and the questions ranged from HoloLens 2’s level of comfort, to the level of holograms’ overlay.

Finally, in the fourth section, the surgeons were presented with a description of future improvements of the application, such as the automatic recognition of the objects (possibly using computer vision, thus removing the need to use QR codes), and the addition of information to tell if the participant managed to hit the target or not, automatically. Then, this section has 2 open-ended questions, asking for improvements and changes of the application with the future work already applied.

The questions were presented as follows:

1. **Section 1:**
    - Do you think it would be useful to invest in this kind of technology?
    - Do you think this technology could be good for the patients, even if indirectly?
    - Do you think this kind of technology would differentiate ULSSA positively?
    - How could this technology be used to fulfill its entire potential?
2. **Section 2:**
    - The task was mentally demanding.
    - The task was physically demanding.
    - The task took too long to complete.
    - The task was completed successfully.
    - I had to make a lot of effort to complete the task.
    - I felt irritable and/or frustrated during the task.
3. **Section 3:**
    - The HoloLens 2 is easily adjustable.
    - The HoloLens 2 is light.
    - The HoloLens 2 is comfortable.
    - The HoloLens 2 is intuitive.
    - The HoloLens 2 is interactive enough.
    - The HoloLens 2 has a quick reaction time between my command and its response.
    - The field of vision of the HoloLens 2 is big enough.
    - There is a good overlay of the holograms with the real world.
    - I found it hard to learn the gestures to use in HoloLens 2.
    - I felt sick after using HoloLens 2.
    - I had headaches after using HoloLens 2.

- The HoloLens 2 is a useful tool to be used in healthcare, namely in surgical training.

4. **Section 4:**
    - Taking the improvements into consideration, what would you add to the application?
    - What would you change in the new application?

The questionnaire could have been completely standardized; however, since the goal was to have a more personalized opinion of the users, this was not the chosen approach. Even though the NASA Task Load Index was used, its scale was adapted to this questionnaire's needs. Moreover, a standard questionnaire could have provided an easier statistical analysis and easily comparable results, but it would lack personalized questions and qualitative analysis. Nevertheless, a questionnaire which could have been considered is the User Experience Questionnaire, which exists in more than 30 languages, and is able to measure comprehensively the attractiveness, stimulation, novelty, efficiency, perspicuity and dependability of a product. It has 26 points, which are measured in a 7-point scale [187].

5.4. Results

First of all, the application was tested by Adélio Vilaça (MD), who suggested the addition of the green target directly in the femur model, and, in a second test, said that the hologram of the femur had to be overlayed in a more precise manner. In a third iteration, the position of the green dot had to be adjusted, and the QR code of the motor had to be repositioned. These suggestions were taken into consideration and applied accordingly, as it was seen in the Development section.

Afterwards, the application was ready to be validated by the surgeons. Adélio Vilaça (MD) covered the model of the knee, as one can see in Figure 51, to simulate a patient's skin.

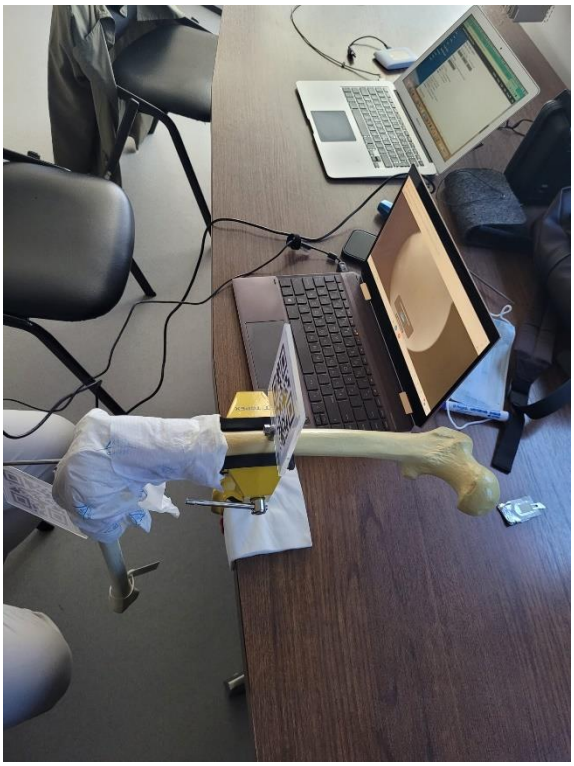

Figure 51 – Complete model of the knee.

In order to compare the application with a more traditional approach, a surgical simulation protocol was proposed:

- First, the surgeon would, with an arthroscopic camera connected via USB to a computer, visualize a blue dot marked in the physical model of the femur, and hit the dot with a puncture tool, while being timed (the video available at this link provides a better visualization of the protocol).

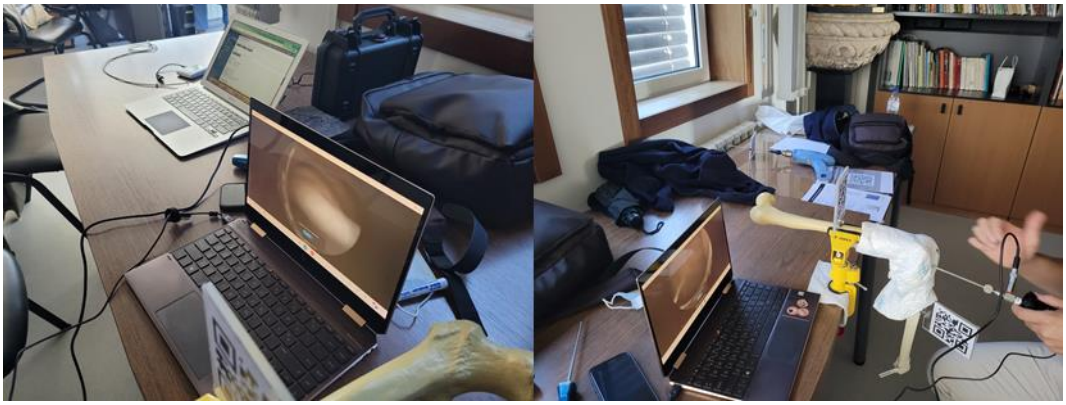

Figure 52 - Experimental apparatus with the arthroscopic camera.

- Afterwards, the surgeon would try the MR application, where they would hit the green dot of the virtual model of the femur with the tip of the drill, while being

timed (Figure 53; and the video present at this link, which provides a better visualization of the protocol being described).

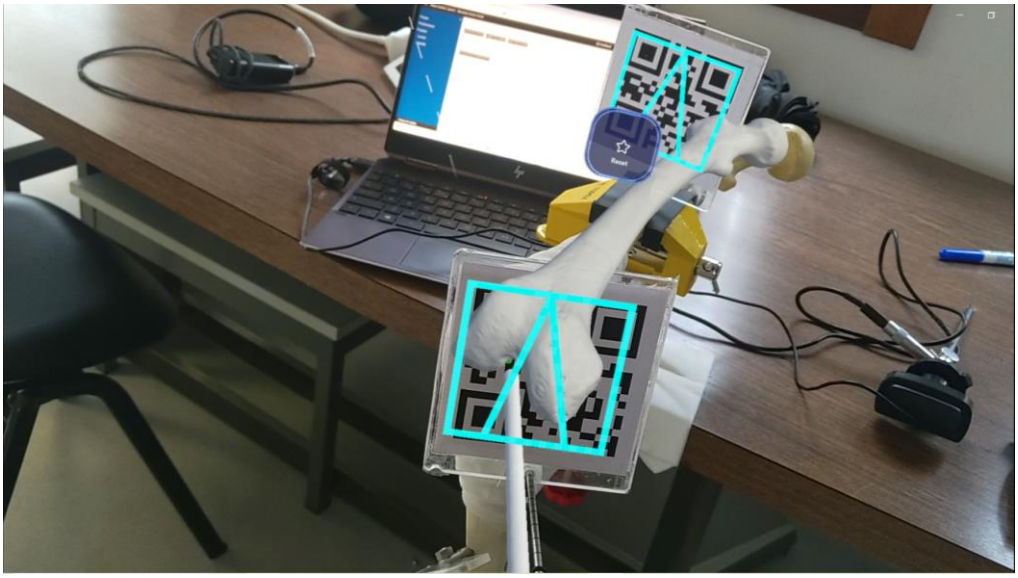

Figure 53 - Experimental apparatus with the MR application (with the motor hitting the green dot in the femur).

