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APPLICATION OF AUGMENTED REALITY IN ORTHOPEDIC SURGERY

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Abstract

Purpose—Augmented Reality (AR) is a novel cutting-edge technology which is being employed by various surgical fields for navigation, including orthopedic surgery. In our pre-clinical studies, we implemented AR in two key domains of orthopedic surgery, i.e. orthopedic oncology and total hip arthroplasty (THA) for surgical guidance and to assess its accuracy.

Methods– For revision total hip arthroplasty (rTHA), AR-guided system was developed for the reaming of large acetabular defect, with the goal of enhancing the precision of custom implant placement on patient-specific phantom. This technique was evaluated against conventional approaches (Free-hand and Patient specific instrumentation (PSI)) i.e., to determine comparative accuracy. The accuracy was evaluated in terms of achieved inclination and anteversion against planned angulation as well as deviation across x,y and z axis. For orthopedic oncology, we explored the application of AR in tumor resection, aiming to facilitate negative-margin excisions and reduce recurrence risk. The accuracy was assessed using cutting guides with different groves (1mm, 2mm and 3mm) in order to assess achieved osteotomy lines. The study utilized advanced AR-HMDs, namely Microsoft HoloLens 2 and Magic Leap 2, and conducted comparative analyses to evaluate their respective performance and accuracy.

Results—In revision hip arthroplasty, AR guidance and PSI-assisted reaming demonstrate superior accuracy compared to the conventional freehand method. Both

PSI and AR-assisted reaming techniques achieved absolute errors of less than 3° in post-implantation inclination and anteversion, whereas the freehand method exhibited errors exceeding 3°. Deviations along the x, y, and z axes were not statistically significant. For AR-assisted osteotomies, the Magic Leap 2 outperformed the HoloLens 2, achieving accuracy rates of 82%, 95%, and 100% within 1 mm, 2 mm, and 3 mm of planned osteotomy lines, respectively, compared to 65%, 85%, and 95% for the HoloLens 2. Additionally, an ergonomics survey indicated more favorable outcomes for the Magic Leap 2.

Conclusions – In revision hip arthroplasty, AR and PSI-assisted reaming exhibit greater precision than the conventional freehand method with respect to inclination and anteversion outcomes. In the context of oncological resections, the Magic Leap 2 demonstrates superior surgical accuracy and ergonomic performance compared to the HoloLens 2.

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Chapter 1 INTRODUCTION

1.1 Research introduction

Orthopedic surgery encompasses a wide range of interventions targeting musculoskeletal disorders, arthroplasty and orthopedic oncology representing two of its most technically demanding subspecialties(1). Both domains necessitate meticulous preoperative planning and precise intraoperative execution to optimize patient outcomes(2, 3).

This doctoral research focused on integrating augmented reality (AR) into orthopedic surgical workflows to enhance intraoperative navigation and accuracy. Specifically, the study aimed to evaluate the feasibility and precision of AR using two prominent head-mounted displays (HMDs), namely Magic Leap 2 and Microsoft HoloLens 2; across two clinical scenarios: revision total hip arthroplasty (rTHA) for large acetabular defects and tumor resection in orthopedic oncology.

AR, when applied to surgery, facilitates real-time overlay of three-dimensional (3D) anatomical models directly into the surgeon's visual field, either through HMDs or display interfaces. This visualization allows for an intuitive understanding of complex anatomical relationships and improves spatial orientation during critical procedures.

In the context of THA, AR guidance was used to assist the reaming process (preparing the acetabulum to receive a custom implant). Furthermore, AR-assisted reaming was systematically compared with two conventional approaches: patient-specific instruments

(PSIs) and the freehand method, in order to quantify differences in reaming accuracy and implant positioning.

Similarly, in orthopedic oncology, AR was employed to project preoperatively planned resection margins directly onto patient-specific phantoms. This method aimed to support the surgeon in achieving negative margins, a critical factor in minimizing local recurrence. The effectiveness of AR in guiding these resections was quantitatively assessed using predefined accuracy metrics.

Following promising outcomes in preclinical phantom-based studies, the feasibility of applying AR in actual surgical settings was explored in the operating room. These investigations served to validate the practical applicability and robustness of AR technology under clinical conditions.

In conclusion, the findings of this thesis highlight the potential of AR to significantly enhance surgical precision, reduce intraoperative uncertainties, and ultimately improve clinical outcomes in orthopedic surgery. While the results are encouraging, further clinical validation, larger sample sizes, and refinement of AR integration protocols are necessary before routine implementation in operating rooms can be fully realized.

1.2 Background

1.2.1 Augmented Reality

AR, or more broadly Mixed Reality (MR), represents a transformative technological advancement that enables the seamless integration of computer-generated digital content with the physical environment. This creates an interactive and immersive visual experience in which virtual elements are superimposed onto real-world surroundings, allowing users to engage dynamically with a hybrid virtual-physical space in real time(4).

The foundational concept of AR was first actualized in 1968 by Ivan Sutherland who developed the earliest HMD-based AR system(5). Since then, AR has evolved substantially, with widespread adoption across diverse sectors such as entertainment, gaming, sports, and retail. Notably, improvements in wearable hardware design and computing capabilities have enhanced the accessibility and functionality of AR systems, leading to growing interest and investment, particularly from the entertainment industry. These technological strides have also facilitated AR's transition into healthcare, where its utility, especially in surgical applications, continues to expand rapidly(6).

In the surgical domain, AR has emerged as a promising adjunctive tool that enhances a surgeon's perceptual and cognitive capacities by visualizing complex three-dimensional anatomical structures directly within the surgeon's line of sight, either through HMDs or external display monitors. By overlaying preoperative imaging data and anatomical models onto the real operative field, AR provides an intuitive spatial understanding of underlying tissues, which can be especially advantageous in procedures requiring precise anatomical localization.

