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Mixed Reality for Orthopedic Elbow Surgery Training and Operating Room Applications: A Preliminary Analysis

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Abstract

The use of Mixed Reality in medicine is widely documented to be a candidate to revolutionize surgical interventions. In this paper we present a system to simulate k-wire placement, that is a common orthopedic procedure used to stabilize fractures, dislocations, and other traumatic injuries. With the described system, it is possible to leverage Mixed Reality (MR) and advanced visualization techniques applied on a surgical simulation phantom to enhance surgical training and critical orthopedic surgical procedures. This analysis is centered on evaluating the precision and proficiency of k-wire placement in an elbow surgical phantom, designed with a 3D modeling software starting from a virtual 3D anatomical reference. By visually superimposing 3D reconstructions of internal structures and the target K-wire positioning on the physical model, it is expected not only to improve the learning curve but also to establish a foundation for potential real-time surgical guidance in challenging clinical scenarios. The performance is measured as the difference between K-wires real placement in respect to target position; the quantitative measurements are then used to compare the risk of iatrogenic injury to nerves and vascular structures of MR-guided vs non MR-guided simulated interventions.

CCS Concepts

• ***Applied computing*** → ***Life and medical sciences;*** • ***Computing methodologies*** → *Computer graphics;* ***Mixed / augmented reality;***

1. Introduction

Advancements in technology have revolutionized the field of orthopedic surgical training, offering innovative approaches to enhance the acquisition of surgical skills. Traditional training methods often cannot accurately replicate the complexities of surgical procedures, especially those involving delicate joints like the elbow. However, the emergence of Mixed Reality (MR) systems has changed the game by merging digital and physical worlds to create immersive learning environments.

The benefits of incorporating MR simulation in orthopedic surgical training are manifold. These systems provide impartial and measurable evaluations of surgical skills, eliminating the need for real-time supervision. They also reduce the need for recurrent disposable expenses and offer a diverse range of simulation scenarios. Additionally, the proficiency gained in VR simulation can be seamlessly transferred to real-life situations, making it convenient for residents to access VR consoles in their own designated spaces [NWG*14].

Moreover, the cost-effectiveness of VR units compared to traditional cadaver or fresh-frozen specimen laboratories makes them a viable alternative. The advantages inherent in simulation education, such as practicing high-risk scenarios without endangering patients and developing clinical and communication skills, extend seamlessly to Virtual Reality (VR) simulation.

However, the integration of VR simulation into surgical education poses challenges. The initial financial investment required for acquiring and establishing VR simulation systems needs careful planning and resource allocation. Tactile realism is another obstacle to consider, as the lack of tactile feedback in some simulations may impact trainees' perception and the accuracy of their subsequent surgeries. Ongoing research and development efforts are crucial to enhancing haptic feedback and tactile fidelity in VR simulations [ZLK23].

To overcome these issues, we propose a novel MR system for training k-wire fixation of elbow fractures, a procedure involving the use of a surgical drill for implanting a thin (1 to 3 mm diameter)

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metal rod (k-wire) (Figure 1) to fix the relative position of fractured bone segments until fusion. The setup combines 3D printing technology, MR, and advanced visualization techniques. The system utilizes a 3D-printed physical phantom that accurately replicates the elbow joint's anatomy. The integration of Mixed Reality (MR) brings a layer of digital augmentation to the physical realm by overlaying a 3D anatomical model onto the phantom. This dynamic visual blend enhances trainees' perception of anatomical structures and their relationships.

The MR system also offers unique guidance during k-wire fixation procedures, combining tactile feedback from the phantom and real-time visual guidance from the AR system. This empowers trainees to refine their motor skills and decision-making processes in a controlled and realistic environment.

To achieve this, the proposed configuration uses the second-generation Hololens head-mounted display as a graphical overlay platform. The system relies on environment understanding capability, sensor data processing, and integration of platforms such as MRTK, Vuforia, and Windows Holographic OS.

This paper aims to explore the role of Mixed Reality systems in transforming orthopedic surgical training. It examines the technical components, pedagogical benefits, implications for surgical proficiency, and challenges of implementing such systems. By combining insights from technology, education, and surgery, this paper provides a comprehensive understanding of the transformative potential of Mixed Reality in orthopedic surgical training.

In the subsequent sections, we will delve into the technical components of the MR system, elucidate the pedagogical benefits of its application, examine the implications for surgical proficiency, and address the challenges that must be surmounted for its widespread integration. This paper aims to provide a comprehensive understanding of the transformative potential of Mixed Reality systems in orthopedic surgical training. It combines insights from technological, educational, and surgical perspectives to offer a holistic perspective.