- The surgeon would then repeat the previous steps, in order to understand how the simulation times would vary from the first iteration to the second iteration.

The first 2 surgeons did not follow this exact protocol: the first one only tried out the MR application, and the second did not repeat the protocol both times. Nevertheless, they replied to the inquiry of satisfaction, since they had both tried the MR app.

The protocol was explained briefly at the beginning, and a short introduction to Microsoft HoloLens 2 was made (the surgeons were told to touch the holograms as if they were a touch screen).

The software used to connect the arthroscopic camera to the computer is the Debut Video Capture and Screen Recorder software, which allows the user to record their own computer screen and webcam [188] (Figure 52).

The surgeons were timed while doing both tasks, as was described in the protocol above, in order to compare both methods (Table 11 – the values are in seconds). The accuracy of the simulations was thought to be calculated; however, it could not be. The hologram of the femur was a “standard” hologram, it was not a digitalization of the physical one. Because of that, even if it was overlayed with as much precision as possible, it still was

not completely accurate, because it did not correspond to the “real-life” model. Moreover, the blue dot did not match the exact place as the green dot. To compare the accuracies, one could do a simulation on a cadaver, for instance, and do X-rays of both modalities, to later compare the positions of the images.

Table 11 - Surgeons' simulation times (for both iterations of each modality - arthroscopic camera and MR application).

Surgeon / Time (seconds)	**Camera (1st iteration)**	**Camera (2nd iteration)**	**HoloLens 2 (1st iteration)**	**HoloLens 2 (2nd iteration)**
1st surgeon	80	33	10	21
2nd surgeon	43	56	49	35
3rd surgeon	148	88	20	14
4th surgeon	55	88	14	16
5th surgeon	63	20	29	6
6th surgeon	100	65	7	8
7th surgeon	36	25	83	31
8th surgeon	80	79	21	22
9th surgeon	54	16	10	17
10th surgeon	40	23	56	20
11th surgeon	35	14	20	12
12th surgeon	25	45	35	21

It is worth being noted that the time for each simulation started counting, in the case of the arthroscopy, since the moment the surgeons inserted the camera in the bone; and, in the case of the MR, since the moment the surgeons could visualize the holograms of both the motor and the femur; up until the point where the surgeons hit the dots.

With the Excel software, the average and the median of the simulation times were calculated, as presented in Table 12.

Table 12 - Average and median of the simulation times.

	Camera (1st iteration)	**Camera (2nd iteration)**	**HoloLens 2 (1st iteration)**	**HoloLens 2 (2nd iteration)**
Average (seconds)	54.5	39	20.5	18.5
Median (seconds)	63.3	46	29.5	18.6

Thirteen surgeons replied to the questionnaire, and twelve completed the experience entirely. Two of the surgeons who replied to the questionnaire did not complete the experience entirely, and the fourth surgeon who completed the experience did not reply to the questionnaire; thus, making it 11 surgeons in total who both answered the questionnaire and completed the experience entirely. Nevertheless, all the surgeons who replied to the inquiry used the MR application and the Microsoft HoloLens 2, so their answers were still considered.

All surgeons thought it would be useful to invest in this type of technology, and that it would benefit the patients and ULSSA. The surgeons considered that the full potential of this kind of technology could be fulfilled in using it for surgical training, especially for medical interns, and that it is something that could be adjusted for the user and improve the image quality.

As for the section based on the NASA Task Load Index (Figure 54), there was only one statement where no participant disagreed: “The task was completed successfully” (38.5% of the participants strongly agreed, 53.8% agreed, and 7.7% were neutral about it). Some participants thought the task was mentally demanding: 7.7% of the participants strongly agreed with the statement, while 30.8% agreed; however, 38.5% were neutral about it, and 23.1% disagreed. The participants did not think the task was physically demanding: 30.8% strongly disagreed with the statement, 46.2% disagreed, and 23.1% were neutral about it. Moreover, the participants did not feel frustrated during the task: 46.2% strongly disagreed, 38.5% disagreed, and 15.4% of the participants were neutral. One participant (7.7%) thought the task took too long; however, the majority of the participants (61.5%)

disagreed with this sentence, with 15.4% of the participants strongly disagreeing, and 15.4% being neutral about it. Finally, the level of effort also varied: 15.4% of the participants agreed they had to apply a lot of effort to fulfill the task, 15.4% of the participants were neutral about it, 38.5% disagreed, and 30.8% strongly disagreed.

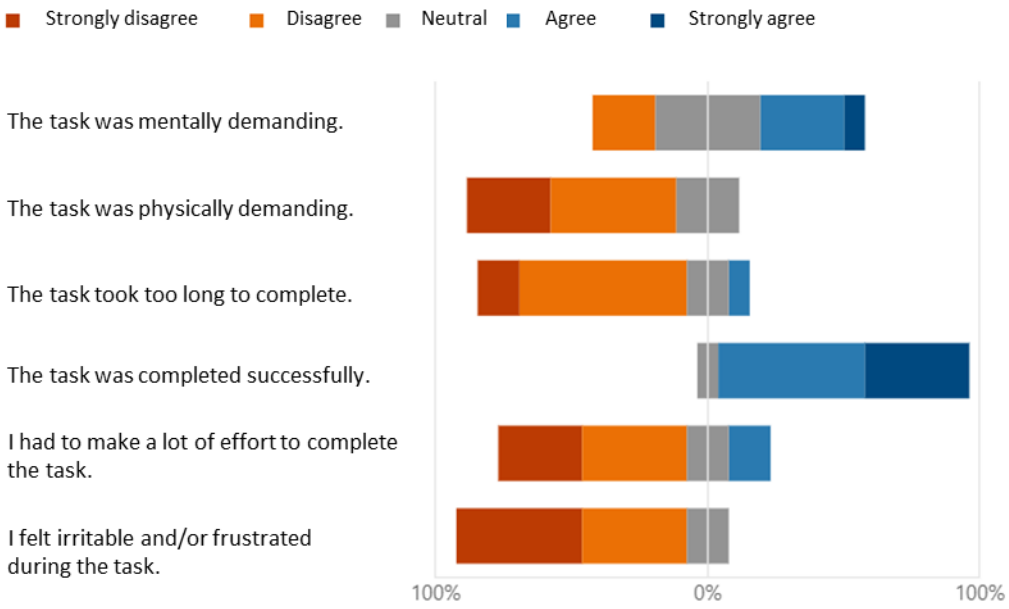

Figure 54 - Answers related to the usability of the application.

As for the HoloLens 2 (Figure 55), the surgeons agreed that the headset is sufficiently interactive, adjustable, and a useful tool to be used in health, namely in surgical training. Moreover, the surgeons said they did not feel indisposed or headache after using HoloLens 2. The rest of the sentences had more differences between the surgeons, namely the statement regarding the response time of the HoloLens 2, where 46.2% of the surgeons disagreed it was quick, 15.4% were neutral, and 38.5% agreed.

