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AFFORDABLE AUGMENTED REALITY FOR SPINE SURGERY: AN EMPIRICAL INVESTIGATION INTO IMPROVING VISUALIZATION AND SURGICAL ACCURACY

Iqra Aslam, Muhammad Jasim Saeed, Zarmina Jahangir, Kanza Zafar, Muhammad Awais Sattar
Riphah International University, Lahore, Pakistan

Abstract. *The minimally invasive spine surgery, sometimes referred to as MISS, has changed spinal therapy by minimizing the length of time required for recovery, as well as the amount of worry and suffering that patients experience. Before we can consider the surgery to have been successful, there is a critical problem that has to be addressed. The use of augmented reality technology has been gaining traction over the course of the last few years as a method of improving the accuracy of MISS management. This research has a significant focus on the applications of augmented reality in minimally invasive spine surgery as its core investigation. The use of augmented reality (AR) technology, which supports medical professionals in performing difficult spine procedures, allows for the provision of real-time placement suggestions as well as information that is specific to the patient. This has a number of major benefits, some of which include improved vision, more accurate tool placement, and less problems. In order to include augmented reality into MISS, it was necessary to have a user interface that was easy to use, a data integration system that was comprehensive, and recording mechanisms that were reliable. It is necessary to make the necessary modifications to the registration process, delays, and physical issues before bringing it into clinical practice. This procedure must be completed before it can be implemented. In the context of this research project, an application for smartphones that is integrated with augmented reality is currently being created with the purpose of boosting minimally invasive spine surgery. "The innovation of this research is the creation of a mobile AR interface that bridges the gap between accessibility and high-quality surgical visualization tools, offering an alternative to traditional AR systems." This AR smartphone application is the first of its type to combine cost, accessibility, and sophisticated visualization features, resulting in a whole new approach to surgical help that is unlike any other surgical procedure.Using Unity3D, the Vuforia AR camera, and C#, the software is able to create an augmented reality (AR) experience for mobile devices. This objective is realized via the utilization of these three components. Technology that are regarded to be industry standards include HoloLens and head-mounted displays (HMDs), which are examples of augmented reality technology. On the other hand, the vast majority of people are unable to make use of them because of the tremendous cost that they carry. When it comes to visualizing three-dimensional MRI spine pictures, this technology offers an approach that is more efficient and economical. Taking into consideration the results of this study, it would seem that surveys and formal evaluations that make use of MISS and augmented reality might possibly be beneficial. By using augmented reality (AR), medical practitioners may be able to more effectively see important structures, plan surgical operations, and identify the required equipment, which may eventually result in improved patient outcomes. Increasing the capabilities of augmented reality technology, finding new uses for it, and incorporating artificial intelligence-driven decision improvement are the goals of the researchers.*

Keywords: Augmented Reality, Minimally Invasive Spine Surgery, surgical accuracy, patient outcomes

NIEDROGA RZECZYWISTOŚĆ ROZSZERZONA W CHIRURGII KRĘGOSŁUPA: BADANIE EMPIRYCZNE DOTYCZĄCE POPRAWY WIZUALIZACJI I DOKŁADNOŚCI CHIRURGICZNEJ

Streszczenie. *Minimalnie inwazyjna chirurgia kręgosłupa, czasami określana jako MISS, zmieniła terapię kręgosłupa, minimalizując czas potrzebny na powrót do zdrowia, a także ilość zmartwień i cierpienia, których doświadczają pacjenci. Zanim jednak będziemy mogli uznać operację za udaną, należy rozwiązać pewien krytyczny problem. Wykorzystanie technologii rozszerzonej rzeczywistości zyskuje na popularności w ciągu ostatnich kilku lat jako metoda poprawy dokładności zarządzania MISS. Niniejsze badania koncentrują się na zastosowaniach rzeczywistości rozszerzonej w minimalnie inwazyjnej chirurgii kręgosłupa. Zastosowanie technologii rzeczywistości rozszerzonej (AR), która wspiera specjalistów medycznych w wykonywaniu trudnych zabiegów kręgosłupa, pozwala na dostarczanie sugestii dotyczących umiejscowienia w czasie rzeczywistym, a także informacji specyficznych dla pacjenta. Wiąże się to z wieloma ważnymi korzyściami, z których niektóre obejmują lepsze widzenie, dokładniejsze umieszczanie narzędzi i mniej problemów. Aby włączyć rzeczywistość rozszerzoną do MISS, konieczne było posiadanie łatwego w użyciu interfejsu użytkownika, kompleksowego systemu integracji danych i niezawodnych mechanizmów rejestracji. Konieczne jest dokonanie niezbędnych modyfikacji procesu rejestracji, opóźnień i kwestii fizycznych przed wprowadzeniem go do praktyki klinicznej. Procedura ta musi zostać zakończona przed jej wdrożeniem. W kontekście tego projektu badawczego tworzona jest obecnie aplikacja na smartfony, która jest zintegrowana z rozszerzoną rzeczywistością w celu usprawnienia minimalnie inwazyjnej chirurgii kręgosłupa. „Innowacyjność tego badania polega na stworzeniu mobilnego interfejsu AR, który wypełnia lukę między dostępnością a wysokiej jakości narzędziami do wizualizacji chirurgicznej, oferując alternatywę dla tradycyjnych systemów AR". Ta aplikacja AR na smartfony jest pierwszą tego typu, która łączy koszty, dostępność i zaawansowane funkcje wizualizacji, co skutkuje zupełnie nowym podejściem do pomocy chirurgicznej, która nie przypomina żadnej innej procedury chirurgicznej. Korzystając z Unity3D, kamery Vuforia AR i C#, oprogramowanie jest w stanie stworzyć rozszerzoną rzeczywistość (AR) na urządzenia mobilne. Cel ten jest realizowany poprzez wykorzystanie tych trzech komponentów. Technologie uważane za standardy branżowe obejmują HoloLens i wyświetlacze montowane na głowie (HMD), które są przykładami technologii rzeczywistości rozszerzonej. Z drugiej strony, zdecydowana większość osób nie jest w stanie z nich skorzystać ze względu na ogromny koszt, jaki ze sobą niosą. Jeśli chodzi o wizualizację trójwymiarowych obrazów MRI kręgosłupa, technologia ta oferuje podejście, które jest bardziej wydajne i ekonomiczne. Biorąc pod uwagę wyniki tego badania, wydaje się, że ankiety i formalne oceny wykorzystujące MISS i rzeczywistość rozszerzoną mogą być korzystne. Korzystając z rzeczywistości rozszerzonej (AR), lekarze mogą być w stanie skuteczniej widzieć ważne struktury, planować operacje chirurgiczne i identyfikować wymagany sprzęt, co ostatecznie może skutkować lepszymi wynikami pacjentów. Celem naukowców jest zwiększenie możliwości technologii rzeczywistości rozszerzonej, znalezienie dla niej nowych zastosowań i wprowadzenie usprawnień decyzyjnych opartych na sztucznej inteligencji.*

Słowa kluczowe: rozszerzona rzeczywistość, małoinwazyjna chirurgia kręgosłupa, precyzja chirurgiczna, wyniki leczenia pacjentów