2. Related work

The implementation of Mixed Reality (MR) systems in orthopedic surgery training has garnered substantial attention from researchers and practitioners alike. We don't aim to provide a full overview, but we refer the reader to the various recent surveys discussing the recent developments in the field [VRZ*17; BIM*22]. For what concerns the clinical aspects, Lex et al. [LKTB23] conducted a comprehensive review of clinical applications of augmented reality in orthopedic surgery: this study provides insights into the evolving landscape of MR-assisted procedures, highlighting the various surgical specialties and procedures that have benefited from this technology. Similarly, Rossi et al. [RMS*22] conducted a systematic review investigating the use of augmented reality in orthopedic surgery, particularly in total joint arthroplasty. Their study explores how AR enhances visualization, planning, and execution of procedures, thereby potentially leading to improved patient outcomes. Combalia et al. [CSD23] delves into immersive virtual reality applications in orthopedics: their narrative review examines the potential of immersive virtual reality environments to simulate surgical scenarios, aiding in training and skill development.

For what concerns the systems proposed in literature, we discuss the recent research that is close to our framework and delves into various aspects of MR's role in enhancing surgical training and preoperative planning. For what concerns elbow surgery, Tanji et al. [TNI*22] introduced a novel application of MR in total elbow arthroplasty. Their system provides real-time guidance during the procedure. By overlaying critical information on the surgeon's field of view, this approach exemplifies how MR systems can offer valuable support in real surgical scenarios, elevating precision and reducing the risk of errors. Fischer et al. [FFL*16] conducted a preclinical usability study of augmented reality concepts for K-wire placement. Their work explores the potential of augmented reality in enhancing the accuracy of K-wire placement procedures. Differently from them, we propose a training system based on the usage of a physical phantom, and able to provide different surgical scenarios with the same physical sample. For what concerns preoperative planning, Alemayehu et al. [AZT*21] explored the integration of 3D printing technology to enhance orthopedic surgery planning. Their study demonstrates the advantages of utilizing physical models for visualizing complex anatomical structures before surgery, thereby aiding in surgical decision-making. Bitschi et al. [BFG*23] contributed to the preoperative visualization domain with their study on complex tibial plateau fractures. Their work compares the benefits of preoperative mixed-reality visualization against traditional methods such as CT scans and 3D printing, showcasing the advantages of MR techniques in fracture assessment and surgical planning. Onuma et al. [OSA*23] explored the use of augmented reality in anterior decompression and fusion procedures for cervical ossification of the posterior longitudinal ligament. Their study highlights how MR can enhance precision and decision-making during complex spinal surgeries. The feasibility of MR in oncology-related surgical planning was investigated by Wong et al. [WSWK23]. Their proof-of-concept study demonstrates that MR enhances 3D visualization of bone tumors, aiding surgical planning in orthopedic oncology. The application of personalized guides through 3D printing was introduced by Duan et al. [DHF*18]: their study showcases the potential of such guides in arthroscopic ankle arthrodesis, indicating the personalized benefits of integrating additive manufacturing technologies in orthopedic surgery. The evolution of virtual reality in shoulder and elbow surgery was discussed by Lohre et al. [LWAG20]: they chart the progression of virtual reality applications, highlighting how technology has evolved to address the unique challenges of these specialized areas of orthopedics. Cate et al. [CBC*23] examined the status of virtual reality simulation education for orthopedic residents: their study sheds light on the need for a shift in focus in virtual reality education for orthopedic residents, emphasizing skill development and surgical proficiency. Lee et al. [LFT*17] ventured into multi-modal imaging, model-based tracking, and mixed-reality visualization for orthopedic surgery: their study presents a holistic approach to image guidance and visualization in surgical scenarios. The promising potential of augmented reality in glenoid component placement during reverse shoulder arthroplasty was showcased by Schlueter-Brust et al. [SHK*21]: their proof-of-concept study demonstrates the role of MR in ensuring accurate implant positioning. Trehin et al. [TBJ*23] addressed scapula registration in shoulder arthroplasty using mixed reality: their work contributes to enhancing the accuracy of registration processes, crucial for successful surgical outcomes. Rojas et al. [RLH*22] exemplified how augmented reality can support glenoid component placement during reverse shoulder arthroplasty. Their approach highlights the potential of MR in improving surgical precision. Cofano et al. [CDB*21] expanded the application of augmented reality beyond surgery into remote assistance: their work showcase the versatility of MR in enhancing collaboration and communication in medical practice. Very recently, systems integrating 3D printing and Mixed Reality have been proposed to provide a training testbed for various surgical specialties: Peng et al. [PXC*23] focus on neurosurgical ventricular and haematoma puncture training, Valenzuela et al. [VI23] developed a system for assessing and interpreting the outcomes of left main Percutaneous coronary interventions (PCIs) procedures, and finally Zhou et al. [ZYJ*23] created a MR-based surgical navigation system for hypertensive intracerebral hemorrhage. Collectively, all these studies underscore the growing significance of Mixed Reality systems in orthopedic surgery, ranging from preoperative planning to intraoperative guidance and surgical training. They provide insights into how MR's integration with advanced visualization techniques, 3D printing, and mixed reality can elevate surgical proficiency, patient outcomes, and the overall practice of orthopedics. To this end, all the discussed systems exhibit similarities with our proposed framework: the main difference is the fact that our system is specialized to elbow surgery and integrates the usage of Mixed Reality with the development of high quality physical phantoms for a correct rendition of haptics sensations.