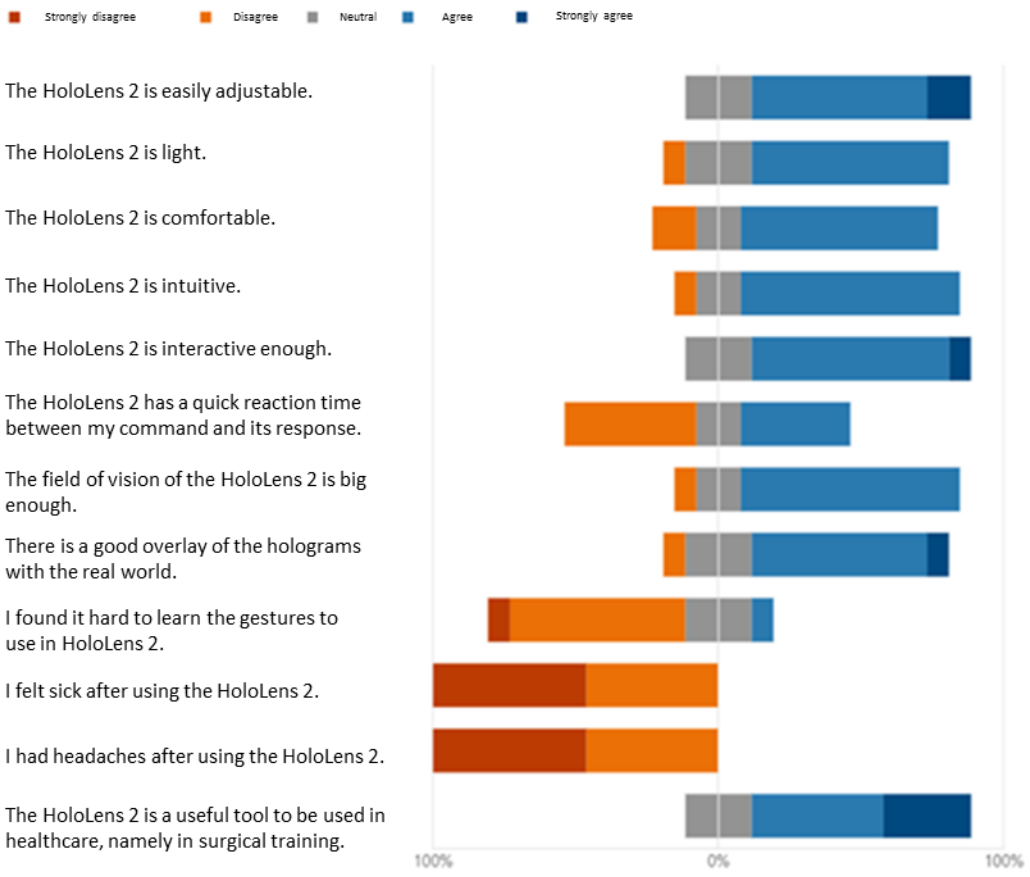

Figure 55 - Answers related to the usefulness of the HoloLens 2.

Regarding the application's improvements, while most answers claimed they would not change anything, some answers stated that the image should be more stable, the application should have a quicker response time, and other joints should be present. As for what would change in the application, the answers were also related to the response time, and a higher sensitivity.

5.5. Discussion of the Results

Regarding the time spent doing both simulations, it is noted that the surgeons reduced the time spent in the second simulation, when compared to the first. This was to be expected, since they could find the dot faster, knowing its position previously. In surgical training, this is good, since the surgeons are able to learn and adapt in the next times they have to perform the same task. The time spent in the HoloLens 2 simulation was usually lower than the time spent in the arthroscopic camera simulation, with one case being much lower

(7 seconds vs. 100 seconds), and another case being much higher (83 seconds vs. 36 seconds). This is promising, since they were able to adapt to a technology the majority of them had not had previous experience with rather quickly. The average time in all cases was lower than one minute, with only the median for the first iteration of the arthroscopy camera being slightly higher. This is a good indicative, since it means surgeons were able to complete the task in a relatively short amount of time. Some surgeons mentioned they had previous experience with arthroscopic simulations, in a course they took. Another surgeon mentioned he had tried HoloLens 2 in the past. These kinds of conditions might have influenced the time they took to complete the simulations, and it would be interesting to investigate this possible connection in a future study.

The results in the questionnaire show promise, since all the surgeons were quite open about the potential of MR technology, and thought it would be beneficial to invest in it. In addition, even though some people found the task mentally demanding, they were all able to complete it successfully. As for the HoloLens 2, there are some limitations regarding the equipment, such as the response time between the user's command and the headset's answer. However, surgeons still found it to be a useful tool to be used in surgical training.

The application's response time might have been improved with the use of a 3D model of the femur containing less triangles in its mesh (thus increasing the application's frame rate). Moreover, the fact that the application is continuously tracking for QR codes might reduce its performance [178]. In addition, the lighting conditions of the room might have played a role in the QR code detection, as well as the distance that the surgeon was in relation to the QR code (mainly in the case of the motor, which had to be moved during the simulation). The QR codes had 10 cm sides, since QR codes smaller than 5 cm are not detected, and if they are between 5 cm and 10 cm, they are not detected as easily. Finally, the angle with which the QR code of the motor was placed might have had some influence in the quickness of its detection, since it was detected faster when it was in a flat plane [176].

As was seen in Liu *et al.* (2021), HoloLens 2's users might experience eye fatigue after a prolonged amount of time, such as half an hour [125]. Since this simulation took approximately one minute to complete, it would be interesting to evaluate, in the future, the effects of HoloLens 2 in eye strain, when using the device for a longer amount of time.

Moreover, in the future, surgeons could be offered some training with the HoloLens 2 before the simulations, to become familiarized with the voice commands and the gestures to control the device. This could potentially reduce the response time of the HoloLens 2, since the users would be able to provide more confident commands.

Whenever a new person uses the device, Microsoft HoloLens 2 presents the user with a pop-up window asking them if they want to calibrate and adjust the device to their eyes. Some surgeons did not do this calibration, which means they might have experienced a lower sensitivity [189].

Some future improvements could include indicating the direction of the femoral tunnel, instead of only its position. This would be particularly helpful in surgeries where the surgeons have to drill in multiple places. Besides, the user would be able to see how much time has passed since the beginning of the simulation. Moreover, instead of the tunnel being "manually" recognized, there could be a certain sound playing when the user hit the green dot, or some kind of pop-up window could appear with a message, such as "You found the position of the femoral tunnel, the simulation is now complete". The addition of a bar on the top of the application, similar to mobile guitar tuners, would also be a source of automation. In this scenario, as one can see in Figure 56, the arrow would indicate the direction of the drill, and the color of the zone would indicate its position, with green being the ideal zone, yellow the intermediate, and the red color would indicate that the user was far from hitting the femoral tunnel. This would allow for an automation of the process, accompanied by a progress report, informing the participants of how well they did. The prototype in Figure 56 was designed using Figma, which is a platform to conceptualize applications [190].

Figure 56 - Prototype of a future ideation of the application.

It would also be interesting to measure the accuracy in a future test, by assuring that the model of the femur matched its hologram, and that the position of the femoral tunnel was the exact same in both the arthroscopic camera and the Microsoft HoloLens 2 simulations.

Microsoft HoloLens 2 was the available hardware, and it was mentioned more than once during the literature review, therefore, it was the chosen headset. However, there are other MR headsets, discussed in this dissertation, which would be interesting to explore and compare the MR applications (their response time, for instance, as well as the hologram quality and general usability). For example, Magic Leap 2 are able to track fiducial markers, such as QR codes [191].

Other libraries and frameworks could have also been used, instead of using QR codes, such as Vuforia Model Targets, which work with object recognition, and allow the user to track objects in the "real world". However, Vuforia does not allow the publishing of the application with Model Targets when using a free plan; for this to happen, the developer would have to purchase the Premium plan [192], [193]. Another option would be Microsoft Dynamics 365 Guides, which allow you to attach anchors to specific objects. Nevertheless, a license is needed in order to use Dynamics 365 Guides, and it would be a similar solution to the one used in this dissertation [194].

In order to use this application in a surgical setting, it would have to be personalized for each patient. To do that, a 3D model of the patient's anatomy would have to be obtained

through their CT or MRI scans. The DICOM data from these models could be imported to software, such as 3D Slicer [195] or Materialise Mimics [196], in order to then obtain their automatic segmentation, and import the 3D model to the Unity application, being replaced for each patient. This model of the bone would have to have less triangles than the model of the femur used, in an attempt to optimize the application by increasing its frame rate and improving its GPU.

The optimization process of the application could have been improved as well. The frame rate, the CPU and the GPU were explored, but there are other variables which would also be important, such as the network, even though the target frame rate is the easiest variable to consider when assessing an application's performance. Since this application is probably GPU bounded, some recommendations to improve GPU (and the frame rate) were followed, such as reducing the polygon count, and the number of transparent objects [180].

All things considered, the surgeons seemed enthusiastic about the MR application, and believed it could be potentially beneficial to be used in surgical training. All of the surgeons completed the simulation successfully and were able to adapt to the Microsoft HoloLens 2.

6. Expectations and Hypothesis

There is a growing tendency in the use of MR in healthcare. In the United States of America, this market has been valued at 178.56 billion dollars in 2022, and it is expected to increase to 9,925.6 billion dollars by 2032, in just 10 years [197]. Taking this into consideration, it is expected that an MR solution will prove feasible and viable.