AR-assisted surgery holds considerable potential in tasks such as tumor localization, delineation of resection margins in orthopedic oncology as well as navigation in THA. Its

use can therefore contribute to greater surgical precision, potentially minimizing intraoperative errors and improving patient outcomes. HMDs are particularly advantageous in surgical AR applications due to their ability to offer an egocentric, surgeon-centered perspective, which enhances ergonomic efficiency compared to traditional screen-based computer-assisted surgical systems. This feature enables the surgeon to maintain continuous visual engagement with the operative field without diverting attention to external imaging displays, thereby supporting workflow continuity and procedural focus(7).

A central ambition of AR in surgery is its application in real-time intraoperative navigation. This involves the accurate registration of preoperative imaging datasets, such as CT or MRI scans, with the live surgical field using anatomical landmarks as reference points. By achieving this spatial alignment, AR systems can guide the surgeon throughout the procedure, enabling highly accurate execution of planned interventions. As the technology matures, AR stands to become an integral component of image-guided surgery, particularly in complex procedures.

Registration and tracking in AR-based surgical navigation

Registration is a fundamental process in computer-assisted and AR based surgical navigation systems(8). It refers to the precise alignment between virtual preoperative data and the real-world intraoperative anatomy. Accurate registration ensures that augmented virtual content, overlaid onto the surgical field, is spatially coherent and clinically reliable. Without effective registration, the clinical utility of AR systems is

significantly compromised, as visual misalignments could lead to surgical inaccuracies and increase the risk of complications.

AR navigation systems generally employ two principal methods for registration: marker-based and marker-less techniques. While some investigations have explored the use of manual registration(9, 10), this approach is generally regarded as insufficiently precise for the execution of surgical procedures, particularly those requiring high spatial accuracy. A concise overview of the principal registration methods is provided below:

- Marker-based registration involves the use of physical fiducial markers, such as ArUco or QR codes, which are rigidly attached to the patient's anatomy or to reference frames within the surgical field. These markers are recognized by the HMD's built-in camera or an external camera system, enabling real-time tracking of the patient's position. Once identified, the AR system registers the virtual model by matching the spatial relationship between the marker and the 3D anatomical structures. This technique is widely adopted due to its relative simplicity and high accuracy under controlled conditions.

- Marker-less registration, by contrast, eliminates the need for physical markers and relies on a combination of computer vision algorithms, depth sensors, inertial measurement unit (IMU) data, and, in some applications, Global Positioning System (GPS) data(11). Through the identification of natural features such as object contours, surface geometry, and depth maps, these systems are capable of constructing a spatial understanding of the scene and aligning it with virtual content in real time. Although marker-less methods are less invasive and more

flexible, they are generally more computationally intensive and susceptible to environmental variability (e.g., lighting, occlusions), which may affect registration accuracy.

At the core of all registration techniques is the process of tracking, the continuous monitoring of the position and orientation of objects, such as surgical instruments, patient reference points, or head-mounted displays, relative to a fixed coordinate system(12). The accuracy and stability of the tracking method directly influence the fidelity of registration and, by extension, the overall safety and effectiveness of AR-guided procedures.

In surgical settings, robust registration and tracking are essential not only for maintaining the integrity of image guidance throughout the procedure but also for enabling real-time interaction with dynamic anatomical structures. This is particularly important in orthopedic oncology and arthroplasty, where precise localization of tumors or bone defects is critical for complete resection or accurate implant placement.

Thus, the integration of reliable registration and tracking systems is foundational to the successful deployment of AR in surgery. Ongoing advancements in sensor fusion, computer vision, and machine learning are expected to further improve the robustness, adaptability, and clinical applicability of AR-assisted navigation technologies.

1.2.2 AR HMD's

Unlike traditional displays, AR HMDs overlay contextual, spatially registered digital information directly onto the user's view of the real environment, facilitating an immersive and interactive experience(13).

Among the commercially available AR HMDs, Microsoft HoloLens 2 is currently the most prominent and widely researched platform, offering features that cater to both enterprise and medical applications. However, till date, according to authors best knowledge, Magic Leap 2 has not been utilized in medical applications of orthopedic surgery. In this study, we tried to evaluate the accuracy of both above mentioned devices.

1- **HoloLens 2:**

HoloLens 2 is among the most widely utilized AR devices in clinical practice and is one of the navigational device systems employed by healthcare professionals globally.

As the second-generation mixed reality headset developed by Microsoft, it offers an immersive AR experience through a high-resolution, see-through visor that projects 3D holograms directly into the user's field of vision. This enables real-time integration of virtual content with the physical environment, supporting intuitive spatial interaction. The headset is equipped with advanced sensors, including depth-sensing cameras, eye-tracking technology, and an inertial measurement unit (IMU), which together ensure precise environmental mapping and accurate recognition of user input. Additionally, the

built-in camera facilitates image capture and supports computer vision algorithms critical for object tracking and spatial registration(14). These combined features make HoloLens 2 a highly effective tool for medical applications such as surgical planning(15), intraoperative navigation(16), and clinical education(17, 18).

In medical education, HoloLens 2 has significantly contributed by offering an immersive platform for advanced learning. This mixed reality gadget allows medical students and experts to perceive anatomical structures in three dimensions, hence improving spatial comprehension and clinical reasoning. It can generate precise holographic simulations of the human body, enabling users to virtually dissect cadavers, analyze complex organ systems, and investigate disease states in an interactive and highly realistic setting(19).