3. Surgical procedure: elbow K-wire fixation

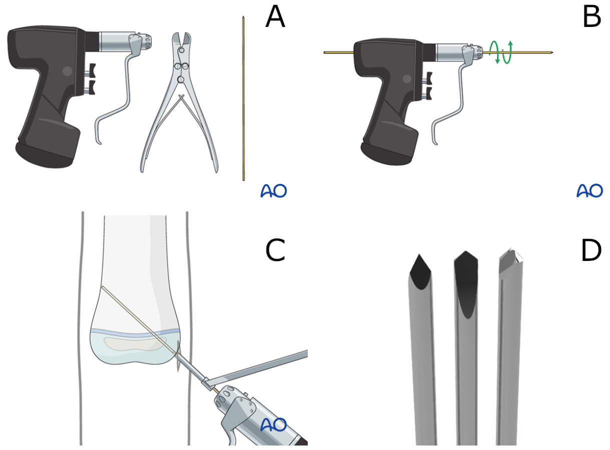

Figure 1: *Overview of k-wire fixation procedure. A: orthopedic drill, K-wire shears and K-wire; B: mounting principle of K-wire on orthopedic drill; C: insertion of K-wire into bone, it's possible to observe a guiding tool through which the K-wire is inserted; D: rendering of most common K-wire tips, here are dsiplayed only 2cm of the extremities of 3 1.6mm K-wires. Courtesy of www.aofoundation.org.*

K-wire elbow fixation surgery, also known as percutaneous pinning or wire fixation, is a common orthopedic procedure used to stabilize fractures, dislocations, and other traumatic injuries of the elbow joint [MEW12]. The technique involves using a drill for inserting thin, stainless steel wires (known as K-wires) through the skin and into the bone to hold fractured bone fragments in proper alignment during the healing process (see Fig. 1). This minimally invasive approach is favored for its reduced tissue damage and faster recovery compared to open surgeries [CMM*21]. K-wire elbow fixation is indicated for various cases, including:

- *Fractures* of the radial head, olecranon, or other parts of the ulna or radius;
- *Complex elbow fractures* that require temporary stabilization before more definitive treatment;
- *Pediatric fractures* as children's bones are often more amenable to this non-invasive approach;
- *Dislocations or subluxations* of the elbow joint;

The frequency of K-wire elbow fixation varies based on the incidence of traumatic injuries and the demographics of the patient population. It is commonly employed for the treatment of radial head fractures, olecranon fractures, and certain supracondylar fractures in children. While K-wire fixation is generally considered safe and effective, there are inherent risks associated with the procedure:

- Infection: any surgical procedure carries a risk of infection at the insertion site;
- Pin Migration: K-wires can potentially move or migrate, necessitating additional interventions;
- Pin Tract Infection: infections can occur at the entry and exit points of the wires through the skin.
- Nerve or Vessel Injury: incorrect wire placement can damage adjacent nerves or blood vessels;
- Loss of Reduction: improper alignment of fractured fragments can lead to poor healing outcomes;

For all these reason, one of the key aspects for a successful procedure and for a correct recovery is the correct placement of K-wires for what concerns both the position and the orientation. Training in K-wire elbow fixation surgery is an integral aspect of orthopedic surgical education. As this technique requires precise placement of wires to achieve stable fixation, proper training is essential to minimize complications. Training typically involves the following components:

- Didactic Learning: surgeons-in-training learn the theoretical aspects of the procedure, including indications, patient selection, anatomical considerations, and potential complications;
- Simulated Training: trainees practice on anatomical models or cadavers to develop familiarity with wire insertion techniques, appropriate angles, and depth of insertion;
- Hands-On Training: under the supervision of experienced surgeons, trainees begin by observing and assisting in real surgical procedures. As their proficiency improves, they gradually progress to performing K-wire insertions under guidance;
- Virtual and Mixed Reality Training: cutting-edge techniques involve the use of virtual and mixed reality systems to simulate surgical scenarios. These systems provide a controlled environment for trainees to practice wire insertion techniques, enhancing spatial awareness and procedural skills;