As MR tools are expected to be more applied in the future of surgery, they should be combined with other types of technology, such as 5G [198]. ULSSA has recently implemented 5G in the operating block [199], thus allowing for the experimentation of MR devices in the surgery rooms.

Since MR tools have been implemented with satisfactory accuracies in the operating room [117], [135], the developed tool is expected to be accurate and easily integrated within the operating room environment. It could also have real-time sharing of content [134], such as images, video and audio, if possible, so as to guarantee real-time feedback between the medical professionals.

When used by nonsurgical staff in Kos *et al.* (2023), MR tools did not disrupt the workflow. It is hoped that the proposed tool will similarly not disturb this process, for both the nonsurgical and the surgical workers.

MR equipment has been considered safe to use in surgery, both for the surgeons and the patients, as well as accurate, and able to reduce operation times [98], [117], [134], [135]. So, it is expected that the developed tool will equally fulfill these requirements.

This type of gear, when applied to surgery, has been described as “low-cost” [134]. The MR application should then be economical, in order for it to be more likely considered as a solution.

Training with this type of technology allows for the use of simulations, which improve the confidence of the medical students, thus lowering their errors [143], [144]. Consequently, it is anticipated that, if the MR tool is used with this application in mind, it is able to enrich the learning experience for the students.

As for the hypothesis, depending on the chosen applicability, the MR tool should be used to have a positive impact in surgical training, by ameliorating the teaching conditions, and possibly the reduction of radiation used during surgery.

7. Conclusions and Future Work

In this section, the limitations, main conclusions, and future work will be presented.

7.1. Limitations and Difficulties

This work presents itself with some potential risks, difficulties and limitations.

Starting with the Delphi study, incorporating a different type of analysis, such as statistical methods, could yield a greater amount of quantitative information.

Moving on to the MR application, the lack of familiarity with the tools being used, namely Unity, was a nuisance initially. However, this was alleviated by learning more about the tools, through watching tutorials, completing small exercises and with the assistance of professionals.

Surgeons mostly mentioned HoloLens 2's time of reaction between their commands and its answer. This could have been improved by further optimizing the application.

Moreover, even though this application was designed for surgical training, in the future, if the application is further developed to be used in surgical practice, it might be difficult to implement it in the operating room due to a potential lack of sterility or ethical concerns. However, if the application is for the surgeons only, and not used in the patients directly, then it will not have to go through an extensive ethical analysis.

7.2. Main Conclusions

This work is focused on evaluating the potential of MR tools to be used in surgery (whether in practice or in training). To achieve this, a state-of-the-art analysis was made, through a query in 2 different databases, Scopus and PubMed. Some main applications for MR in surgery were found, namely the use of 3D models, either of organs or of other structures, such as cancers; for the assistance in screw placement; for the non-surgical staff; for remote surgical training, for telemedicine, and for surgical simulation. MR tools

also have the potential to mitigate some challenges in the operating room, such as the lack of real-time communication between operating rooms, and human error, through the use of simulations. Ethical concerns, such as patient consent for the use of data, and regulations for medical devices, should be taken into consideration.

All of this was used in the conceptualization of the Delphi study, and, in a later phase, in the development of the prototype of the MR tool.

The main application of MR in surgery, according to the experts who answered the Delphi study, is surgical navigation and orientation. Even though there are possibly some limitations in the implementation of these tools in surgery, namely their cost, there are also benefits, such as an increased accuracy and safety in the procedures.

The results of the application's evaluation were mostly positive as well, with the surgeons highlighting the potential of MR tools, even if the response time between the user's command and the Microsoft HoloLens 2's answer was not always fast enough. However, every surgeon was able to successfully complete the simulation, averaging a total time of less than one minute.

7.3. Future Work

Even though the application showed promise, some recommendations for future works will be made. It would be useful, in order to optimize the application further, to reduce the number of triangles in the femur's mesh. Moreover, the model of the femur would have to be personalized if this application were ever to be used in a surgical setting, with the use of imaging techniques and 3D reconstruction software. It would be interesting to test an application with the same purposes, but on a different device, and using different libraries. In addition, this application could have some extra functionalities, such as indicating the direction of the femoral tunnel, and it could have been more automatized. Finally, in future tests, it would be beneficial to measure the application's accuracy.

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9. Appendixes

In this section, a planification of this dissertation, IJUP'S abstract, and a summary of the state of the art are presented.

9.1. Gantt Diagram

Table 13 and Table 14 show a Gantt diagram with the different project tasks and times divided into both semesters. Week 1, in the first semester, corresponds to the one starting on the 25th of September 2023. As for the second semester, the first week corresponds to the one starting on February 5th, 2024.

Table 13 - Gantt diagram with the planification for the first semester.

#	Task	Week											
		1	2	3	4	5	6	7	8	9	10	11	12
1	Collecting articles for the state of the art												
2	Selecting the articles for the state of the art												
3	Reading the articles for the state of the art												
4	Writing the state of the art												
5	Writing the introduction												
6	Understand how the Welphi platform works												
7	Delphi study - conceptualization												
8	Delphi study – rounds and results												
9	Watching Unity tutorials												
10	Requirements gathering												

Table 14 - Gantt diagram with the planification of the second semester.

#	Task	Week																					
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	Mockup of the tool																						
2	Feedback and improvement of the tool																						
3	Elaboration of the application																						
4	Feedback and improvement of the application																						
5	Testing the application																						
6	Case study																						
7	Results of the case study																						
8	Writing discussion and conclusions																						

9.2. IJUP's Abstract

In this subsection, the abstract submitted and presented at IJUP, titled "Assessment of the impact of mixed reality tools in surgical practice and training", will be shared:

Background & Aim: Mixed reality (MR) is a technology which combines the real and the virtual world. This is a promising tool, in which headsets, such as the Microsoft HoloLens 2, have been used in surgery. This study delves into the exploration of MR tools and their relevance in surgery. Additionally, the work outlines the design of a national Delphi study and the development of a case study, focusing on applying MR to orthopedic surgical training. **Methods:** A search query was directed in 2 different databases, with a total of 113 results. Excluding duplicates and articles not found relevant, a total of 35 articles were reviewed and analyzed. This process was aided with the Rayyan platform. The Delphi study is being conducted since January 2024. Participants were selected based on their experience with immersive technologies when applied to surgery. The 1st round has been created. Its insights will be vital in the requirements gathering phase of the MR application, which will be developed using Unity. **Results:** Through the

state-of-the-art analysis, the potential of MR in surgery was shown. The Delphi study was validated by 3 experts and the answers of the 1st round are being collected and will be analyzed. The MR application will be tested in a simulated scenario using Sawbones. It is expected this tool will be a safe resource for surgical training. **Conclusions:** The main uses of MR in surgery consist in the use of 3D models from the patient's anatomy, viewed in HoloLens 2, as well as surgical training and simulation. Ethical concerns might be eased in using these tools in surgical training, instead of intraoperatively. Issues with eye fatigue may be solved in combining MR with 5G technology. Despite having its challenges, MR technology has several benefits when applied to surgery, namely an increasing safety, accuracy, and confidence from the doctors when performing the procedures.

Keywords: Extended Reality; Microsoft HoloLens 2; Orthopedic Surgery; Surgical Training; Delphi Study.

9.3. State of the Art Summary

Table 15 shows a summary of the analysis of the state of the art, including the year and the source, the used technology, the application, the indicators and results, the pros, the cons and the proposals of future works for each article.

Table 15 - State of the art summary.

Year and source	Used technology	Application	Indicators/ results	Pros	Cons	Proposals of future works
2022 [25]	Microsoft HoloLens, Unity networking (UNet), Visual Studio, HoloToolkit, GrabCAD.	Surgery, since it allows for the visualization of 3 components: a 3D organ model, volumetric imaging data, and tissue morphology (captured during the operation).	A questionnaire to evaluate the participants' satisfaction was conducted, with a Likert scale. Most of the surgeons felt the platform was useful, especially to be used in neurosurgery. Participants provided feedback and some of their suggestions were implemented.	It is a versatile platform. It allows for the visualizatio n of data during surgery. Surgeons found the platform intuitive.	It uses Microsoft HoloLens, rather than the most recent version, Microsoft HoloLens 2. There was a small number of surgeons to test the platform. Since 44% of the participants were neurosurgeons , the results might be biased towards this specialty.	Conducting studies with more participants (with higher variety in their specialties).