Introduction

"Enhancing Precision: Augmented Reality in Minimally Invasive Spine Surgery" describes a new way to use augmented reality (AR) to change the field of minimally invasive spine surgery (MISS).This study tries to come up with a creative way to combine Unity3D, Vuforia AR camera technology, and the computer language C# to make a mobile app that gives doctors supreme viewing tools. By using augmented reality, the app makes it possible for 2D MRI spine pictures to be seamlessly superimposed on patients' bodies. This is all started by reading a QR code. This revolutionary technology gets rid of the need for expensive head-mounted screens or Hololens devices by letting doctors see detailed internal details in the operating room. For a long time, people have used mirrors, lenses, and light sources to make illusions and virtual pictures appear in real life. Still, Ivan Sutherland was the first person to really make AR work. Sketchpad was the first interactive graphics program. It was created by Ivan Sutherland at MIT in 1963. As you can see in (Fig. 1), AR technology has changed a lot from its start to 2022. The work of Bottani et al. looks at the AR literature that was written between 2006 and 2017. Also, Sereno et al. use a methodical study to go over all the literature that has already been written on how computer-supported joint work and AR can work together. The originality of this research lies in its ability to bring AR-assisted surgical visualization to widely accessible mobile platforms, revolutionizing spine surgery by providing a low-cost, scalable alternative to conventional AR systems. This AR mobile platform is a revolutionary development in the medical profession because no other technique or application like it has been created for surgical usage. In addition to being a clever use of technology and removing the burden and expense associated with head-mounted display devices for surgeons, we created an augmented reality (AR) application. Because it increases surgical precision and speed, this AR method has major advantages for medical practice. By offering real-time visual information without requiring additional equipment, it makes surgery simpler for physicians. Making AR technology more accessible for surgical procedures, this invention also solves problems associated with digital spatial interactions, such as pain from the device. This work represents a substantial step toward safer and more accurate minimally invasive spine surgery, despite obstacles such as guaranteeing the correct placement of pedicle pins. This technique might transform surgical procedures with continued advancements, helping patients and medical professionals alike.

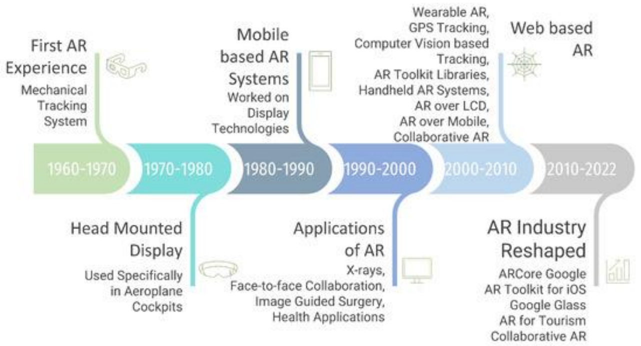

Fig. 1. AR technology

1. Motivation

Augmented reality (AR) has emerged as a groundbreaking technology across various fields, including entertainment and social media. Its most valuable potential, however, lies in the medical domain, particularly in minimally invasive spine surgery (MISS). AR enables surgeons to overlay digital visuals on real-world views, which enhances precision and accuracy during procedures. This technology has proven especially beneficial in neurosurgery and orthopedics, where it has improved safety and efficiency. AR-guided systems, such as heads-up displays and head-mounted devices, reduce distractions, streamline surgeries, increase accuracy, and lower radiation exposure. For instance, the FDA-approved XVision AR system is a significant advancement in MISS, facilitating wider adoption among spine surgeons [14]. Additionally, research shows that integrating AR with artificial intelligence (AI) and visual tracking further enhances surgical precision and can lead to improved patient outcomes [15]. AR's ability to project MRI data in real-time provides surgeons with detailed 3D imaging during procedures, offering greater clarity. This study introduces an affordable mobile AR solution to make advanced surgical visualization tools accessible to more surgeons, reducing reliance on costly hardware. Unlike previous surgical visualisation tools or traditional AR systems, this mobile AR application is the first of its type and provides an affordable, accessible option for spine surgery that can maintains the accuracy and dependability. This has resulted in the development of tools like the "Enhancing Precision: Augmented Reality in Minimally Invasive Spine Surgery" app, which uses affordable technologies like Unity3D and Vuforia AR for improved surgical guidance, avoiding the need for expensive hardware [15].

2. Problem statement

In minimally invasive spine surgery (MISS), correct findings remain a barrier that this study aims to address. Surgeons still have difficulty controlling the intricate spine system, despite the advantages that modern imaging technology provide, such as lowering patient anxiety and expediting healing. With its real-time visuals, augmented reality (AR) holds great promise for improving accuracy and spatial comprehension. All technological, organizational, and functional challenges need to be handled, nevertheless, before AR and MISS can be merged successfully. In order to improve surgical precision and patient outcomes, this study explicitly attempts to ascertain if augmented reality technology is feasible and usable in medical imaging and operating systems. The smartphone app "Enhancing Precision: Augmented Reality in Minimally Invasive Spine Surgery" uses AR to try to provide a less expensive option.

3. Objectives and scope

A project called *Augmented Reality in Minimally Invasive Spine Surgery* wants to look into and use augmented reality (AR) technology to make minimally invasive spine treatments (MISS) more accurate and effective. The main goal is to find out if and how well it works to use AR in surgery, with the main focus on making it easier to see, find your way around, and place instruments during treatments. The primary objective of this research is to develop and evaluate an affordable, user-friendly AR system that enhances visualization, navigation, and precision in spine surgeries, making the technology accessible to a wider range of medical practitioners. This smartphone augmented reality application is noteworthy since it is the first of its type in the surgical field and provides enhanced visualisation and assistance using easily available AR tools at a lower cost than costly AR devices. The work includes a lot of important areas, such as creating and improving AR systems that are specifically made for spine surgery, studying how they affect surgical outcomes and patient safety, and looking into how they could be used to teach and train surgeons. The study also aims to look into the technology issues and limits of using AR in MISS, like making the system more reliable, making it easier for people to use, and making the user experience better. This study aims to make it easier for AR technology to be used in spinal surgery by helping us learn more about it and coming up with ways to get around the problems that are currently standing in the way. The goal is for AR to become widely used in clinical practice, which will ultimately lead to better patient care and outcomes.

4. Methodology

The method used to create the augmented reality (AR) app for minimally invasive spine surgery (MISS) is based on blending virtual information into the real world without any problems. Our method uses Unity3D, the Vuforia AR camera, and the computer language C# to make a cheap solution that doesn't need expensive gear like Hololens or head-mounted displays (HMD).

1) **AR Core Library Integration:** The AR app uses the AR Core library, a complex system made to handle complicated calculation about where and how big virtual things should be in a real world. This framework uses smartphones to correctly measure the lighting conditions around it, which makes virtual things look more real in a range of lighting conditions. Strong motion tracking algorithms also keep the phone's exact sense of where it is in relation to its surroundings. This makes sure that virtual items keep their shape and size. With this feature, you can naturally interact with virtual material by doing things like moving it and zooming in and out.

2) **2D MRI Spine Scans Overlay:** The main feature of the app is reading QR codes to put 2D MRI spine scans on top of the patient's body. Using Vuforia AR camera technology, the

app smoothly merges the MRI pictures into a three-dimensional view. This makes it easier for doctors to see the structure of the spine during surgery. With this easy-to-use and quick screen, doctors can look at and study the spine's complex parts with great accuracy and precision.

3) **Guidance during Surgery:** The AR app is a useful tool for improving guidance during minimally invasive spine surgery. The app improves doctors' sense of space by adding real-time MRI pictures to the operating room. This lets them move more correctly through complicated spine structures. Augmented reality patches let surgeons interact with them, changing virtual models to fit the patient's body and make sure they do a perfect job during surgery. This moving guide system helps make surgery more accurate, faster, and safer, which eventually improves patient results.