HoloLens 2 also has become a revolutionary instrument in contemporary surgical practice, garnering growing recognition for its capacity to improve intraoperative visualization and planning. This sophisticated device allows surgeons to superimpose patient-specific imaging data, such as CT and MRI images, directly onto the operating field in real time. The technique offers a dynamic augmented vision by superimposing high resolution images, enabling the accurate localization of essential anatomical structures. Thus, surgeons can strategize incisions more efficiently and perform intricate surgeries with enhanced assurance and more accuracy (20).

In addition to its direct surgical applications, this device can also enhances telemedicine capabilities. The device's real time data integration and display functionalities render it an essential tool in situations necessitating remote expert help. The approach improves intraoperative decision making by linking operating teams with remote specialists,

perhaps resulting in better clinical results in complex surgical cases(21). This application is especially important in environments with restricted access to subspecialty expertise, thereby providing a conduit to high-quality care irrespective of geographic limitations.

Besides its intraoperative advantages, HoloLens 2 plays a significant role in patient education and the informed consent procedure. Medical practitioners can utilize the technology to produce interactive, three-dimensional representations of many medical disorders, facilitating the elucidation of intricate diagnoses or treatment strategies in a clear and appealing manner. The technology may generate realistic 3D models of tumors, vascular malformations, or other diseased entities, aiding patients and their families in understanding the complexities of their ailments and the corresponding treatment options(22). This visualization enhances comprehension and enables patients to engage actively in their healthcare decisions, promoting a more collaborative patient-physician relationship.

The diverse applications of HoloLens 2 in surgical navigation, telemedicine, and patient education highlight its potential to transform the medical industry. The gadget connects digital imaging with real surgical settings, facilitating a paradigm change in which enhanced visualization tools improve the technical execution of surgical procedures and the overall quality of patient care. As technology advances and merges with other digital advancements, it is expected that its therapeutic uses will expand, solidifying its position as a fundamental aspect of contemporary surgical practice.

2- Magic Leap 2

Magic Leap 2 is another advance AR HMD engineered to provide high fidelity spatial computing experiences, especially in professional and medical settings. Launched in 2022, it enhances its predecessor (Magic Leap 1) with notable advancements in visual clarity, field of view, and comfort, rendering it more appropriate for clinical and surgical applications.

The device, weighing around 260 grams, boasts a 70-degree diagonal field of view, high-resolution stereoscopic displays, eye tracking, and environmental sensing capabilities, enabling exact overlay of digital content into the real world. The device operates on a wearable computation pack, facilitating intricate 3D rendering independently of external gear(23).

Magic Leap 2 is compatible with OpenXR, Unity, and Unreal Engine, facilitating the development of advanced AR apps, including those designed for preoperative planning(24), intraoperative navigation, and surgical teaching. Its advanced spatial mapping and continuous 3D anchoring render it exceptionally suitable for orthopedic treatments, where accuracy and anatomical visualization are paramount.

In one of porcine model study, Frisk et al. evaluated the accuracy and workflow of an AR-assisted hybrid navigation protocol using the Magic Leap 2 HMD for minimally invasive pedicle screw placement. The method attained optimal accuracy across all cannulations facilitated by intraoperative CBCT and AR overlays(25).

Neves et al. (2020) evaluated Magic Leap for external frontal sinus surgery in six cadaver heads, using CT-based holograms. The procedure was successfully completed

in all cases, with a mean contour error of 1.4 ± 4.1 mm and one minor complication, demonstrating the technique's feasibility and accuracy(26).

In a feasibility study employing Magic Leap 2 for home-based gait and balance training in individuals with Parkinson's disease, participants exhibited high adherence (104%), reported no falls (only four near-falls), and demonstrated modest but positive improvements in mobility assessments(27).

In summary, Magic Leap 2 demonstrates significant potential as a clinical augmented reality instrument, providing great precision in surgical operations and ensuring safe, effective application in rehabilitation. It facilitates accurate navigation in surgical procedures and promotes interactive, at-home rehabilitation. Although it has yet to receive FDA approval, its performance and usability render it a useful tool in both surgical and therapeutic applications.

1.2.3 Revision total hip arthroplasty

In Europe, the incidence of revision total hip arthroplasty has consistently risen due to the aging demographic and increasing primary THA volumes. Between 2001 and 2015, Italy recorded 109,746 revisions, with mechanical complications; such as aseptic loosening and graft failure constituting roughly one-third of the cases(28).

In contrast, periprosthetic osteolysis, which signifies considerable bone loss, is reported in roughly 6–7% of revision cases in extensive European datasets(29). The incidence of THA is anticipated to rise, with projections indicating a 43% to 70% increase in the frequency of rTHA from 2014 to 2030(30).

Large acetabular defects provide a considerable problem in revision THA. The depletion of bone supplies, alteration of anatomical landmarks, and impaired biomechanics require intricate reconstructive approaches. These deformities are often categorized according to Paprosky (type IIIA/IIIB) or AAOS (type III/IV), which impact surgical decision-making and reconstructive strategy(31).

The principal objectives in addressing these deficiencies are the restoration of the hip center of rotation (CoR), stable fixation, enduring osseointegration, and, optimally, the restoration of bone stock for potential future revisions.

Paprosky's classification of large acetabular defects:

The paprosky approach classifies acetabular defects into three primary categories based on hip center displacement, the integrity of essential structural features (superior dome, medial wall "teardrop," and ischial/posterior rim), and the stability of acetabular columns(32).

Type I: Minimal bone loss

Type 1 defects are characterized by minimal or absent bone loss. The acetabular rim and both the anterior and posterior columns remain intact, with no notable migration of the acetabular component. This type signifies optimal conditions for revision, and standard uncemented hemispherical cups can typically be implanted with satisfactory initial stability. Bone grafting is typically irrelevant, and long-term results are advantageous owing to the conservation of host bone stock(33).