2022 [110]	CT and MRI data (DICOM) were reconstructed by Mimics 19.0, obtaining 3D digital model of knee joint. This model was printed into a solid model (3D printing). The digital 3D data were opened using HoloLens 2, through a computer and MiDIVI cloud.	Surgery, total knee arthoplasty.	The range of motion of the knee joint was normal; the patient began to walk with a walker on the second day after the surgery; recovery was good; position of prosthesis and force line after 3 months was good.	Operation plan was worked out (surgery was simulated); prevision of difficulties with the possibility of figuring out a solution beforehand; it was not necessary the use of more equipment such as mobile phones and computer, to see 3D images, only a HoloLens 2; satisfactory post-operative results.	Registration problem of MR technology, which was solved by combining 3D printing and MR technology ("volume amplification method").	The registration effect, using the "volume amplification method", needs further verification.
2020 [117]	Midivi 3D reconstruction was used, with DICOM files, CT scan, with different masks and thresholds. 3D structure of the target vertebra. Design of lumbar pedicle screw	Surgery, lumbar pedicle screws implantation.	Using SPSS 20.0 and using t-test of comparison of the mean of 2 samples, the 2 groups were compared. Fisher's exact survey test evaluated enumeration data. Group A (MR) had less	MR makes screw placement safe, accurate, and easy to perform surgery. It reduces the number of times C-arm fluoroscopy is used, making the	The number of cases was small; and the follow-up time was short.	To analyze statistically the registration correlation between real and virtual screw placement, and to collect large number of cases, it is needed more prospective

	was done in its respective module. Surgeons in group A used HoloLens 2 connected to the MR system. The glasses identified the lesion segments. C-arm fluoroscopy was done to place the bilateral pedicle screws and check the tapping position.		bleeding, higher success rate of first threading, a shorter operation time, and fewer intraoperative C-arm X-ray irradiation.	doctors go through less harm.		randomized controlled studies of this method, and other screw placement methods.
2021 [134]	The surgeon and team members used MR headsets, the visual information was shared to computers and smartphones, so the nurses could see, as well as to other MR headsets, which the medical doctors being trained had. 12 general oncological surgeries were performed.	Surgical training in laparotomic and laparoscopic cancer surgery.	Three 10-point Likert scale surveys were distributed around the 5 trainees. The first one was regarding the carcinoma surgery, the second one was referring to the gastrectomy, and the third one was regarding all the 12 surgeries. The trainees rated their experiences in	Since this was during the Covid-19 pandemic, it enabled the training activity (which would have been impossible otherwise); and it allowed the sharing of real-time multimedia contents. Low-cost equipment.	The synchronization of the MR headset with the Digital Imaging Player and the DICOM database.	This tool could be used in future potential pandemics by other institutions.

			the first 2 surveys as 8 or 9 (on average), and the overall safety as 7 (with reference to Covid-19).			
2023 [127]	3D models were used combining automatic and manual segmentation; the algorithm and the holograms were in a cloud; HoloLens 2 was used to view the holograms; the holographic field of view of the primary user was streamed to monitors for the rest of the team to see. Members of the rest of the team (nonsurgical) were also given the chance to use the MR headset.	Neurosurgical OR, with nonsurgical team members such as nurses, anesthesiologist and a microphysicist.	A questionnaire consisting of 5 binary questions, with each of the main questions being followed by questions with a 7-point Likert scale. The majority of participants understood there is a clinical purpose in hologram use, in a way where MR improves the understanding of the pathology dimensions and the spatial orientation.	It was the first study researching the impact of MR tools on the workflow of the nonsurgical workers in the neurosurgical operating room. There was a mostly positive view of the use of these tools among the team. MR, according to the staff interviewed, did not lead to higher stress levels or flow disruptions. Also, there was potential utility	Small population of study; participants could have been interviewed more than once to show evolution through time; a quantitative evolution of the impact of MR would have been needed; the questionnaire was not standardized.	A bigger number of participants; control group of professionals without as much MR experience; include quantitative measurements; try to validate the questionnaire to be used as a standard.

				demonstrated by these tools.		
2023 [135]	There are several components to this system. AR-based 3D surgical video pipeline, where a digital surgical microscope has a software XR interface; an external 2D camera; and an audio/video mixer, fusing the streams. Video and audio are streamed to remote locations. There is bi-directional audio communication between the professionals doing the training, and	Surgical assistance and training, particularly during the Covid-19 pandemic. Cochlear implant surgery.	A questionnaire was conducted in order to get trainee feedback. They found the annotations valuable, as well as the stereo visualization, which holds a didactic value. The interaction with a moderator in the OR and the ability to ask questions to the surgeon was also seen as valuable. The accuracy requirements for cochlear implant procedures were fulfilled	It is a scalable solution for education and training in surgery. The lack of image-based annotation was improved by the platform. A 3D live stream was followed by trainees in remote locations. 2 countries were involved in the process, so TeleSTAR has the ability to improve international collaboration in regard to surgical	The majority of the participants did not have a knowledge of stereovision and 3D. Only 58% of the participants agreed that head mounted displays are an option as a visualization tool.	A larger training platform is being planned, with features such as virtual answers from the trainees, identifying surgical landmarks, and estimating the tumor size in a parallel way, during surgery.

	the trainees. Network is configured, so there is security and low latency (guaranteed by a DMZ - demilitarized zone). The system has 3 main tools: annotation tool, which allows to annotate the surgical scene; multispectral analysis; and 3D reconstruction (of the patient's anatomy). Some trainees watched the stream with the assistance of head mounted displays, while others watched through YouTube.		by the stereo image-based measurement unit.	education. The course design is interactive.		

2023 [98]	The 3D holograms were created by preoperative positron emission tomography-computed tomography (PET-CT), and visualized using Microsoft HoloLens 2 glasses. The surgeon was able to see images of the pelvic anatomy, as well as the location of the rectal cancer in the hologram.	Rectal cancer surgery.	The blood loss was 30 ml and the operation time was 261 minutes. The postoperative course of the patient was considered uneventful, and she is relapse-free. HoloLens 2 and intraoperative holograms were considered useful.	The hologram was seen as useful and safe to use during surgery. Moreover, a better understanding of the patient's pelvic anatomy was provided. The hologram might be magnified, and the 3D model can be observed from various angles.	Only one case was reported. Maybe a larger number of cases would be beneficial.	In the future, more study is necessary, to do more cases. In addition, it is predicted that if all surgeons of the team use the same headset, then they could discuss and communicate more actively, since they would be sharing the same holographic view. Moreover, this type of tool could be useful to educate surgeons.
2023 [100]	Associating Liver Partition and Portal Vein Ligation for Staged Hepatectomy (ALPPS) was combined with HoloLens, in a way where a 3D model of the liver of the patient, generated by Visible Patient, was projected to	Colorectal liver metastases.	Tumor necrosis was achieved, without vital tumor cells; after three months, there was no recurrence of the cancer disease.	The hologram was used for the decision-making process, since it increased the surgeon's understanding of where the metastases were located, and calculated	Differences in blood loss or in the operation time were not detected.	In the future, there needs to be an evaluation on the impact of this kind of tools in post-operative mortality, morbidity, and the oncological outcome after extended hepatobiliary surgery.

	the surgical site, in order to better prepare the central vessels in the liver hilum, and help with the surgical navigation.			the Future Liver Remnant (FLR) with a higher accuracy.		
2023 [109]	The CarnaLife Holo application was used to read DICOM data of a CT (obtained pre-surgery with the SOMATOM Definition AS), and display it as 3D volume rendering data. Microsoft HoloLens was used by the surgeon, while the hologram was being projected onto their field of view.	Extraction of maxillary mesiodens.	There were no postoperative complications; the cost did not increase to the patient; the surgery was considered more accurate and safer.	MR allows for a clearer visualization of the target tooth, due to the hologram; and the surgical field does not need to be moved by using this technology.	The weight of the HoloLens (although there is an improved weight distribution in HoloLens 2); the manual superimposition of the virtual object is difficult; the holograms have to be pre-prepared.	In the future, the investigators want to research MR technology applied to other conditions.