4) This method makes use of the capabilities of smartphones to evaluate the circumstances of the ambient lighting, which results in an increase in the level of realism of virtual objects when they are exposed to different light settings. Furthermore, the smartphone is able to retain an accurate sense of its location in relation to the surroundings because to the powerful motion tracking. It is essential to have this feature because it allows the virtual objects to keep their orientation and size, responding in a natural way to the actions of the user, such as rotating, zooming in, and zooming out.

5. Literature review

The incorporation of augmented reality (AR) technology is significantly advancing minimally invasive treatments. In recent years, there has been a notable increase in medical research articles focused on AR applications; however, the variability in research aims, data collection techniques, and methodologies has made it challenging for meta-analyses to draw meaningful comparisons. Most of the studies conducted are exploratory, with only a few providing substantial insights into their effects on patient interactions. An analysis of 31 studies published between 2018 and 2023 indicates that AR has the potential to enhance minimally invasive surgery (MIS) through capabilities such as AR-guided navigation, improved educational and training methods, and enhanced user-environment interactions. Among these studies, 16 specifically addressed the use of AR-based guidance, while six were centred on prototype developments.

The research included a variety of study types: one prospective collaborative clinical study, one retrospective clinical analysis, one prospective case-controlled study, one case report, one clinical investigation, and five review articles. AR facilitates significant interactions by providing real-time visuals, creating engaging experiences in clinical environments [23]. Over the years, AR systems have been conceptualized and implemented across various medical disciplines, including neurosurgery, radiotherapy, orthopaedics, and plastic surgery. The discussion of AR in neurosurgery dates back to 1986, when Roberts et al. first suggested the projection of CT images onto surgical lenses. This concept further evolved with the use of fluoroscopy in 1998 to visualize arterial structures and the application of AR in neurosurgery cameras in 2002 [19].

5.1. AR-guided navigation

In minimally invasive surgery (MIS), the integration of augmented reality (AR) for surgical navigation has shown promising advancements. Xu et al. emphasize the necessity of surgical tracking devices to enhance navigational accuracy in these procedures. They point out that conventional surgical guidance systems often struggle with issues such as signal inaccuracies and physical constraints, which can lead to information loss during surgeries [32]. To address these challenges, they propose utilizing AR for intraoperative monitoring.

In a notable study by Butler et al., AR was employed to assist in the placement of pedicle screws during spine surgery, conducted by three seasoned surgeons across two universities. Between June 2020 and March 2022, they successfully performed 164 MIS operations, placing a total of 606 pedicle screws using AR technology, which featured near-eye transparent monitors and wireless headsets. This setup provided surgeons with real-time 3D images, facilitating enhanced visualization of the surgical field compared to traditional two-dimensional optics [5].

Additionally, Lecointre et al. developed an AR-based robotic system to accurately identify lymph nodes during laparoscopic surgeries, demonstrating the potential of AR to enhance precision in minimally invasive procedures [18]. Felix et al. further explored the effectiveness of AR in spine surgeries, achieving a remarkable 96% accuracy in pedicle screw placements across a sample of 124 screws implanted in cadavers. They noted minimal deviation in placement accuracy, suggesting that AR can significantly augment navigational capabilities in both open and minimally invasive surgeries [9].

Research by Yuk et al. has shown that AR outperforms other technologies like virtual reality (VR) and mixed reality (MR) in neurosurgical training and planning, highlighting the versatile applications of AR in surgical settings [33]. In knee surgeries, Chen et al. developed an AR navigation system that provided real-time anatomical information, achieving a variance of only 0.32 mm in surgical placements, thus demonstrating the technology's ability to enhance accuracy compared to traditional methods [7].

Benmahdjoub et al.'s systematic review indicates that AR can improve navigation systems by enhancing depth perception and hand-eye coordination during craniomaxillofacial surgeries, despite the need for further user evaluation studies [2]. Hussain et al. affirm that AR navigation technologies are as precise as conventional methods but offer improved ergonomics and visibility, emphasizing the importance of ongoing research to enhance safety and reliability in surgical environments [16]. AR technology presents transformative potential in minimally invasive surgery, streamlining processes and improving outcomes across various surgical disciplines. Their real-time AR system navigates robotic surgery. Modular in vivo robotic surgical monitoring was developed. Separating the surgical technique into phases allows for optimum supervision, according to scientists. Software reuse in similar timeframes [13]. Chauvet et al. invented AR laparoscopic myomectomy at pace. MRI and DTI showed uterine muscle fibres. This viewpoint helped surgeons decide to cut. AR/DTI fibre tractography may treat uterine tumours. Good fibre alignment helps laparoscopic myomectomy surgeons find the beginning spot. Scarring and uterine difficulties may decrease with fibre orientation after surgery [6]. Super microsurgical LVA was shown to be simpler on 30 upper limb secondary Iymphocdema patients by Brcbant et al. An AR imaging system and near-infrared surgical camera demonstrated lymphatic super microsurgery. The authors claim AR works, requires little surgery. And has few complications. Due to technological problems, AR advice cannot help all processes and devices [3].

5.2. Improving education and training

Wild et al. introduced the Surgeon system, which leverages sensors and augmented reality (AR) to enhance surgeons' visual capabilities. In their study, 60 novice laparoscopic surgeons were randomly assigned to two groups: one received verbal instructions followed by AR visualizations on the operating room screen, while the other experienced the reverse sequence. The training included performing a laparoscopic cholecystectomy (LC) on a pig model after initial basic laparoscopic training. The implementation of telestration with AR significantly enhances and secures training in minimally invasive surgery (MIS) [31]. Gholizadeh et al. reviewed the literature on liver surgical image guidance, highlighting the role of AR in assisting liver surgeons by improving visibility of blood vessels and tumors during complex procedures. They concluded that AR technology can ensure the safety and success of liver surgeries, suggesting that its integration into practice may enhance hepatobiliary surgical outcomes. However, further clinical studies are needed to evaluate whether AR can reduce postoperative complications and fatalities [12]. Godzik et al. discussed the potential of virtual reality (VR) and AR in spine surgery and training. They noted that initial experiences with VR and AR demonstrate their applicability and ease of use, indicating a need for further research and collaboration between industry and academia to explore the full potential of these technologies in spine surgery education and clinical practice [11]. Lastly, Pratt and Arora addressed advancements in imaging technologies, specifically AR, in the context of transoral robotic surgery (TORS). They suggested that employing visual assistance during TORS could enhance registration accuracy, particularly given the challenging anatomy surrounding the tongue base and oropharynx [24].

5.3. Building improved use-environment interfaces

Thabit et al. evaluated an augmented reality (AR)-based suture viewing system developed for minimally invasive spring-assisted craniectomy. They found that the AR system's mean distance of 2.4 mm is sufficient for surgical procedures, allowing for the identification of cranial sutures without manual palpation, which aids in the planning of minimally invasive craniosynostosis surgery [28]. Stewart et al. proposed augmenting bedside robotics with an AR headset to facilitate 3D body modeling during surgical procedures, enhancing overall efficiency. Their study involved a physician assistant, a medical student, three surgical residents, and two attending surgeons performing authorized operations in a simulated abdominal cavity using a docking station-connected surgical robot. The exercises were conducted with either a bedside monitor or an AR device that provided 2D or 3D visualization. The researchers discovered that high-resolution 3D AR significantly improved the speed and accuracy of complex tasks [27].