- Continuing Medical Education: even after becoming proficient, orthopedic surgeons continue to update their skills through workshops, conferences, and continuing education courses. This ensures that they stay current with the latest techniques and advancements in the field;

In recent years, Mixed Reality (MR) systems, are emerging as innovative tools for training in orthopedic procedures like K-wire fixation. MR systems provide an immersive and interactive platform where trainees can practice wire insertion on accurate anatomical models while receiving real-time guidance, enhancing their skills and confidence before performing the procedure on actual patients [HKM*22]. In conclusion, K-wire elbow fixation surgery is a widely used technique for stabilizing fractures and dislocations involving the elbow joint. It is indicated for various traumatic injuries, especially in cases where a minimally invasive approach is preferred. Training in this procedure involves a combination of didactic learning, simulated practice, hands-on experience, and, increasingly, the integration of virtual and augmented/mixed reality technologies. Proper training is vital to ensure safe and successful outcomes for patients undergoing K-wire elbow fixation surgery.

4. Methodology

The objective of demonstrating the applicability of Mixed Reality (MR) in Orthopedic Surgery has been pursued through an experimental setup comprising two key elements:

- *Software and Hardware Components*;
- *Simulation Phantom.*

The primary hardware component in this setup is the Hololens 2, developed by Microsoft. This device, in conjunction with the Unity platform, facilitates the development of a C#-based application. The primary objective of this application is to seamlessly integrate digital content into the physical environment.

In the defined technical context, the primary objective is to superimpose digitally-rendered anatomical structures onto a surgically-accurate phantom of the human elbow. This configuration is devised to emulate the operative setting, where real intervening tissues obscure underlying critical structures vital for surgical intervention. Through mixed reality, these pivotal internal details are made visually accessible, facilitating a more streamlined and precise surgical protocol. One of the significant benefits of this digital integration is the potential to markedly reduce the reliance on radiological imaging, thereby minimizing the exposure to high doses of ionizing radiation for medical personnel, patients, and surrounding staff.

4.1. System Architecture: Application Hardware and Software

Hardware Specifications: Devices and Systems *Hololens 2* is a holographic computing platform based on the Holographic OS, which is employed in this scenario to facilitate the mixed reality experience. It incorporates various sensors, including 4 visible light cameras, 2 Infrared (IR) cameras, a 1-MP Time-of-Flight depth sensor, as well as an accelerometer, gyroscope, and magnetometer. Additionally, it features an 8-MP still camera and supports 1080p30 video recording [Mica].

The recorded data empower this device to comprehend the context. Its capabilities are categorized into two domains:

- *Human Understanding*: this encompasses hand tracking, eye tracking, and voice recognition;
- *Environment Understanding*: this involves six degrees of freedom (6DoF) tracking, spatial mapping, and mixed reality capture.

Of particular significance is the depth acquisition capability. Information recorded in the *two-dimensional space* (RGB photogrammetry) is correlated with the *third dimension* (depth map). This approach allows for in-depth analysis of what the user perceives and how they interact.

Software Modules: Tools and Features Vuforia™is an augmented reality (AR) development platform that empowers developers to craft immersive AR experiences on various platforms, including Hololens 2. The integration of Vuforia™with Unity provides developers with a robust toolkit for building AR applications.

To establish the mixed reality environment on HoloLens 2, the Mixed Reality Toolkit (MRTK) was employed within the Unity framework. This allowed for the utilization of the "understanding capability" and "reality interactivity" features. Through the utilization of MRTK, a comprehensive set of components and features became accessible, facilitating cross-platform app development [Micc; Micb].

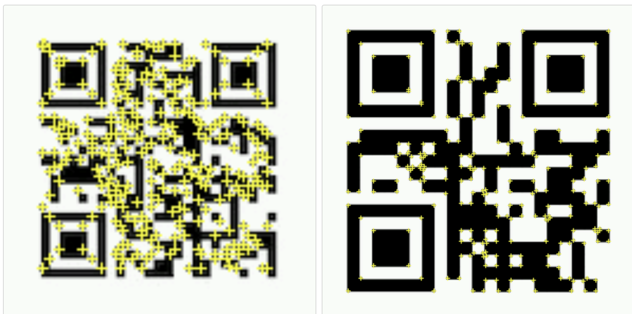

Figure 2: *Extracted Features on QR Codes. The QR code on the left is associated with the dummy, while the one on the right is associated with the drill stand.*

Vuforia In this scenario, Vuforia is employed for QR code tracking. The Image Target Behavior and Target Manager provided by the developer are utilized to recognize QR codes based on a set of distinctive features found within the image patterns. As documented in numerous studies, this approach surpasses alternative image recognition methods due to its reduced inference time and ease of identification, even under suboptimal image quality conditions [KPB20].