2022 [136]	The paths of the external and internal iliac arteriovenous systems, as well as swollen lymph nodes, were transformed into 3D images by the SYNAPSE VINCENT (preoperative phase). This was done for surgical training and surgical simulation. The surgeon evaluated the errors between the simulation and the surgery, after the procedure was done.	Rectal cancer surgery (lateral lymph node dissection).	This technology is thought to be able to be used for navigation and surgical simulation during the robotic surgery, and also before.	SYNAPSE VINCENT was considered to help both younger and more experienced surgeons, because it helps to perform the surgery. For younger surgeons, they can become familiarized with the procedure and learn anatomy more quickly (good learning curve). The procedure was thought to be safe.	The platform could be tested in more patients, as only 2 patients were studied.	In the future, the investigators want to expand their analysis with more definitive results.

2019 [131]	Several cases have been described, such as the communication between doctors and patients, through 3D models of the patients' data; surgical training, through reconstructed image models with 3D printing (combined with an MR headset); surgical guidance, through 3D anatomical models of tumors, visualized in MR headsets, and by superimposing special markers at the needed position in the human body; teaching with remote visualization, by broadcasting a live surgery, superimposing the patient's 3D model;	Clinical training. Orthopedic surgery. Broadcast of surgery.	It can give additional technical guidance to medical students; it connects people separated geographically; it helps patients better understand the procedures; and it makes for a safer surgical plan.	It can help to help patients understand their diseases and surgical plans; it can help doctors make a safer surgical scheme; in surgical training, it might assist in shortening the training time.	3D image reconstruction might be affected by noise and artifacts; some small structures are hard to reconstruct; the slower image processing time might cause delay; human-computer interactions might not be convenient enough.	In the near future, MR might be used in the visualization of medical operations, as well as being combined with intelligent medicine.

	and combining MR with artificial intelligence, by intelligently detecting and segmenting lesions, and displaying them with MR.					
2021 [119]	3D models were built from CT data. Afterwards, they were 3D printed. The 3D printed lumbar model had pedicle screws inserted into it, with the help of the MR navigation system. The position of the vertebrae was then determined using 3-point registration.	Lumbar fracture.	Using the MR device, no extra X-ray was necessary during the operation. The pain level was assessed with the Oswestry Disability Index (ODI) and the visual analog scale (VAS). For the statistical analysis, SPSS was utilized.	The use of an MR system in this kind of surgery was considered safe, feasible, and accurate.	Several limitations were considered in this case study. The surgeons need training to endure the eye strain. Moreover, some visual discomfort might happen. In addition, light might be limiting. Finally, it is difficult to simulate the soft tissues.	Perhaps conduct a study with more cases and including controls.

2023 [106]	DICOM data from CT scans were used. After the reconstruction of the 3D model, using artificial intelligence to identify the coalition parts in need of resection, the holograms were created with the HoloLicyo headset. These glasses were worn by a senior surgeon, who operated on all 6 patients. 3 markers were used to manually co-register the holograms, in order to superimpose them with the anatomical structures of the patient.	Talocalcaneal coalition resection.	The holographic model was able to be superimposed with the anatomy of the patient. During surgery, it was not needed any additional X-ray. The patients did not present stiffness after the operation.	The visualization was clear. There were no significant complications afterwards. This system was considered practical, radiation-free, and effective to use in this type of surgery.	Some limitations have arisen in this study. The accuracy of the registration process needs to be improved. Also, there might be some eye discomfort. Moreover, this case study did not have controls.	Confirm the results in randomized studies.

2022 [101]	The patients' CT or MRI data were transformed in holograms, and displayed during surgery with the Microsoft HoloLens 2 headset. These holograms consisted of 3D models of anatomical structures of the patients. The CarnaLife Holo system software was used for the 3D visualization of DICOM data.	Liver and pancreatic tumor.	The use of the holograms was considered to be useful in order to present the tumor size and its locations. Moreover, the real anatomy of the patient was more easily comparable to the holographic one. No complications were recorded.	The treatment using MR is personalized. The use of MR in this type of surgery allowed for a more precise setting of the needles used. The sterility was maintained through voice commands and hand gestures in the HoloLens 2 headset.	Comparing HoloLens 1 and 2, HoloLens 1 are heavier and present a smaller field of view. Both headsets were used in this study, in order to be compared. Moreover, only 8 cases were considered; maybe a larger study would be interesting.	A study with more cases would possibly be interesting; the use of MR might be a way to personalize the treatment of advanced cancers.
2019 [121]	A method based on markers was proposed in this work for estimating the pose of the C-arm. A marker was designed in order to do the estimation of the pose of the C-arm, based in perspective invariants. Both simulated data with MATLAB	C-arm pose estimation.	The marker was considered to be efficient. The marker could be detected precisely and automatically in the images, even when they did not have low projectivity.	This is a fast method for estimating the pose of the C-arm. The structure is shown in images with high projectivity. The marker's automatic detection is efficient.	There might be inconsistencies in the perspective invariants due to the distortion of the X-ray images, these have to be corrected beforehand.	The used method's shape might be modified, and other mathematical models might be used, in order for the method to be extended.

	and real data were used to test this system. In the second case, the OpenGL library in C++ was used. Moreover, a 3D model of the anatomy could be superimposed on the X-ray.					
2022 [102]	DICOM data from CT images were imported into TM-MIS 1.0 software, and there was 3D reconstruction of the patient's anatomy, specifically their liver, blood vessels, and tumor. The surgeon wore the HoloLens headset to do surgical planning, by calculating in real time the residual liver volume and the resection. During the surgery, the hologram was fused with the patient's anatomy	Hepatectomy surgery for hepatocellular carcinoma.	When comparing both groups, the group with the MR surgery had shorter operation time, less bleeding volume, and less postoperative complications.	MR in this context was considered to have value, and it is considered to improve the perioperative outcomes of this procedure.	Several limitations were considered in this study. The respiratory movements of the patients, as well as the morphological changes of the liver, caused some challenges in fusing the 3D holograms into the liver. Moreover, it is necessary to have cases from different centers.	In the future, it might be beneficial to do a study with more cases, and with cases from different centers.

	(liver), or it was located above the surgical field (surgical navigation).					
2023 [137]	The RISP platform is able to connect the operating surgeon with a remote consultant. The surgeon wears the Microsoft HoloLens 2 headset, and streams the surgery in real-time. They are able to communicate via voice. The consultant is able to leave 3D annotations and display medical images in a floating window in the surgeon's field of view. The surgeon is able to	Surgical telementoring.	The accuracy of the annotations had an average of less than 2 mm; however, it still presented some bigger accuracies. The platform was considered stable and responsive. The experience of the users was mostly positive.	The platform is considered quick to set up, and easy to use. The 3D annotations are accurate.	This is still a preliminary study, with a sample size that is not big. The accuracy of the annotations is inconsistent (in some cases, there are larger inaccuracies). The experiments are still abstract.	The accuracy issue with the annotations will be fixed. It is thought to be beneficial to design mock scenarios with cadavers to test the developed platform.

	interact with the holograms through hand gestures and voice. Unity engine was used, as well as several toolkits and libraries, such as the Mixed Reality Toolkit, HoloLens2ForCV, HoloLensCameraStream, HoloLens2ResearchMode-Unity, and MixedReality-WebRTC. Python was also used.					
2021 [105]	2 cases were considered in this study: VR for surgical simulation, and MR for surgical navigation. 3D holograms were created from the patient's DICOM CT data. In the first case, the 3D views were visualized in the Windows Mixed Reality Headset. In	Lateral temporal bone resection.	The usage of these tools for surgical navigation and simulation is thought to be fit for clinical practice.	Using VR tools for simulation was considered to be intuitive, and the use of these tools, as well as MR for surgical navigation, was thought to be fit for daily clinical usage. Moreover, since "Holoeyes	Since the 3D holograms are created by subjective assessment (even though they are based in the CT data), they might increase surgeon's overconfidence. It is important to note that these tools cannot guarantee a good performance during surgery, since	In the future, it is necessary extra study to evaluate the impact of navigation and simulation during surgery using these kinds of tools.

	the second case, after converting the 3D images into STL files, they were uploaded to the "Holoeyes XR" web application, and the case-specific holograms were viewed in Microsoft HoloLens during surgery.			XR" is a web application, it can be assessed anywhere globally.	the surgeon has to be able to deal with unexpected complications.	
2021 [108]	Microsoft HoloLens 2 with Dynamics 365 Remote Assistance, in order to have technical support from the manufacturers remotely during arthroscopies.	Orthopedic surgery - remote application of prosthesis.	From analyzing previous cases in the industry, and consulting with orthopedic surgeons, it was concluded that the use of MR during arthroscopies could be useful, in order to avoid displacements and reduce the risk of infections, as well as reducing CO2 emissions.	The use of HoloLens 2 can be beneficial in remote consulting with a manufacturer, since it would reduce the dislocations, increase flexibility in the schedules, and reduce the risk of infections and the prosthesis cost.	It is still a preliminary study, only the requirements were identified, so it would benefit to be applied in a practical case study.	This method could be applied in the future of prosthetic application.