Rush et al. discussed the practical application of AR technology in spine surgery centers, noting that AR can help surgeons focus by minimizing distractions associated with incisions, radiation exposure, and pedicle screw placement. They emphasized that most AR applications are used to overlay 3D body images prior to robotic minimally invasive surgeries [25]. Forte and colleagues introduced interactive AR tools for robotic surgery, evaluating features such as live operating room video, 2D pre-surgery imaging, 3D resection measurements, and a voice-activated equipment alert system. Their low-cost surgical robot, equipped with stereo cameras, was used by eight experienced surgeons during dry lab lymphadenectomies, demonstrating the benefits of easy access to patient medical data, operational distance calculations, and audio guidance [10].

Wendler et al. highlighted the importance of new molecular imaging technologies in enabling precise surgery. These innovations utilize artificial intelligence (AI), computer-aided design (CAD), molecular imaging, and surgical guidance to enhance surgical outcomes [30]. Li et al. noted that advancements in mixed reality (MR) and AR are changing the landscape of surgical procedures. They developed a novel mathematical technique that accurately displays soft tissue surface contours from images, even in the presence of specular highlights. Their approach provides a more reliable method for dense point-to-point image matching compared to existing techniques, particularly for characterizing and matching features in soft tissues [22].

Jia et al. identified challenges in using real-time AR for minimally invasive surgery (MIS) without effective tracking devices, as changing surgical conditions complicate procedures. They proposed a 6-degree-of-freedom (6DoF) motion tracking system that combines sophisticated 2D target tracking, nonlinear pose optimization, and SLAM tracking loss recovery to improve AR usability. Their findings indicated that ORBSLAM2 may be less reliable than their proposed methods due to issues like motion deflection and tracking blur caused by dense fog [17]. Wang et al. demonstrated that ensuring accuracy in AR applications for MIS requires effective monitoring of the target organ's 6DoF state using pre-surgical images. They presented a successful endoscopic AR tracking approach that utilizes dense and regional data, incorporating occlusion processing and appearance matching to enhance reliability, as evidenced by fake datasets and virtual surgical testing [29].

5.4. Analysis of the literature review

Research by Butler and colleagues highlights the significant progress and ongoing challenges in using augmented reality (AR) for minimally invasive therapies. Their studies on AR-assisted percutaneous minimally invasive surgery (MIS) for spine pedicle screw placement demonstrate how AR can improve precision and efficiency, ultimately enhancing patient care. Butler et al. showcase the advantages of AR in improving surgeon navigation during various procedures, such as those involving the spine, hip, and laparoscopic surgeries. AR-guided percutaneous MIS has proven to be a game-changer, offering enhanced safety and accuracy in handling complex cases and reshaping surgical techniques.

Similarly, Wild et al. emphasize AR’s impact on training and education in minimally invasive surgery. The iSurgeon system exemplifies how AR-based training can create interactive and realistic learning environments for new surgeons, enabling skill development in a safe, controlled manner. Additionally, Thabit et al. introduced an AR-supported suture guidance system, which enhances surgical precision by improving visual accuracy and user interaction with the environment. Their findings show that AR facilitates more precise procedures while minimizing risks, thus promoting safer surgeries.

Despite these advancements, certain challenges persist, such as the need for ongoing system optimization, resolution of technical limitations, and an evaluation of long-term implications. Cost and scalability remain critical factors in ensuring that AR technology becomes widely adopted in clinical settings.

The reviewed literature showcases AR's ability to redefine minimally invasive therapies, with contributions from researchers like Butler and Wild underscoring its role in improving surgical precision and patient outcomes. However, this mobile AR application stands out as a unique innovation, offering an affordable and accessible solution to AR technology in surgery. Unlike existing systems, this application eliminates the need for costly AR hardware while maintaining high-quality visualization, making it a groundbreaking advancement in the field. This novel approach paves the way for greater integration of AR into clinical practice, enhancing collaboration and innovation in surgical care.

5.5. Transformative contribution of AR

Augmented reality (AR) has made remarkable strides in the field of minimally invasive spine surgery (MISS), fundamentally changing surgical techniques and enhancing patient care. Ongoing research focuses on the advancement and refinement of AR systems tailored for spinal procedures, significantly boosting surgical precision and overall patient outcomes. Extensive evaluations have demonstrated the viability of AR-guided navigation, which enables surgeons to visualize patient anatomy in real time and accurately navigate through intricate spinal structures [4]. Additionally, the process of integrating advanced imaging techniques, such as MRI and CT scans, into AR systems has been optimized, leading to improved surgical planning and execution. Comprehensive studies, including systematic reviews and clinical trials, have examined the advantages and limitations of AR technology in minimally invasive spine surgery, thereby promoting its broader implementation in clinical settings. Consequently, the application of AR has led to significant enhancements in spine surgical practices, resulting in better patient outcomes and higher standards of care [4].

6. Proposed architecture

In this section we talk in more depth about the design of the system and the new way of doing things that is suggested to use Augmented Reality (AR) to make minimally invasive spine surgery more accurate and useful. The current research shows that AR technologies could totally change the way surgery is done, especially when it comes to accuracy and using methods that are as little damage as possible. The suggested system design has a few key parts. By mixing virtual reality with real-time pictures, these make the surgery area easier to see and point surgical tools at the right spot. The goal of this structure is to use the advanced features of AR technology to make spine surgeries much more accurate, lower the risks of surgery, and improve outcomes for patients.

6.1. Architecture of AR system

Augmented reality (AR) systems, specifically tailored for medical use, enable the integration of digital content within healthcare environments, significantly enhancing and speeding up medical procedures. These systems combine advanced hardware and software to provide precise imaging and real-time information to medical professionals. Using high-resolution sensors, sophisticated cameras, and various input devices, AR systems capture intricate visual and spatial data, making them effective in both fast-paced operating rooms and more controlled exam settings [1]. The captured data is processed in real-time by powerful computing systems, allowing AR content such as anatomical visuals, surgical guides, and biochemical information to be overlaid onto the user's view of the physical environment. This real-time display assists surgeons in determining where to make incisions or identifying areas to avoid, enhancing procedural accuracy [21]. Tracking and monitoring technologies ensure that AR content remains dynamic and adjusts continuously based on the user's movements. This real-time interactivity is vital for effective AR integration, maintaining alignment between digital overlays and real-world elements. Medical professionals commonly use AR headsets and heads-up displays, which provide an unobstructed view of the physical world while delivering essential digital information through high-definition displays designed to minimize interference [1]. The effectiveness of AR in healthcare relies on high precision and interactivity, which in turn improve diagnostic and surgical accuracy, reduce errors, and enhance overall patient outcomes. The design of AR systems in medical settings extends beyond the simple overlay of digital information, aiming to seamlessly blend the real and virtual worlds, empowering healthcare practitioners and fostering new advancements in patient care and medical education [21].

6.2. Building blocks of augmented reality frameworks

Specifically designed for minimally invasive spine surgery (MISS), the augmented reality (AR) framework that we have deployed in our study is made up of many vital parts, each of which contributes to the smooth integration of virtual information into the environment that is really present in the world (Fig. 2).

1) Image Capture Module: One essential part that handles the photos captured by the smartphone camera is the image capture module. Vital visual information, including anatomical details and surgical tool locations, are extracted from these pictures through analysis. This module makes sure that the pertinent information about the surgical environment is precisely recorded and ready for AR modeling, which serves as the basis for the application's further stages.