As illustrated in Figure 2 in the QR image, features highlighted in yellow are extracted from the QR codes. These features will be employed to compute the pose of the QR code, attributed

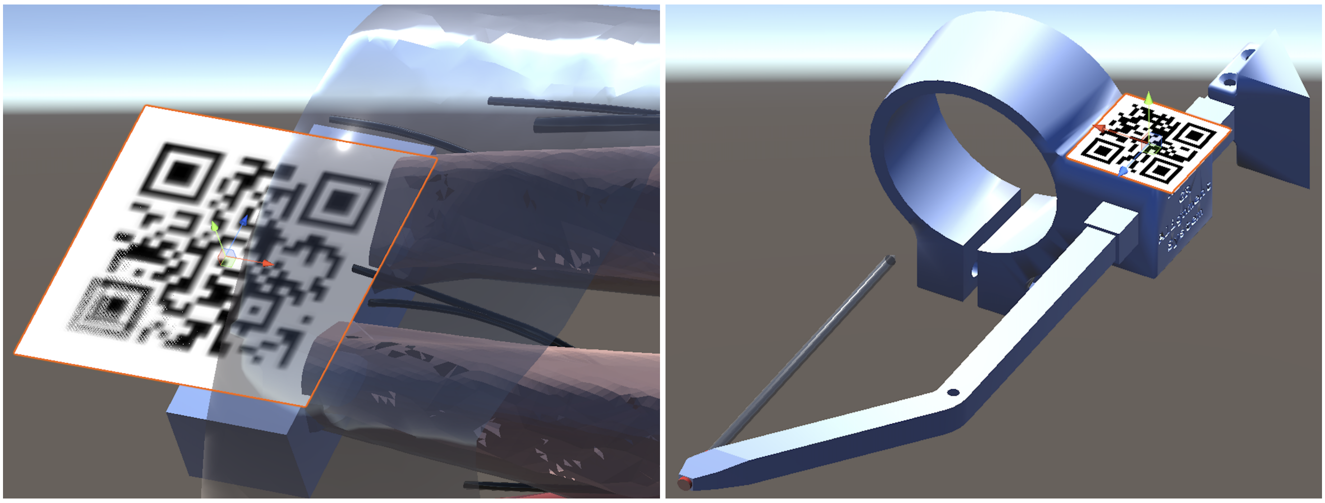

Figure 3: *Alignment of QR Codes on Virtual Elements with Corresponding Real-World Positions. Each QR code is depicted with its local reference system.*

based on the local reference system depicted in Figure 3. The poses of the coordinate systems will be utilized for the calculation of relative positions and relative orientations of the elements of interest, potentially involving translation and rotation operations.

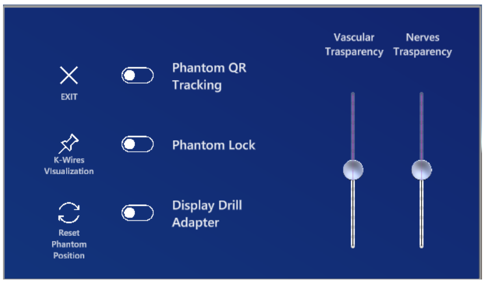

Figure 4: *User Interface for the Designed System in the Specific Application*

MRTK The Microsoft Mixed Reality Toolkit (MRTK), developed as a support tool for Hololens platform development, was utilized in the creation of the user interface, as depicted in Figure 4. Users have the ability to highlight structures of interest by adjusting transparency, manipulate virtual objects in terms of their position and dimensions for a quick and detailed view of specific anatomy, and control the display of elements that may facilitate or hinder the alignment with the target point for the k-wires (adapter drill structure and k-wires).

4.2. Simulation phantom

Physical phantom allow to isolate variables of interest in which the system is intended to be tested, excluding individual variability all while avoiding ethical and safety drawbacks. A robust literature report the use of simulation models to demonstrate the efficacy of this emerging technology [PMN*18; HLR22]. The Simulation phantom is designed and built giving priority to precision in shape reproduction, reality in material consistency and radio-density. Regarding the former we exploit the use of 3D printing technology to reach sub-millimeter accuracy, for the other parameters we based our decision on prior literature [SAP20] and in-house testing.