2019 [99]	Two cases were analyzed: visualizing the liver anatomy by segmenting the liver MRI, combined with lesions, in ITK-Snap; and visualizing the liver anatomy, combined with lesions, in 3D models, using Poisson surface reconstruction, and being seen in Microsoft HoloLens.	Visualization of liver anatomy.	The accuracy of the MRI system was slightly better or the same as the MR system, except in tasks where spatial understanding was required. Spatial understanding might be important for surgical planning. The participants thought the field of view of the HoloLens was satisfactory (4 out of 6) and the comfort was good (5 out of 6).	The MR system decreases time, and it might increase accuracy, where it is necessary to have a spatial understanding of the anatomy.	There was not a big number of participants in the study. Stress may have played a factor in the rate of correct tasks, due to trying to complete them in a timely manner.	It would be interesting to have more data in order to evaluate the comfort of the participants in continuous usage.

2019 [115]	The authors used a computer vision algorithm in order to achieve a marker-less registration of PET-CT application. The facial landmarks are extracted from a video obtained by the Microsoft HoloLens's RBG camera, combined with the Spatial-Mapping API. Starting from the PET-CT scan, the segmentation of the volume of interest was done with the MeVisLab application using thresholds. The 3D mesh was loaded in the application, which was developed with Visual Studio and C# (Unity3D), with the tools OpenCV,	Maxillofacial surgery (tumor resection).	An initial training was necessary; however, the participants felt comfortable with the tool. The application was found most useful to be used in an educational environment. The survey was based on ISO-9241/110. The error of the positioning was 3 mm larger in the marker-less approach, when compared to the marker-based approach.	The specialists have evaluated the application in a positive way, and they showed interest in this type of tool, thinking it might bring higher quality standards.	A basic knowledge in the medical field is required to understand the application and its information. To reduce the error, calibration for automatic registration is needed. HoloLens does not give information about the depth on a millimeter scale, so the surgeon can only visualize the 3D model in certain directions.	In the future, an all-in-one tool might be developed with more advanced devices, such as the Microsoft HoloLens 2.

	DlibFaceLandmarkDetector, and HoloToolkit. The algorithm detects 2D pixel-location of the facial features. To reduce the error from spatial reconstruction, it was introduced a control step, derived from triangle similarity.					
2021 [113]	Using CT data, segmented by Materialize Mimics, the region was extracted by performing region growing. These data were used in an application for Microsoft HoloLens using Unity and Visual Studio Community. A 3D model was prepared using a 3D printer. Images from post-resection	Resection of maxillary tumor.	The surgery lasted 109 minutes and there was na hemorrhage volume of 118 g. It was necessary 10 minutes to prepare the Microsoft HoloLens before the operation. Eighteen months past surgery, the swelling disappeared, the alveolar morphology that was planned during the surgery was	This tool was considered safe, and it lowered the time of the procedure. Surgeons were able to operate with a shared perception. The visualizatio n of the anatomical structures was improved, thus making the surgery safer. The operation was considered	It might be hard to add the anatomical structure image if the operator of the tool is inexperienced.	MR has potential to be used in other conditions in the future, such as several applications within oral surgery.

	were shared before surgery between the surgical staff. During surgery, the 3 surgical staff wore the HoloLens, in order to understand the anatomic morphology of the structures. The 3D image, seen by all surgeons, was superimposed on the patient.		reached, and the patient did not have a recurrence.	more precise due to the use of 3D models.		
2018 [103]	An MR navigation tool was developed, in which a hologram is overlayed onto the patient. This hologram is visualized in Microsoft HoloLens, and it is obtained through CT data. The CT images are manually segmented with the Mimics software. Automatic registration	Liver tumors radiofrequency ablasion.	A comparison trial between CT-guided surgery and MR-guided surgery was performed. The error of the system using the MR tool was smaller. Moreover, a user study was done, where it was concluded that the use of MR guidance is able to improve the performance of the procedure.	The use of the MR tool has the potential to make the surgery simpler, more precise, and more efficient. Moreover, it was considered to be a more intuitive and natural surgical mode.	The tool only works on the abdominal phantom, which means the registration issue can be tackled only with simple boundary conditions, lacking the compensation for respiratory motion. Moreover, the MR headset might present some delays. Finally, the view of the headset might	In the future, the authors plan to develop a method to reach an accurate registration in a real clinic setting. Moreover, they intend to do respiratory modeling for the target shifting.

	was performed. The contact motion of the liver and the tumor was compensated with the computation of the accurate deformation of the soft tissue.				not be big enough.	
2019 [122]	Two groups were considered in this study: the first one used MR, the second used a more traditional approach (C-arm fluoroscopy) for comparison. In the first group, CT data was transformed into a 3D model by inputting the data into M3D digital medical software, through segmentation. Afterwards, the CAD image was constructed and imported	Percutaneous kyphoplasty for the treatment of osteoporotic vertebral compression fracture.	There were 2 groups in this study: surgeons who operated with a combination of MR and C-arm fluoroscopy, and surgeons who operated exclusively with C-arm fluoroscopy. In the first group, X-ray irradiation was lower, the relative vertebral height increased. SPSS V.11.0 software was used to analyze the results.	There was more pain relief after the surgery with MR; the surgery was accurate; there was a more considerable height improvement.	There is a small number of cases; there is not a real-time MRI image acquisition with MR; it is required C-arm fluoroscopy assistance due to some HoloLens disadvantages, such as the small brightness and field of vision.	Long-term research is required.

	to the computer. The MR headset used was Microsoft HoloLens. C-arm fluoroscopy was also used to adjust the CAD image during operation. Thus, the holograms could be combined with the patient. This allowed accurate needle insertion.					
2019 [112]	DICOM data from CT and MRI were collected before surgery. This data was reconstructed, and a 3D model was made with the Mimics 19.0 software. To make the registration process, 3D printing was used. The registration instrument built was sterilized.	Total hip arthroplasty.	The patient had a good recovery after surgery, and no surgical complications. The method was considered effective and feasible.	The surgery was more precise, individualized, and the operation time did not increase in a significant way. MR allows for the patients to have a clearer understanding of the procedure. It can also be useful in the planning, to have a	MR has a registration problem (which is why 3D printing was used in combination to solve it). There is a small surgical field.	More cases would be useful.

	Afterwards, it was input into the Microsoft MR headset.			better understanding of the area of the lesion and problem prediction. Moreover, the surgery with 3D models is safe and accurate.		
2021 [125]	DICOM data from CT scans were imported into the Mimics software and a 3D model was reconstructed. The model was loaded to the MR Midivi System, and it was visualized on the Microsoft HoloLens 2, as well as the procedural site and the working plan. A G-arm was used to perform fluoroscopy. Some procedures were performed with MR, such as positioning	Transforaminal Percutaneous Endoscopic Lumbar Disectomy.	The outcomes of this study were evaluated with the numerical rating scale and Oswestry Disability index. There was a comparison between patients treated with the MR tools and conventional methods. No statistical difference was found between the 2 groups; however, the MR tools reduced the time of surgery and the exposure to radiation, but increased eye fatigue.	The use of MR technology decreased the amount of radiation. It also decreased the surgery time, and it shortened the learning curve of the residents. Moreover, the surgery was considered less difficult.	This work presented some limitations. There was a small sample size. Moreover, the users of this tool experienced eye fatigue when using the headset for more than half an hour. Fluoroscopy is still required to assist this procedure.	A bigger sample size would be useful.

	the working sheath and inserting the needle; these procedures were confirmed with the fluoroscopy.					
2020 [138]	Unity, Microsoft HoloLens, Leap Motion. A mesh of the bone is generated through a CT scan (Invesalius3 software was used to reconstruct the virtual objects). Using Vuforia, a 3D printed bone is used as a target (the real object is associated with the virtual one). Leap Motion was used to track the user's hands, and to detect precise finger movement. Two software, MeshLab and	Cutting virtual bones (simulation).	The elements are interactive, the virtual cut is almost instantaneous and multiple objects are managed, the bone does not lose shape quality after being cut.	This application was considered helpful for the doctors. The velocity when cutting the virtual object was high, allowing a simulation of the surgery in the physical world.	The user's experience might not be as realistic as it could be, since it used bones with dark material, to avoid the problem of white objects being difficult to track. More hardware, such as the introduction of the Leap Motion, makes the method more expensive.	Using this application for multiple purposes besides healthcare, such as academic training or the gaming industry.