Type II: Moderate bone loss with <3cm of migration

Type 2 defects exhibit moderate osseous loss while maintaining the integrity of the acetabular columns. These deficiencies are further classified into three categories according to the precise region of bone loss:

Subtypes:

- IIA: Marked by superomedial osseous resorption. The acetabular component generally shifts somewhat superiorly, while the columns remain structurally sound. This deformity is frequently addressed using an uncemented hemispherical cup, occasionally supplemented with bone grafts or augmentations to enhance support(34).

- IIB: It involves osseous resorption in the superolateral rim, resulting in the superolateral displacement of the component. Despite the more significant bone loss compared to 2A, the columns remain intact. A porous-coated cup with potentially enhanced augmentation or screw fixation is frequently necessary(35).

- IIC: refers to a more complex defect concerning the medial wall and the teardrop region. The component may shift medially. Structural grafting or reinforcement devices may be necessary, and precautions must be implemented to avert more medial protrusion(36).

Type III: Severe, global bone loss with hip center migration >2–3 cm

Type 3 abnormalities are the most complicated, characterized by significant bone loss and compromised structural integrity of the column. These are categorized into

- IIIA: This deficiency encompasses considerable loss of the superolateral rim and posterior column, accompanied by notable superior migration of the acetabular component (exceeding 3 cm) with Kohler line intact. Ischial osteolysis is frequently noted. Reconstruction generally entails the utilization of augmentations, porous metal components, or customized triflange implants(37).

- IIIB: The most severe form, characterized by extensive rim and column loss and often associated with pelvic discontinuity, a condition where the superior and inferior portions of the pelvis lose continuity. Reconstruction is highly complex, often requiring cup-cage constructs, custom triflange components, or advanced fixation techniques. Bone grafting and biological reconstruction may also be necessary to restore stability and promote osseointegration(38).

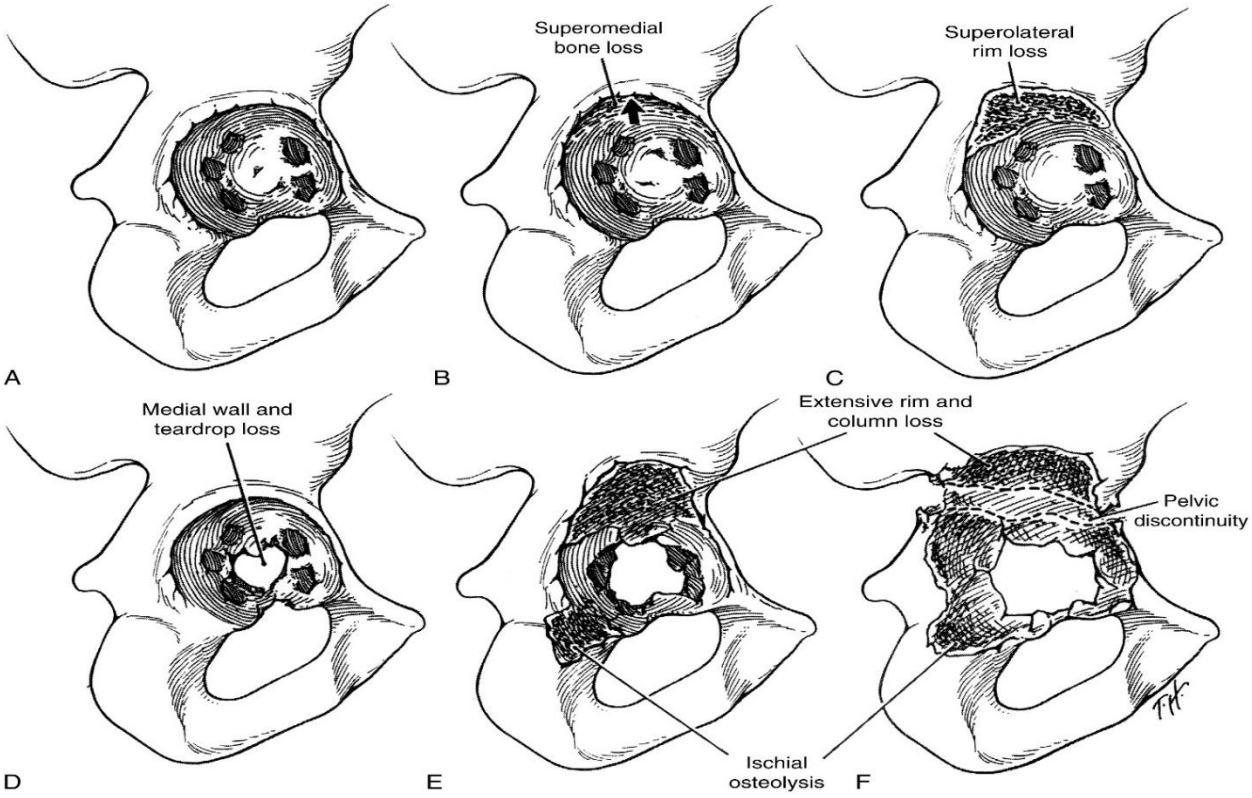


Figure 1: *Paprosky classification of acetabular defects: type 1, type 2a, type 2b, type 2c, type 3a, type 3b (source: Orthobullets)*

Paprosky classification offers a preoperative framework to assess the extent of bone loss and facilitate surgical planning, specifically regarding implant selection and the application of grafts or augmentations.