2) Tracking Module: The tracking module is in charge of keeping the augmented content in line with the outside world. It keeps an eye on the angle and position of the smartphone camera as well as the QR codes that are applied to the patient's body. This guarantees the accurate positioning of the overlay 2D MRI images in relation to the patient's anatomy, giving the surgeon a steady and dependable augmented reality experience.

3) Rendering Module: The rendering module uses Unity3D and Vuforia AR technologies to blend the virtual 2D MRI scans with the real-time photos captured by the smartphone camera. This module creates a coherent and user-friendly augmented view by smoothly blending the virtual and real-world elements. It improves the surgeon's ability to see and traverse the surgical site, increasing precision and possibly enhancing surgical outcomes. It does this by accurately displaying the MRI images across the patient's body.

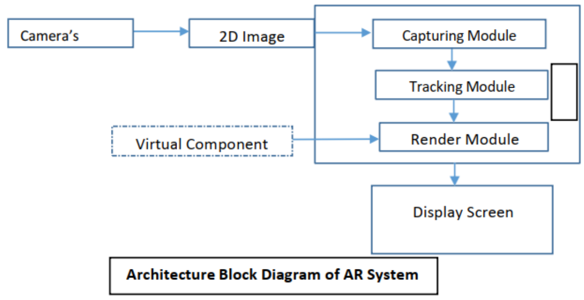

Fig. 2. Architecture of AR

6.3. Components of augmented reality

An Augmented Reality (AR) system is comprised of several components, each of which plays a significant part in the process of generating an immersive and interactive experience by combining digital material with the physical environment, as shown in (Fig. 3). Explanations of each component are as follows:

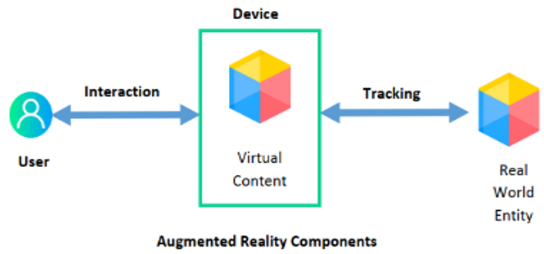

Fig. 3. AR Components

1) User: The user is very important to our AR system. The user is usually a surgeon or other medical worker. During minimally invasive spine surgery, they use virtual reality technology to help them see better and find their way around. Our app is meant to be fast and easy to use so that users can connect with the added content without any problems. This should lead to better surgery results.

2) Interaction: AR interaction includes how the user and the mobile app talk to each other. During surgery, surgeons use different orders and hand movements to move around in the virtual reality system. Scanning QR codes, changing viewing angles, and editing 2D MRI scans are all examples of actions that make the interaction design smooth and effective, giving you full control over the virtual world.

3) Device: The device is what shows AR material on your phone or tablet. Our app is made to work on common mobile devices like smartphones and laptops, so you don't need to buy expensive special tools like head-mounted displays to use it. Using Unity3D and Vuforia AR camera technology, our system takes inputs from the real world, processes real-time MRI data, and then places

it on top of the patient's body to make it easier to see and move during surgery.

4) Virtual Content: Digital content that is placed on top of the real world is called virtual content. This includes 2D MRI spine pictures that are turned into 3D models and shown in real time through the mobile app in our case. Text, images, and models give doctors contextualized information to help them during MISS procedures. This information is easily mixed into the surgery field to improve accuracy.

5) Tracking: Tracking is necessary to make sure that virtual material is correctly aligned with the real world. Our app uses powerful computer vision techniques and sensor data to exactly find the phone's location and position in relation to the patient's body. This makes sure that the augmented reality overlays stay in place in real space while the surgeon moves around the operating room.

6) Real World Entities: These are the actual things that are in the operating room, like the patient's body and the surgery instruments. Digital information, like 3D images of MRI scans, are superimposed on the patient's body by our AR technology, which makes these real-world things better. This combination makes it easier for doctors to work with the body of their patients, which improves the accuracy of surgery and the health of their patients.

6.4. AR integration process for MISS

Augmented reality (AR) has the potential to contribute significantly to the improvement of the precision and effectiveness of minimally invasive spine surgery (MISS). The use of augmented reality (AR) in the context of surgical procedures relies on the utilization of improved imaging methods and real-time data overlay in order to enhance the surgeon's capability to accurately target and treat impaired spinal areas [8]. There are three crucial phases that make up the system architecture that was designed for using augmented reality in spine surgery:

1) Imaging and data collection: At this very important stage, the process starts with collecting real-time image data, mostly 2D MRI spine scans, using mobile devices with Vuforia AR camera technology. Through QR code reading, this cutting-edge technology makes it possible to seamlessly add the scans to the patient's body. The application handles and displays the MRI scans using the C# computer language and the Unity3D platform. This turns them into interactive three-dimensional models of the patient's spinal tissue. This new method gives doctors instant access to high-fidelity images that are being captured in real time. This lets them look at and study the spine's complex features with a level of clarity and accuracy that has never been seen before.

2) Augmentation of the Surgical Field: After getting the image data, the AR app starts to improve surgery by superimposing the drawn MRI pictures on top of the patient's body in real time. By using advanced computer vision techniques and picture processing methods, the app makes it possible for the surgeon to see virtual versions of the spine without any problems. This addition makes it easier for doctors to see where the complicated parts of the spine are in relation to the rest of the body of the patient during surgery. The app helps doctors precisely navigate through the surgery site by giving them a dynamic and live viewing tool.This lets them make smart choices and perform complex moves with trust and accuracy.

3) Accurate Guidance for Surgical Operations: The augmented reality app is a useful tool for giving precise instructions to the surgeon during the most important part of surgery. Surgeons can change the virtual versions of instruments and implants by using easy-to understand user interfaces. This lets them make sure the instruments and implants are placed correctly and line up with the patient's body. The app improves the surgeon's ability to do exact and minimally invasive treatments by giving real-time feedback and visualizing surgical actions. This leads to better patient results and higher surgical safety.

7. AR application implementation requirement

AR Application Implementation Requirements are the necessary steps to create and launch an AR app. These criteria guarantee that the AR system works, fits user demands, and integrates into its intended setting, such as minimally invasive spine surgery.

Setting up the development environment for implementing augmented reality in Minimally Invasive Spine Surgery (MISS) involves configuring both the hardware and software components necessary to support the creation, testing, and deployment of the AR system. This environment is pivotal for developing an application that is both robust and responsive to the needs of surgical procedures.

7.1. Hardware requirement

1) Smartphones and Augmented Reality Cameras:
Smartphones and AR cameras are very important components of the computer hardware configuration for MISS. The principal devices that are used for the purpose of presenting augmented reality overlays and taking real-time video footage of the surgical area are smartphones. These smartphones are equipped with cameras of a high quality and strong processing capabilities. It is vital to have augmented reality cameras, whether they are built into smartphones or independent devices, in order to capture sophisticated images. These cameras have features such as depth sensing and higher resolution, which improve the accuracy and efficacy of augmented reality overlays.

2) Additional Peripheral Devices:
The functionality of the augmented reality system may be improved by the addition of additional peripheral devices. These devices include external displays, specialized input devices like as tablets or styluses, and a variety of sensors responsible for monitoring surgical instruments and patient movements. Through the provision of a multitude of contact points and data sources, these peripherals contribute to the development of an all-encompassing surgical toolkit.