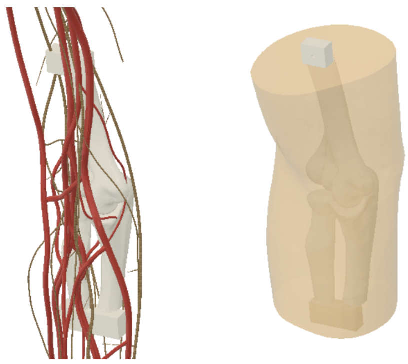

Figure 5: *On the left: Rendering of bones, vessels, and nerves present in the virtual 3D model. On the right: Rendering of humerus, radius, and ulna with soft tissues.*

Virtual 3D model The virtual model is obtained from Blender™"Z-Anatomy Atlas" that is an open source 3D reconstruction of a complete human body. This model is used to design the project and tools to construct the physical phantom, but also as 3D virtual model that is then visualized by the Virtual Reality system. Later it is used to store data about K-wire positioning and to compute angle and position deviation from target K-wire position. It is also possible to make considerations on K-wire distance and damage risk to nearby structures such as nerves, vessels and muscles.

Design principles

- *Reliability*: having sub-millimetric accuracy allows for robust data acquisition comparable among multiple subject;
- *Radiopacity*: since a lot of orthopedic surgical procedures are performed under x-ray guidance, we tested several materials and chose the one more visible under x-rays;
- *Anatomical accuracy*: performing tests on anatomically correct medical dummy projects the scope of the research into the real life application;
- *Reference virtual model with vessels, nerves, muscles*: even thought these structures are not physically present in the medical dummy, virtually taking them into account will grant us the ability to evaluate real life implications;
- *Reusability*: having the possibility to use the same dummy for multiple tests increases the power of the study while reducing costs;
- *Ease of construction*: this allows us to build it without recurring to 3rd parties companies. This increases rapidity of development and adaptability while reducing costs.

Materials The simulation phantom is composed of 2 materials: PLA plastic for bones and silicone for soft tissues.

- *"PLA or poly(lactic acid)"* is the most extensively utilized plastic filament material for 3D printing. It boasts a low melting point, high strength, low thermal expansion, and excellent layer adhesion; however, its heat resistance is notably lacking. The application of copper-infused PLA could yield highly significant findings, as the multiple infill configurations allow the resulting HU range to correctly reproduce marrow bone as seen through X-ray imaging[SAP20];
- *"RTV silicone (room-temperature-vulcanizing silicone)"* is a type of silicone rubber that cures at room temperature. Although 1 component solutions are available, a two-component mix (a base and curative) is preferred for casting applications, like this study case. These materials consist of a base and a curing agent that undergo a chemical reaction and cure to form a flexible and durable rubber mold, even in limited presence of air, like inside a cast.
  Silicone hardness is evaluated on 12 different scales: A, B, C, D, DO, E, M, O, OO, OOO, OOO-S, and R. Each scale results in a value between 0 and 100, with higher values indicating a harder material. To best reproduce soft tissues we chose the softest available to us which corresponds to *"shore A5"*. Nevertheless, real life comparison between silicone and cadaveric soft tissues are subpar and is an interesting aspect to improve in the future.

Manufacturing Manufacturing of the simulation phantom represents an engineering challenge as both bones and soft tissues have complex shapes and a perfect 3D correspondence between virtual and physical phantom is a strict requirement. We opted to use 3D printing technology to transform our virtual phantom model to the physical one. Mounting supports of the bones are fundamental as they allow fixing and stabilization of the bones onto the molds for

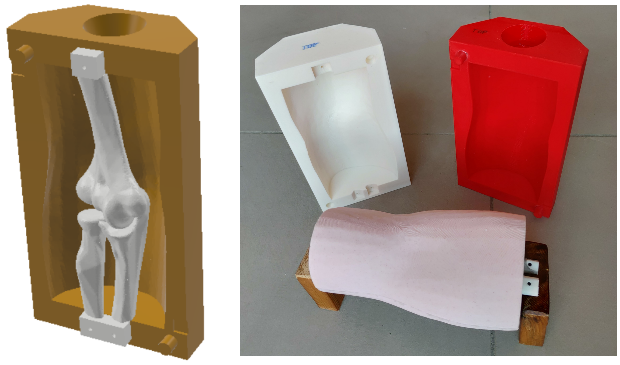

Figure 6: *Left: rendering of humerus, radio and ulna with negative soft tissues mold (side B); Right: physical phantom on wooden supports and molds (from left to right: side A and B)*

the casting process as well as later attachment points to external supports to perform K-wire insertion tests.

The process is composed of 4 phases after which the medical phantom should be a replica with submillimetric accuracy of the virtual 3D model:

1. The articulation ends of humerus, radio and ulna with respective mounting supports are 3D printed in PLA plastic;
2. The negative molds (A and B, figure 6) are printed in PLA on the same type of printer, the settings used are 0.3mm as layer height with 15% infill;
3. Bones are enclosed into the 2 molds and fixed with screws, which keep the bones in position during the casting process;
4. Liquid silicone mixed with the catalyst is poured through the top opening to be later extracted from the mold as a solid component 12h later.