Type II defects typically allow for cementless fixing of hemispherical cups when there is at least 50% contact with host bone. Type III cases frequently necessitate the use of augmentations, cages, or custom implants.

Reliability may range from low to moderate, exhibiting intra- and interobserver variability even among seasoned surgeons; the implementation of instruction and defined protocols enhances consistency(39).

Table 1: Summary of the paprosky classification system for acetabular bone loss and corresponding surgical strategies

Paprosky type	Bone loss	Hip center migration	Columns supportive	Surgical implication
I	Minimal	None	Yes	Standard cup fixation
IIA	Moderate (medial)	Mild superomedial (<3 cm)	Yes	Possible cementless cup + augment
IIB	Superior rim loss	Mild superolateral (<3 cm)	Yes	Use of augments, jumbo cups
IIC	Medial wall loss	Medial (<3 cm)	Yes	Structural graft/lateralization
IIIA	Extensive rim loss	>3 cm superolateral	No	Cups + augments or cage constructs

IIIB	Global loss	>3 cm superomedial	No	Custom triflange or cup-cage

1.2.4 Orthopedic Oncology

Orthopedic oncology involves the diagnosis and treatment of primary bone and soft tissue cancers, along with metastatic malignancies affecting the musculoskeletal system. Primary bone tumors are uncommon, constituting less than 1% of all cancers(40). Osteosarcoma is the predominant malignant bone neoplasm in children and adolescents, exhibiting a yearly incidence of roughly 3–4 occurrences per million within the pediatric demographic(41).

Ewing sarcoma and chondrosarcoma follow in frequency, with Ewing sarcoma more prevalent in individuals under 20 years of age, while chondrosarcoma primarily affects adults over 40 years old(42). Benign bone tumors, including osteochondromas and enchondromas, are more commonly observed than malignant tumors, frequently identified accidentally during imaging conducted for unrelated issues(43).

Metastatic bone disease, however, is far more prevalent than primary bone malignancies and constitutes the most common type of skeletal cancer involvement. The primary malignancies that most frequently metastasis to bone include breast, prostate, lung, thyroid, and kidney carcinomas(44). These secondary lesions substantially increase morbidity through skeletal-related events, including pathological

fractures, spinal cord compression, and intense pain. The axial skeleton, especially the spine, pelvis, and proximal femur, is predominantly affected due to its abundant red marrow and arterial supply(45). The escalating worldwide cancer burden is anticipated to elevate the prevalence of metastatic bone disease, underscoring the increasing significance of orthopedic oncology in comprehensive cancer management.

Epidemiology and classification of pelvic bone tumors:

Pelvic bone tumors constitute a relatively rare yet clinically important category of musculoskeletal neoplasms. Pelvic bone tumors constitute a distinct and complex category of neoplasms, presenting considerable diagnostic and therapeutic difficulties owing to their deep anatomical location, proximity to neurovascular and visceral organs, and challenges in obtaining clear surgical margins. Comprehending their epidemiology and classification is crucial for precise diagnosis, treatment formulation, and prognosis evaluation.

The pelvis constitutes roughly 15–16.5% of all primary malignant bone cancers(46). In the pelvic region, malignancies are more prevalent than benign lesions among primary bone tumors; one study indicated that 62% of pelvic osseous tumors were malignant(47).

The most commonly observed histological subtypes of primary malignant tumors in the pelvis include chondrosarcoma, Ewing sarcoma, and osteosarcoma. Chondrosarcoma constitutes approximately 24% of pelvic cancers, rendering it the most prevalent, succeeded by Ewing sarcoma at approximately 16% and osteosarcoma at roughly 9%.

Other sarcomas, including fibrosarcoma and malignant fibrous histiocytoma (MFH), account for a minor proportion, approximately 5%. Globally, osteosarcoma constitutes approximately 20–40% of primary bone cancer cases, Ewing sarcoma accounts for less than 20%, and chondrosarcoma exhibits varied incidence, often representing around 30% of all bone sarcomas. This pattern underscores the prevalence of chondrosarcoma in the pelvic area, whereas osteosarcoma and Ewing sarcoma are more frequently observed in alternative anatomical sites(48).

Anatomical classification: Enneking–Dunham system:

The Enneking–Dunham system, established in 1978, is the most well recognized anatomical classification for pelvic bone cancers(49). This methodology categorizes the pelvis into zones according to surgical anatomy, facilitating oncological resection and reconstruction methodologies.

Type 1: Type I pertains to the ilium, characterized by tumors situated in the iliac wing. Resections are typically less complex because the ilium does not directly participate in hip joint function, and reconstruction is usually unwarranted until the tumor invades adjacent vital tissues like the sacroiliac joint.

Type 2: Type II pertains to the periacetabular area, which includes the acetabulum or hip socket, and is regarded as the most complex due to the essential function of the hip joint in weight-bearing and locomotion. Tumors in this region typically necessitate significant resection and intricate reconstruction methods, including prosthetic implants or biological reconstructions, to restore hip functionality.

Type 3: Type III encompasses malignancies of the pubis and ischium, which are less critical for load transfer, rendering resections comparatively uncomplicated and typically not necessitating rebuilding unless soft tissue or urogenital structures are affected.

Type 4: Certain modified classifications incorporate a Type IV to characterize cancers that infiltrate the sacrum or sacroiliac joint. These pose considerable surgical difficulties owing to their adjacency to critical neurovascular structures and their influence on pelvic stability.

Tumors may also span multiple zones, such as Type I+II or Type II+III, increasing the complexity of surgical management. Overall, the Enneking and Dunham classification provides a clear anatomical framework to guide the approach to pelvic tumor resection and the decision-making process for reconstruction.