	Blender were used for the 3D modelling of the bone meshes.					
2020 [116]	This article has compared 4 different registration methods, and described the implementation of the adaptive physics-based non-rigid registration (A-PBNRR) method on HoloLens, and also combined with deep learning for a better accuracy.	Image-guided neurosurgery.	Four methods of registration were compared: B-Spline, PBNRR, Rigid Registration, and A-PBNRR. The latter was considered slower than PBNRR and rigid registration, but it had the best accuracy when resection was present, and it was still sufficiently fast to fulfill the requirements of image-guided neurosurgery. When combined with deep learning, A-PBNRR	The A-PBNRR method was the best among the compared registration methods at modeling deformation.	This method presented 2 limitations. The accuracy was not consistently under 2 mm. Also, intraoperative MRIs are not widely used due to their price, so a method to yield high accuracies with intraoperative ultrasounds could be developed, which is harder.	The registration accuracy could be improved in future studies, as well as decrease computation times.

			yielded better results regarding accuracy. This technique, combined with MR, is thought to be beneficial for image-guided neurosurgery.			
2021 [123]	A surgical simulation was performed, within a fully equipped surgical room, including a C-arm. A 3D-printed model of a patient's spine was based on their CT data. The C-arm was radiation-free, and the X-ray images were simulated. This was done in order to retrospectively assess flow disruptions and see if they lead to performance failures.	Simulated vertebroplasty.	Performance failures were not associated with the occurrence of a flow disruption.	The 3D-printed model allowed for a realistic simulation of the procedures needed to perform a vertebroplasty.	Several limitations were found in this study. There was not a big number of participants. The pressure existing in the operating room cannot be mimicked adequately. The effect of flow disruptions on decision making could not be assessed. There is a need to carefully consider the transferability of this study to other specialties.	Further studies would be beneficial to focus on the relationship between patient safety and flow disruptions.

2021 [114]	Microsoft HoloLens were used to visualize the user interface (UI) of a surgical robot which already existed in the surgical setting. Surgical instructions were transmitted from a surgical robot to the MR headset. The workflow print screens were transmitted to a computer with USB connection, and then the images were transformed with a C# software, and their data was transmitted to HoloLens, with a C# application and the assistance of Unity.	Robot-assisted patellofemoral-arthroplasty.	The subjects did not have to change their surgical techniques significantly. There was a positive consensus about the MR system being useful, and it did not cause significant physical stress or eye fatigue.	There is potential associated with the use of these tools combined with medical robotics. The price of these headsets was not considered a hindrance. The integration of MR in the framework of a robot-assisted platform was successful.	Neck strain is a possible consequence of the extended use of MR headsets. The sample size of the study was small. The conditions were controlled, meaning there were less challenges present, when compared to an operating room. Plastic bone is also less challenging than real bone.	In future studies, the impact of in-situ holograms in the guidance could be examined, as well as evaluating the impact of neck strain.

2023 [124]	In order to adapt the universal framework of intraoperative performance to spine surgery, a computer-assisted assessment was developed, and a simulation of an OR was done using MR. A spine model of the patient was 3D-printed, based on their CT data. Soft tissue enveloped the model. The C-arm used provided radiation-free X-ray images (since these were simulated).	Simulated workplace-based assessment in vertebroplasty.	The observational assessment and the performance scores considering the surgeons' experience were evaluated. Robust evidence was found on the validity of this method.	The annotation tools used were considered to be interactive. The performance indicators to the universal framework were defined, and it was considered feasible.	There was a limited use of performance metrics. Surgeons might have presented some lack of familiarity with the simulation, thus not achieving their full potential. The sample size was limited.	Further study of more specific performance methods could be beneficial. Moreover, future studies could exist with a higher number of participants. Finally, they should be able to validate this technique in several surgical procedures.

2023 [107]	A screw connected to a frame of reference with a tracker was attached to the bone, and then a CT scan was performed. From CT scans and its corresponding DICOM data, the pelvis and the tracker were segmented into 3D models using the Mimics Medical software. Through the image capture in real-time, an automatic calculation of the coordinates was performed, in order to achieve automatic registration with a high precision. This technology was used for the trajectory planning for closed reduction.	Pelvic fracture reduction.	The quality of the reduction was considered to be excellent. The fractures had no complications in the healing process. The recovery was good.	The understanding of the procedure was considered to be more straightforward to the young surgeons. This study shows promise. More experiments are being conducted.	Some limitations were found in this study. It was examined only one set of clinical data. Some types of fractures are more difficult to be reduced with this tool.	In the future, it would be beneficial to acquire more samples from other places.

2022 [128]	The system was set up in the surgery and the waiting room and it was based on WebRTC. In the surgery room, there were cameras which recorded video, and a medical computer cart, with a HDMI to USB converter for the video. This video was transmitted to NREAL glasses, an MR headset, where the caregiver was able to communicate with the surgeon in real-time, and see their annotations.	Pediatric inguinal herniorrhaphy.	The setup process in the operating room and the waiting room lasted less than 5 minutes. A questionnaire on the usefulness of this technique was conducted to both the surgeons and the caregivers, with Likert-scale questions. SPSS was used for the statistical analysis. The questionnaire showed a positive opinion.	The technology was considered useful, and it is thought to have increased the satisfaction of the surgeons and the caregivers, as well as adapt the surgical plan in real-time, through tele-consent.	There was not a sufficient number of participants in this study. There was not a control group. The cost-effectiveness has to be evaluated further. The learning curve for the application and installation was long.	The authors plan further study in order to improve the contamination management, the cost-effectiveness and the user experience.

2022 [128]	A digital-twin-enabled system based on Internet of Medical Things (IoMT) was developed for telemedical simulation. This system also combined MR, 5G, and a robust auxiliary classifier generative adversarial network (rAC-GAN). The deep learning model is used to predict lung cancer. A surgical navigation image was projected to the headset worn by the surgeon while remote surgical implementation was occurring (MR was used in the surgical plan and remote diagnosis).	Telemedical simulation.	The rAC-GAN network performed better when compared to the other networks, with an accuracy score of 0.92.	This technology presented a high accuracy. The system improved the performance of the processing of substantial clinical data.	The IoMT platform presented high requirements on the transmission rate of the network in real time.	Some future prospects were considered, such as improving the use of the code to reduce the equipment need, and the strengthening of the DL network to improve the metrics.

2022 [104]	A CBCT (cone-beam computed tomography) was performed to diagnose the patient. The DICOM data was transformed into a 3D view with the help of the 3D Slicer software. Manual segmentation of the structures was performed. The optimal point for the entrance of the endoscopes was computed, with several viewing angles. The planning for the endoscopic access was done. During CBCT, a marker was placed on the patient's head. A head phantom was 3D-printed. The 3D data and the tip of	Odontogenic cyst removal (upper jaw).	During the postoperative period, there were no abnormalities and no pronounced inflammatory reaction. There was a total RMS error between 3 and 6 mm (this error depended on the angle of the visualization).	The use of MR tools is able to individualize the diagnosis and the treatment of the patients, thus improving its quality. The accuracy was improved, and the surgical risks, time and recovery duration were reduced. The direction of the endoscope could be adjusted in real time. This technology was considered safe.	To evaluate the efficiency, maximize the accuracy, and assess the cost-effectiveness, more investigation would be needed.	In the future, it is needed more investigation on this subject.

	the endoscope were visualized in Microsoft HoloLens glasses. The marker could be tracked, and the tip was thus viewed on the headset.					