7.2. Software requirement

1) Unity3d Engine: One of the reasons why Unity3D was chosen is because of its outstanding rendering capabilities, wide support for augmented reality and virtual reality applications, and features that make it easier to create interactive 3D worlds in MISS [25]. The user interface, the simulation of surgical situations, and the incorporation of real-time data into the augmented reality environment will all be created using Unity3D, which will serve as the engine that drives the software component of the program (Fig. 4).

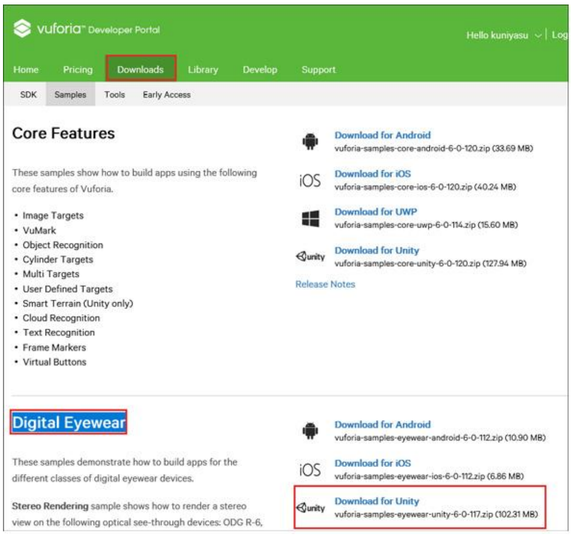

Fig. 4. Unity 3D engine

2) Vuforia AR Platform: The selection of Vuforia is based on the robustness of its augmented reality tracking capabilities, which allow for accurate object detection and tracking in MISS. Vuforia's software development kit (SDK) interfaces without any problems with Unity3D, delivering dependable features like as marker identification, object tracking, and spatial mapping that are essential for the development of augmented reality applications in surgical settings.
3) Supporting Tools and Libraries: In order to facilitate the coding, testing, and debugging of the augmented reality system, the development environment incorporates a variety of supporting tools and libraries. These tools may include integrated development environments (IDEs) such as Visual Studio, version control systems such as Git, and libraries that provide image processing or extra augmented reality functions. They guarantee the robustness, maintainability, and scalability of the system, which improves the development effort and the capabilities of the program.

7.3. AR application development

Unity3D, Vuforia, augmented reality cameras, and smartphones are some of the cutting-edge technologies that are used in the process of developing an augmented reality (AR) system for minimally invasive spine surgery (MISS). These tools are necessary for the development of an augmented reality application that is both user-friendly and effective, and that improves surgical accuracy.

7.4. Development of AR scene

1) Scene Setup In Unity3d: The Unity3D environment is used to create a 3D scene for the AR application, including importing 2D MRI scans of the spine and setting up a virtual surgical field. The scene is configured to simulate real-world lighting, camera angles, and spatial relationships, ensuring accurate AR overlays onto the patient's spine.
2) Incorporating Vuforia Sdk: Image identification and object tracking skills are made possible by integrating the vuforia software development kit (SDK) into the unity3d scenario. These capabilities are especially important for matching virtual objects with the real-world photos that are collected during surgery (Fig. 5) [20].

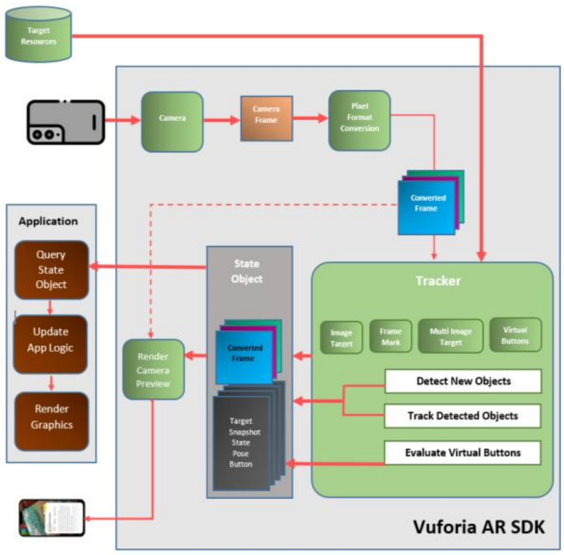

Fig. 5. Vuforia SDK

8. Finding results and analysis

Continuing with the recommended architecture that was discussed in the previous section, an interface "State-of-the-Art: AR Support for Surgeons" that is personalized to meet the requirements of medical professionals has been built in order to give support to them during surgical procedures, particularly those that are regarded as being minimally invasive surgeries. This interface aims to establish a seamless integration with the framework by using the capabilities of the framework that is already in place. As a result, it will improve the accuracy and efficiency of surgical procedures. Following the study, we will look into the results that came from installing this interface, rate the success that was achieved, and give a thorough breakdown of what these findings mean for the progress of surgery methods.

The interface that was created has many elements that are specifically designed to help surgeons during surgery, especially minimally invasive spine surgeries. The AR application interface framework encompasses several crucial features designed to enhance surgical precision and efficiency during minimally invasive spine procedures.

8.1. Key features of AR application design

Welcome Screen: The welcome screen of the AR mobile app has a simple layout with key features for easy use. It shows the app's logo, options for logging in and settings, and information about the app’s features and how to use it. There’s also a help note, a contact link for support, and a tool for accessing different app functions. The app is designed to be an affordable and easy-to-use alternative to expensive AR devices, helping improve surgery precision and patient care for medical professionals. This design ensures a smooth and straightforward user experience (Fig. 6).

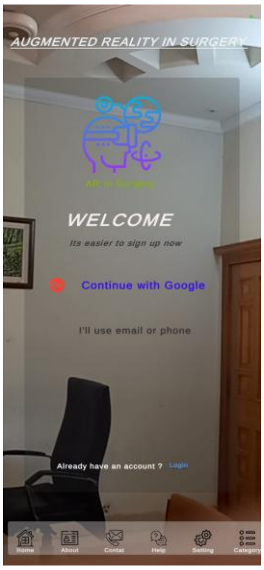

Fig. 6. AR Application

8.2. Main navigation hub of AR application

1) Category: Tools
Download:The main navigation hub of the AR mobile application offers quick access to key features for medical professionals. In the **Tools** category, the **Download** option allows users to save MRI scans to their device, ensuring offline access to important patient data during surgeries (Fig. 7). The **AR** category includes the **Scanning** feature, which enables surgeons to easily scan QR codes to retrieve and integrate patient MRI data into the AR interface for enhanced real-time visualization. These features are designed to streamline workflows and improve surgical efficiency.
2) Category: AR
Scanning: Enables surgeons to scan QR codes, quickly retrieving and integrating patient MRI data into the AR interface.
Overlay: Allows surgeons to project MRI images onto the patient’s body in real-time, improving surgical precision and spatial awareness (Fig. 8).