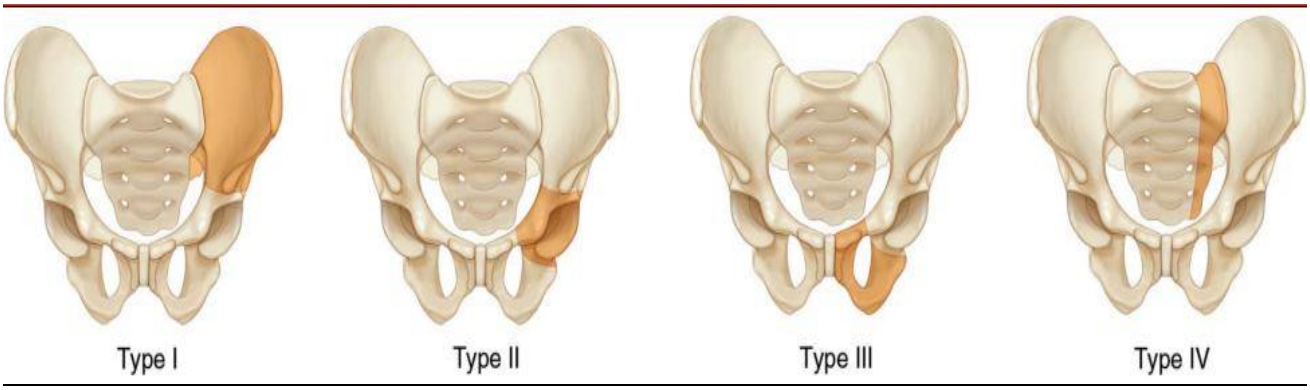


Figure 2: *Enneking and Dunham classification of pelvic resection. Type I involves the iliac wing, type II the periacetabular region, type III the pubic rami, and type IV the sacrum. (source : http://dx.doi.org/10.5435/ JAAOS-22-04-214)*

- Below Table 2 is demonstrating surgical challenges associated with each classification type.

Table 2: Enneking-Dunham classification of pelvic bone tumors

Type	Anatomical region	Structures involved	Surgical challenges
Type I	Ilium	Iliac wing, iliac crest	Close to sacroiliac joint, large surface area
Type II	Periacetabular region	Acetabulum, hip joint	Weight-bearing joint, reconstruction needed
Type III	Ischiopubic region	Ischium, inferior pubic ramus	Proximity to urogenital structures, obturator nerve
Type IV	Sacrum (occasionally included)	Sacroiliac joint, sacral ala	Neurovascular structures, spinal stability considerations

Note: Type IV (sacral region) is not included in the original classification but is used in some contemporary surgical oncologic frameworks

Clinical Relevance and Treatment Implications

Every pelvic region exhibits distinct anatomical and surgical factors. Resection techniques and functional reconstructions differ based on the tumor's location and type. Table 3 delineates surgical objectives and prevalent reconstructive techniques according to classification.

Table 3: *Surgical Approach and Reconstruction by Enneking Zone*

Type	Common tumor types	Surgical approach	Reconstruction options
Type I	Chondrosarcoma, Ewing's	Iliac wing resection	Often no reconstruction required if acetabulum preserved
Type II	Chondrosarcoma, Osteosarcoma	Periacetabular resection (Type II resection)	Endoprosthetic replacement, iliofemoral arthrodesis, custom implants
Type III	Ewing's, Plasmacytoma	Ischiopubic resection	Soft tissue reconstruction; functional impact usually minimal
Type IV	Chordoma, Ewing's	Sacrectomy (partial or total)	Lumbopelvic reconstruction, spinopelvic fixation

In Type II resections, restoring the weight-bearing acetabulum presents significant challenges and frequently necessitates the use of customized 3D-printed implants, saddle prostheses, or pelvic support osteotomies(50)

Type I and III tumors can be excised with generally preserved limb functionality, whereas Type IV tumors pose significant concerns of neurological impairments, pelvic instability, and possible bowel or bladder problems.

1.3 Objective and aims

Objective 1: To check the accuracy of AR-assisted reaming for large acetabular defects during revision total hip arthoplasty

Objective 2: To compare the accuracy of AR-assisted reaming with other standardized techniques. i.e., freehand method and patient-specific intrumentation reaming

Objective 3: To conduct a comparative evaluation of two AR HMDs, i.e., HoloLens 2 and Magic Leap 2, using patient-specific phantom in the context of orthopedic oncology.

This research project aims to explore the clinical applicability of AR in orthopedic surgery through three primary objectives. First, it evaluates the accuracy of AR-assisted reaming in managing large acetabular defects during revision total hip arthroplasty.

Second, it compares the precision of AR-guided reaming with established techniques, namely freehand reaming and patient-specific instrumentation.

Third, it undertakes a comparative assessment of two AR head-mounted displays; HoloLens 2 and Magic Leap 2, by analyzing their performance on patient-specific phantom in the context of orthopedic oncology.

2 Chapter 2 OBJECTIVE 1
ACCURACY OF AR-ASSISTED REAMING FOR LARGE ACETABULAR DEFECTS

2.1 Rationale and Objective

Although AR has been utilized in several orthopedic procedures, such as spinal navigation and implant placement, its application in acetabular reaming remains largely unexplored. Considering the significant risks associated with acetabular preparation and the challenges presented by large acetabular defects, assessing the precision of AR-assisted reaming is essential.

This chapter concentrates on the advancement and preclinical evaluation of an AR-based reaming navigation system. The main aim is to assess the angular and spatial precision of this AR-assisted method utilizing phantom model based on patient with Paprosky Type 3 acetabular abnormality. The research seeks to determine the feasibility of AR as an accurate, accessible, and efficient navigation instrument for acetabular preparation in complex revision THA cases.