Virtual Phantom-Based Consistency Validation Being able to estimate deviation of the physical phantom from virtual model allows us to correct the extrapolated testing data. To accomplish this as well as to be able to import onto the virtual model K-wires position we inserted 10 reference markers on the soft tissue. Inter-markers distances are used to test the physical phantom after mold extraction as well as after positioning it on supports for k-wire placement simulation: this allows us to tweak the positioning in order to correct possible deformations due to gravity and other factors.

5. Mixed-Reality Setup: Real and Virtual Phantom Interaction

As mentioned in the preceding section, the Hololens platform allows surgeons to access digital content. In the context of patient-specific anatomy acquired through medical imaging techniques such as CT, MRI, and PET, this digital content can be superimposed onto the human body, represented by a phantom, to facilitate the surgical procedure.

One issue that arises is the identification of reference points, which is essential due to two primary concerns:

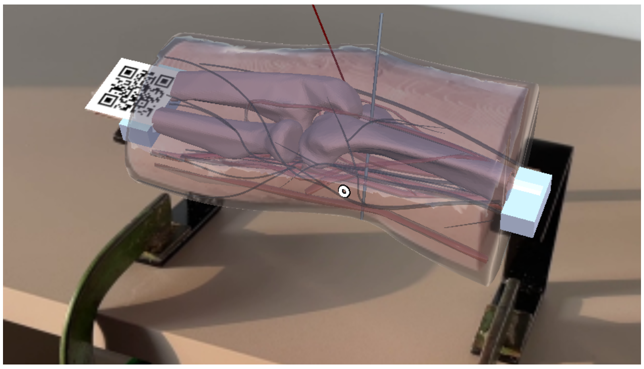

Figure 7: *Digital-Physical Overlay: Elbow Dummy with Vascular, Bones, and Neural Structures*

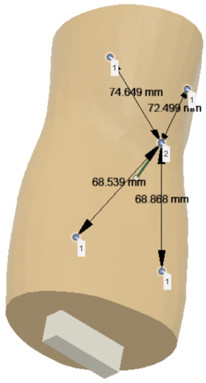

Figure 8: *Virtual representation of K-wire outer end point 3D coordinates triangulation, to fully reconstruct the position of the K-wire also skin entrance point 3D coordinates must be calculated (not represented)*

- Ensuring both the internal and external consistency of the tissue: In this regard, tissues exhibit intrinsic motion, which, in living tissues, can result in shifts that may introduce errors;
- Tissues tend to lose their natural tone after several hours of surgery.

In this scenario, the developed framework enables precise positioning via a QR code. Subsequently, the operator has the flexibility to fine-tune the digital model and conduct in-depth anatomical analysis, facilitating precise procedural planning.

Following this step, it is crucial not to move the phantom to maintain data coherence with the digital content. On the other hand, concerning the digital content, it is of paramount importance to minimize ambient noise disturbances and occluding elements. These factors can reduce the precision of sensor data acquisition, which, in turn, affects the accuracy of visualization in the augmented reality view.

5.1. Real time tracking and measurement

By utilizing the geometry support and leveraging knowledge of K-wires measurements, translation and rotation have been applied to the position and rotation matrices, respectively, in order to obtain the tip position.

Considering the *target pose* and the *tip* pose, given by their positions $\mathbf{p}$ and orientations $\mathbf{R}$:

$$\mathbf{s} = [\mathbf{p} \quad \mathbf{R}] \tag{1}$$

it is possible to calculate the pose matrix, composed of:

- *translation matrix*:

$$\Delta\mathbf{p} = \mathbf{p}_{\text{tip}} - \mathbf{p}_{\text{target}} \tag{2}$$

- *rotation matrix*:

$$\Delta\mathbf{R} = \mathbf{R}_{\mathbf{tip}}^{T} \cdot \mathbf{R}_{\mathbf{target}} \tag{3}$$

The orientation between the two objects is represented as the result of three successive rotations described by *Euler Angles* (α, β, γ) around the x, y, and z axes.

$$\Delta\mathbf{R} = R_z(\gamma)\,R_y(\beta)\,R_x(\alpha)$$

Expanding the rotation matrices across the three axes:

$$\Delta\mathbf{R} = \begin{bmatrix} \cos\gamma & -\sin\gamma & 0 \\ \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{bmatrix}$$

The *orientation* and *position* of a coordinate system relative to another can be represented by a homogeneous transformation matrix:

$$H = \begin{bmatrix} \Delta R & \Delta p \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & x \\ r_{21} & r_{22} & r_{23} & y \\ r_{31} & r_{32} & r_{33} & z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4}$$

Therefore, the angles required to align the target and tip are calculated using the following equations:

$$\begin{aligned} \alpha &= \arctan\left(\frac{r_{21}}{r_{11}}\right) \\ \beta &= \arcsin(-r_{31}) \\ \gamma &= \arctan\left(\frac{r_{32}}{r_{33}}\right) \end{aligned} \tag{5}$$