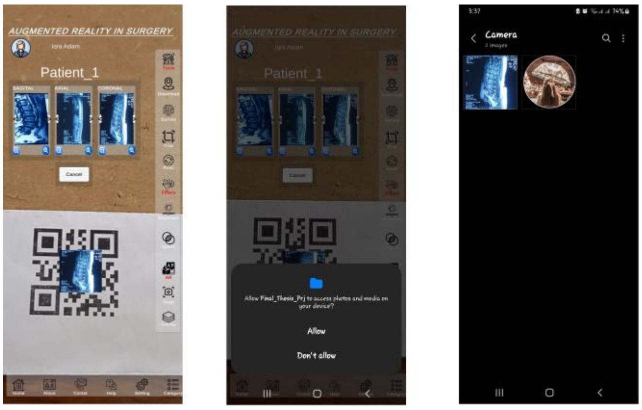

Fig. 7. AR download tool

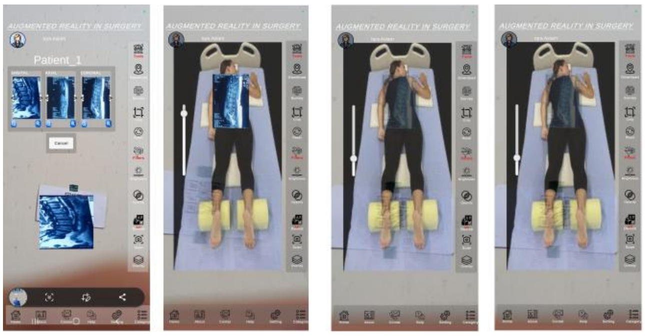

Fig. 8. AR Overlay tool

9. Doctors perspectives on AR application adoption in surgery

We conducted an online survey of healthcare professionals, including doctors, surgeons, nurses, and other medical personnel, to investigate the need for a mobile AR application for surgery as a cost-effective alternative to expensive devices like HoloLens and HMDs.

A poll was conducted to gather insights on the use of AR in surgical settings, focusing on the pros and cons of using mobile-based AR solutions against pricey hardware. Participants weighed the pros and cons of mobile platforms vs classic AR equipment and assessed their knowledge with AR-assisted procedures. Participants were asked to provide examples of how mobile AR technology may ease or complicate medical procedures, as well as recommendations for increasing AR functionality and usability in surgical settings. Furthermore, the study sought healthcare experts' opinions on how mobile AR may affect patient care, safety, and surgical techniques. Individuals were asked to consider the advantages of a mobile AR software for surgical accuracy, procedure time savings, and patient outcomes. The study sought opinions on user interface, usability, and technological problems around existing mobile AR technologies. This poll aimed to gather insights for developing a cost-effective and accessible AR system for surgical applications. We want to improve AR technology for patient care and surgical outcomes by obtaining input from healthcare professionals participating in surgical care.

9.1. Survey questionnaire: key findings

A survey titled "The Need for Development of Augmented Reality Mobile Applications in Surgery" aimed to evaluate the familiarity and interest of healthcare professionals regarding AR technology in surgical settings. The study included 31 participants, comprising 74% males and 26% females, drawn from diverse medical specialties, including neurosurgery (19.4%), urology (12.9%), and general medicine (Fig 9a, 9b, 9c).

1) Familiarity and Utilization of AR Technology:
An impressive 96% of respondents reported being aware of AR technology, but only 29% were currently using it in their practice.Among those utilizing AR, 6.5% employed head-mounted displays (HMDs), 3.2% utilized HoloLens, and 29% used other forms of AR. None reported using mobile AR applications.

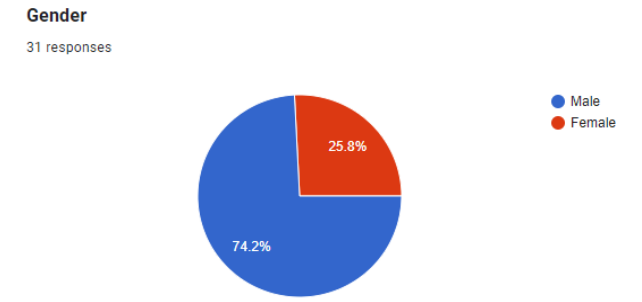

Fig. 9a. AR App user feedback

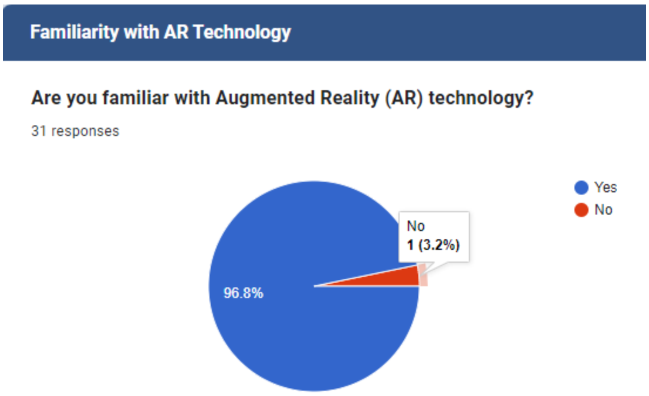

Fig. 9b. AR App user feedback

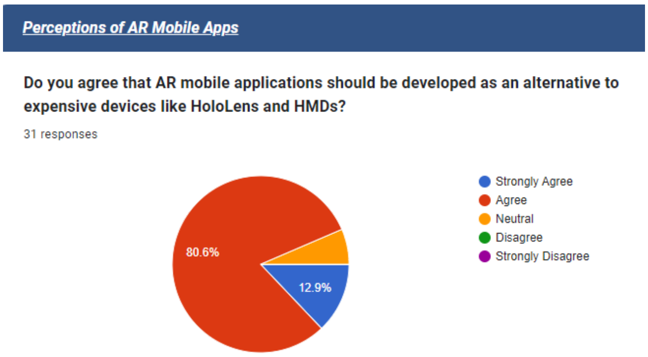

Fig. 9c. AR App user feedback

2) Frequency and Significance of AR Usage: (Fig. 10a,10b,10c)
A notable 80% of respondents expressed concerns regarding the developement of AR application technology.