2.2 Introduction

Total hip arthroplasty is a fundamental operation in orthopedic surgery for patients with severe hip disorders. However, its optimal outcomes depend on the precise restoration of hip biomechanics, especially through the appropriate positioning of the acetabular component(51, 52). Improper alignment during acetabular cup implantation has been linked to problems including premature loosening, restricted range of motion, dislocation, and the necessity for revision surgery(53). Therefore, reaming of acetabulum is a crucial surgical step in total hip arthroplasty for maintaining good implant stability and orientation(54).

Traditional reaming methods, predominantly executed freehand, depend significantly on the surgeon's expertise and the identification of anatomical landmarks. This method is prone to variability and frequently lacks precision, particularly in patients with compromised pelvic anatomy resulting from bone abnormalities, deformities, or prior surgical interventions. Consequently, technological enhancements that improve intraoperative visibility and precisely direct surgical instruments are essential for optimizing outcomes in THA.

Navigation systems and robotic help have been incorporated in surgical workflows to enhance surgical and functional outcomes(55, 56). These technologies utilize preoperative or intraoperative imaging to assist surgeons during the procedure, enhancing uniformity and precision. Nonetheless, constraints including expense, necessary infrastructure, radiation exposure, and significant learning curves have hindered their widespread implementation.

The application of AR has emerged as a potentially useful technique in this field. AR overlays digital content onto the surgeon's real-world view, providing real-time, spatially tracked surgical guidance(57, 58). This is achieved without altering the workflow or depending on external monitors. During essential tasks such as reaming during THA, this visual feedback facilitates a more natural and precise alignment. Moreover, the portability and ease of use of modern AR systems, such as Magic Leap 2, enhance the practicality of these technologies across diverse therapeutic environments.

Numerous research have established the viability and advantages of AR-assisted navigation in total hip arthroplasty. Ogawa et al. were pioneers in developing an AR navigation system aimed at facilitating acetabular cup placement and assessing angular orientation during surgery. Their method facilitated real-time display of intended trajectories, offering an intuitive and non-intrusive solution to enhance the precision of component alignment(59).

In a more rigorous clinical environment, Tanino et al. executed a randomized controlled experiment comparing a portable AR navigation system with the traditional freehand method. Their study indicated that the AR group attained markedly superior precision in cup location and angulation. This underscored augmented reality's potential to enhance surgical precision and standardize outcomes among operators(60).

Subsequent comparison analyses have evaluated the efficacy of AR navigation in relation to alternative technologies, including accelerometer-based systems. Accelerometer-guided navigation, however compact and economical, is prone to

calibration inaccuracies and may provide restricted intraoperative input. Conversely, recent research(61, 62) indicate that AR-based solutions offer improved visual context, facilitating more intuitive control and adjustment of implant orientation throughout the surgery. These data indicate that AR possesses a unique advantage in attaining perfect alignment and minimizing intraoperative ambiguity, especially in intricate anatomical situations.

In our experimental study, we designed and implemented a novel AR-based navigation system specifically tailored for guiding the acetabular reaming process in revision total hip arthroplasty. This system was developed to provide real-time visual feedback, enabling surgeons to align the reamer with a pre-defined optimal trajectory derived from preoperative planning. Using patient-specific 3D-printed pelvic phantom with complex Paprosky Type 3 defect, we conducted multiple reaming and cup implantation trials under AR guidance. After each procedure, we assessed the placement accuracy of the acetabular implant relative to the planned orientation and position. To precisely measure the angular and spatial alignment of the implanted prosthesis, we employed the NDI Aurora electromagnetic tracking (EMT) system, which allowed for real-time estimation of inclination and anteversion angles. Finally, we conducted a feasibility assessment of the AR system within a simulated operating room setting to evaluate its usability, stability, and potential for integration into standard surgical workflows.

2.3 Materials and Methods

2.3.1 Ethical approval and patient selection

Official ethical clearance for the study was accomplished by the Research Ethics Committee of the IRCCS Azienda Ospedaliero-Universitaria di Bologna. For the purpose of this research, one patient was chosen who had previously undergone total hip arthroplasty and presented with substantial acetabular abnormalities that were classified as Paprosky Type 3A. All of the procedural protocols were carried out in accordance with the ethical standards outlined in the Declaration of Helsinki (2013 revision), and the participant gave her agreement after receiving comprehensive and informed information. A complete anonymization of all identifying information was performed in order to guarantee the protection of patient privacy and confidentiality. Demographic and clinical information that was relevant to the study was systematically obtained and tabulated. This information included the patient's age, gender, body mass index (BMI), and a precise classification of the acetabular deformity.

Table 4. *Demographic data of patients from Orthopedic Department*

Age	Sex	BMI	Paprosky's Classification	Surgical Approach (Side)
73y	F	20kg/m^2	Type 3A	Posterior

2.3.2 Study design and setting

This study was aimed at assessing the effectiveness of AR-assisted reaming. The first emphasis was on the feasibility and technical execution of the AR system within a simulated surgical environment. Six experienced orthopedic surgeons with prior AR experience were enlisted to execute acetabular reaming procedures on patient-specific phantom model. The precision of each reaming procedure was documented with advance NDI Aurora (EM) Tracking system. Comparative analysis was done with optimal implant trajectories obtained from preoperative planning.