Data extrapolation about k-wire positioning and relative distances from internal elbow structures is calculated virtually on the 3d modeling software after importing the k-wire onto the virtual 3D model. K-wire position is reconstructed by computing 3D coordinates of outer end point and skin entrance point of K-wire relative to 4 conveniently selected markers (see Fig. 8). Substantially we measure 4 distances from the selected 4 markers on the physical phantom to the outer end and skin entrance point (for a total of 8 measurements), then on the 3d modeling software we draw the K-wire starting from the outer end 3D coordinates and passing through the skin entrance point 3D coordinates for a known length of 11cm. Once the virtual position is reconstructed, the angular and 3D position of the K-wire is computed and compared to the intended target. The distances of the K-wire from virtual internal structures such as nerves and vessels is recorded and stored in a database in order to perform further statistical comparison with K-wires placed without the MR system.

Figure 9: *Guided K-wire Insertion in a Dummy: Virtual Overlay Revealing Internal Structures with the K-wire Tip Indicated by a Red Cylinder. Tracking achieved via QR code mounted on the drill, utilizing Vuforia™instance.*

6. Qualitative assessment

A statistically significant case study data is still lacking, but we could make a qualitative assessment based on preliminary tests. In the video that can be found at this link we show the POV of a surgeon testing the system. The user, wearing AR goggles, is able to superimpose the semi-transparent virtual model including vessels, nerves, and target K-wire onto the physical phantom. By visualizing the positioning of sensitive structures together with the K-wire, the user can place the fixator system and avoid iatrogenic damage. The system recognizes the spatial position and orientation of the drill & K-wire assembly and gives visual feedback once the target insertion position is reached. Depth of insertion is visualized graphically based on visual depth computation. It is crucial to emphasize the significance of haptic feedback perceived by operators when using the drill. Preliminary test reports that the user experienced a perfect correspondence of the virtual K-wire tip contacting with the virtual bone with a change in tactile sensation experienced through the drill handle. This establishes a match between the real and virtual worlds, which is fundamental not only in real patient procedures but also in the educational realm. The integration of 3D visualization, a deep comprehension of anatomical structures, and the integration of haptic feedback can significantly enhance the learning curve for trainees.

7. Conclusions and future work

The preliminary analysis of the Mixed Reality (MR) training system for orthopedic elbow surgery represents a promising tool for improving individual surgical skills, hence enhancing the precision of orthopedic procedures, particularly K-wire fixation. Here are some key conclusions drawn from this analysis:

- *Advancements in Surgical Training*: the integration of Mixed Reality (MR) into surgery training could the potential to revolutionize the acquisition and improvement of surgical skills. The combination of real-world surgical phantoms with digitally augmented anatomical models provides an immersive and experiential learning environment;
- *Improved Spatial Awareness*: the MR system enhances trainees' three-dimensional spatial awareness by superimposing 3D reconstructions of deep structures and target K-wire positions onto physical models. This feature helps to improve the understanding of complex anatomical relationships critical for surgical procedures;
- *Precision and Proficiency*: the MR-guided K-wire placement allows for more precise positioning, reducing the risk of iatrogenic injury to nerves and vascular structures, by clearly showing the position of sensitive deep targets (nerves and vessels);
- *Cost-Effective Training*: while the initial investment in MR technology is significant, it can ultimately provide cost-effective training solutions compared to traditional methods involving cadavers and live specimens.

Despite the promising preliminary results, the system has some limitations that we plan to address in the near future: the current tracking based on QR codes through Vuforia engine may exhibit inaccuracies and lags that may limit the immersive experience. We plan to explore full data-driven and computer-vision-based solutions for real-time tracking of fixed landmarks and surgical tools [EVJ*22].

Future Work As this study is ongoing, further data collection and analysis are needed to provide definitive results. Future work should focus on a quantitative and larger-scale evaluation of the MR system's impact on surgical proficiency and the implementation of a pipeline that could be applied on real surgical cases upon appropriate technical assessments. For the latter, automatized recognition and placement of the virtual reconstruction of the patient's tissues and metal elements from a CT scan or multiple X-ray views should be considered, in order to overcome the tracking accuracy limited by the sole use of the hololens camera.

Furthermore, the system concept has the potential to be expanded by implementing virtual planar guides for surgical cuts, guiding prosthesis placement procedures, screw selection, placement, and extraction guidance, both in a teaching context and in the operating room.

This MR system has the potential to not only enhance surgical training but also provide real-time surgical guidance in challenging clinical scenarios, ultimately improving patient care and safety in orthopedic elbow surgery and beyond.

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