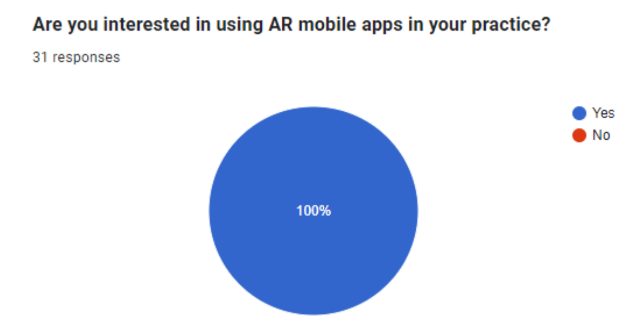

Fig. 10a. AR App user feedback

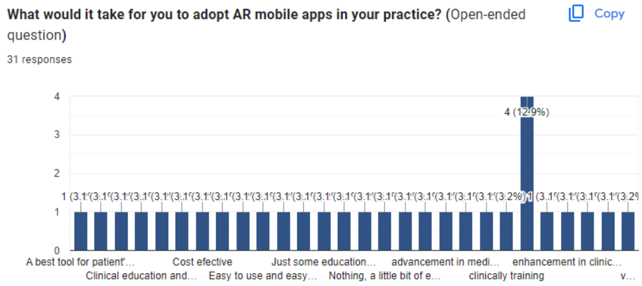

Fig. 10b. AR App user feedback

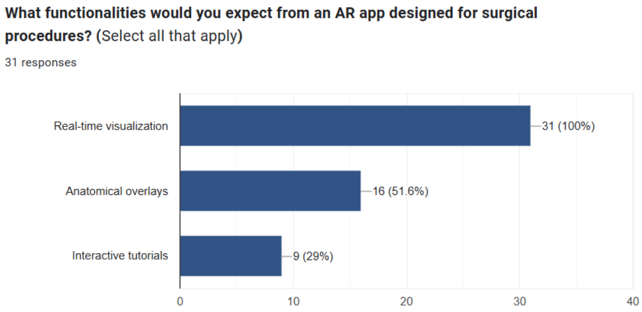

Fig. 10c. AR App user feedback

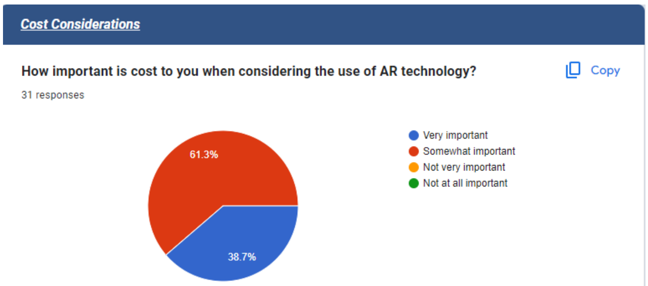

Fig. 11a. AR App user feedback

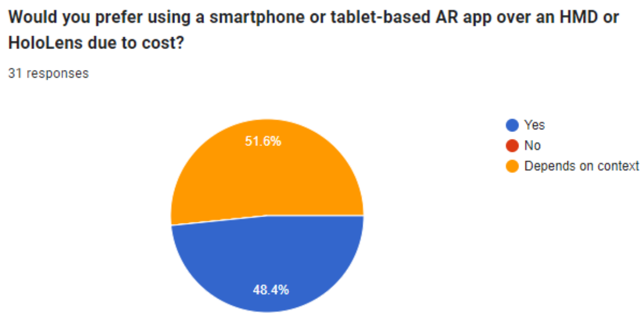

Fig. 11b. AR App user feedback

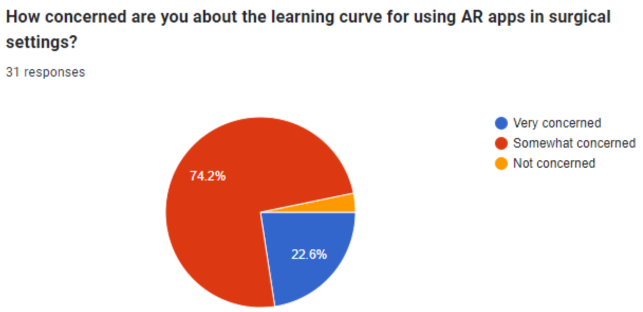

Fig. 11c. AR App user feedback

3) Potential for Adoption and Advantages of Mobile AR Applications:
Looking ahead, 45% of respondents indicated they were very likely to adopt AR mobile applications within the next two years, while 52% felt somewhat likely to do so.
Key features that respondents sought included: real-time visualization (100%), anatomical overlays (31%), and interactive tutorials (9%).
The primary benefits highlighted were easier adaptation (83%), broader accessibility (74%), and cost-effectiveness (77%).

4) Integration with Existing Medical Software:
A significant 96% of respondents showed willingness to collaborate with developers for tailored AR applications.
Regarding surgical precision, 51% expected millimeter-level accuracy, while 48% preferred centimeter-level precision.

5) Feasibility and Benefits of AR Mobile Applications: (Fig. 11a, 11b, 11c).
A positive outlook emerged, with 76% of respondents believing that AR mobile apps could serve as viable alternatives to HMDs and HoloLens. They emphasized advantages such as cost-effectiveness, portability, and compatibility with current tools.
Furthermore, 93.5% expressed interest in incorporating AR mobile apps into their surgical practices.

6) Security Considerations and Recommendations:
When it came to data privacy, 93% of participants supported the use of encryption for protecting information. Additionally, 96% indicated they would recommend AR applications for surgical use.
An overwhelming 93% stated they would adopt AR mobile applications for routine surgical procedures.
The survey reveals a strong interest in the implementation of AR mobile applications in surgery, with emphasis on their cost-effectiveness and ease of use. However, addressing concerns related to functionality, integration, and data security will be essential for broader acceptance and implementation.

10. Conclusion

The development of a cost-effective augmented reality (AR) application for minimally invasive spine surgery (MISS) introduces an innovative alternative to high-cost AR systems, which are often out of reach for many healthcare providers and patients. By utilizing technologies like Unity3D, C#, ARCamera, and the Vuforia SDK, this application improves surgical accuracy by overlaying real-time imaging data such as MRI and CT scans directly into the surgeon's field of view. This approach allows detailed anatomical visualization on widely available devices like smartphones and tablets, eliminating the dependency on expensive head-mounted displays and making advanced surgical tools more accessible and affordable.

In addition to enhancing surgical precision during procedures, the application supports preoperative planning and patient education, contributing to improved patient understanding and satisfaction. Uniquely, this AR mobile application stands out as the first of its kind specifically designed for surgical purposes, setting a new standard in the field. By making advanced AR technology accessible to everyday clinical practice, this solution bridges the gap between innovation and usability, paving the way for improved patient outcomes while minimizing financial constraints.

Future developments could include integration with artificial intelligence (AI) for predictive insights and compatibility with robotic surgical systems, further expanding the application's capabilities and reinforcing its potential to transform the practice of minimally invasive spine surgery.

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M.Sc. Iqra Aslam
e-mail: iqrafatima130@gmail.com

Holds an M.Sc. in computer science from Riphah International University, Lahore Campus, and a B.Sc. in computer science from Lahore College for Women University, Lahore. With a solid academic background, her key interests include application development, computer vision, and machine learning. Passionate about using her skills in these areas to create new technology solutions and support research in computer science.

https://orcid.org/0009-0006-0867-1724

Ph.D. Muhammad Jasim Saeed
e-mail: jasim.saeed@riphah.edu.pk

Received the M.Sc. degree in computer science from Liverpool John Moores University, U.K., and the Ph.D. degree in computer communications and networks from Manchester Metropolitan University, U.K. Currently, he holds the position of an assistant professor and the Head of the Department of Computing, Riphah International University, Lahore Campus, Pakistan.

https://orcid.org/0000-0003-4736-2263

Ph.D. Zarmina Jahangir
e-mail: zarmina.jahangir@riphah.edu.pk

Has an extensive background in computer science with an M.Sc. degree from FAST-NU and a Ph.D. scholar specializing in Software Engineering from COMSATS. With a strong academic foundation and a passion for research, her key interests lie in Software Engineering and Machine Learning.

https://orcid.org/0009-0002-1240-1357

Ph.D. Kanza Zafar
e-mail: kanza.zafar@riphah.edu.pk

A Ph.D. Scholar in Computing at Riphah International University. She has done B.Sc. and M.Sc. in Computer Engineering from Sir Syed University of Engineering Technology, Karachi. Currently, she is serving as Senior Lecturer at Riphah International University, Lahore Campus.
Her research areas are Computer Networks and Information & Cyber Secuirty.

https://orcid.org/0009-0003-1754-9630

Dr. Muhammad Awais Sattar
e-mail: awais.sattar@riphah.edu.pk

Earned his Ph.D. degree in Technical Computer Science and Telecommunication from Lodz University of Technology, Lodz, Poland, in 2022.
Prior to that, he obtained an M.Sc. degree in Electrical Engineering from Rochester Institute of Technology, Dubai, UAE, in 2017, and a B.Sc. degree in Electrical (Computer) Engineering from COMSATS University, Lahore, Pakistan, in 2014. He is currently serving as an assistant professor of Computing at Riphah International University, Lahore Campus, Pakistan.
His research interests encompass machine learning, computer vision, and process tomography.

https://orcid.org/0000-0002-2431-8182