2.3.3 Pre-surgical planning

High-resolution computed tomography (CT) scans of a patient's pelvis was employed to create accurate 3D digital models for preoperative planning. The reconstructions were thoroughly assessed to analyze anatomical features, determine the presence and extent of bony anomalies, and formulate a customized surgical strategy. The planning approach encompassed many essential stages: segmentation of the pelvic and acetabular structures, thorough study of bone quality and defect morphology, and virtual positioning of implants in accordance with anatomical landmarks and biomechanical axes. Furthermore, ideal reaming parameters including trajectory and depth were meticulously planned to guarantee precise prosthetic alignment and joint functionality. The target orientation angles (inclination and anteversion) were predetermined as part of the design process. The completed surgical plan was then included into the AR system and used as the primary reference for intraoperative guidance during the acetabular reaming process.

***Table 5**: Planned inclination and anteversion*

Planned Inclination	Planned Anteversion
50^0	20^0

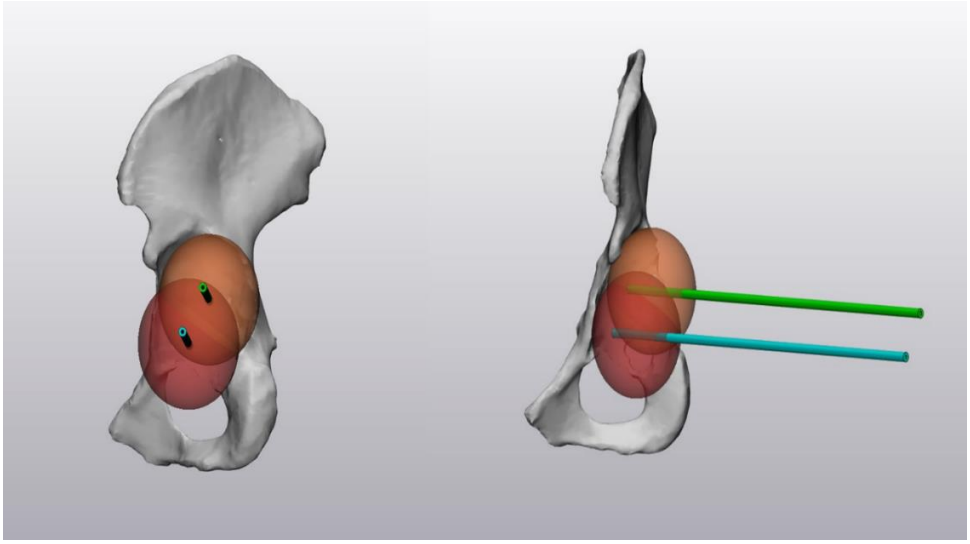


Figure 3: Pre-surgical Planning for Reaming

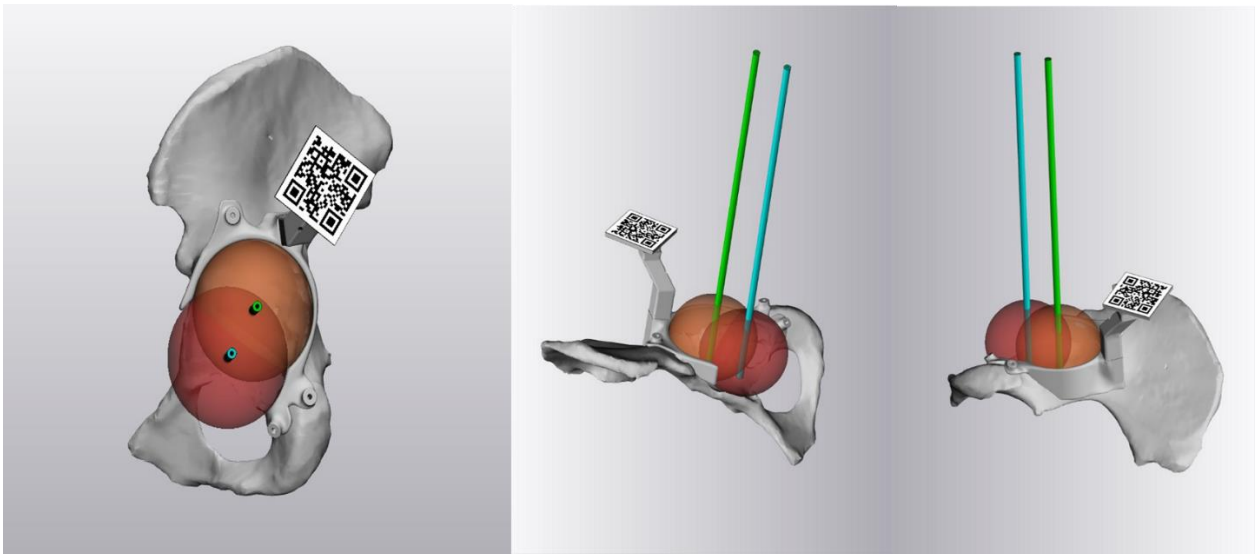


Figure 4: *QR code positioning for AR Guidance*

3D printing of phantoms and implants

Patient-specific pelvic phantom was produced using modern 3D printing technologies to enable experimental validation. Fused Deposition Modeling (FDM) was utilized to mimic the macrostructure of bone architecture, whilst Stereolithography (SLA) was employed to fabricate high-resolution components, including implants. The phantom was built with a stable base, guaranteeing structural integrity during manipulation. A modular, detachable acetabular portion was integrated to provide repeated surgical simulations without jeopardizing the integrity of the remaining model. Polylactic acid (PLA), a robust and lightweight polymer, was chosen to replicate acetabular removeable parts, while a biocompatible resin was utilized to manufacture the patient-specific instruments (PSI) and any necessary specialized instrumentation for the surgery. The modular design of the phantom models allowed for consistent replication of the experimental technique

and provided standardized testing across several trials, thus improving the reproducibility and dependability of the study results.

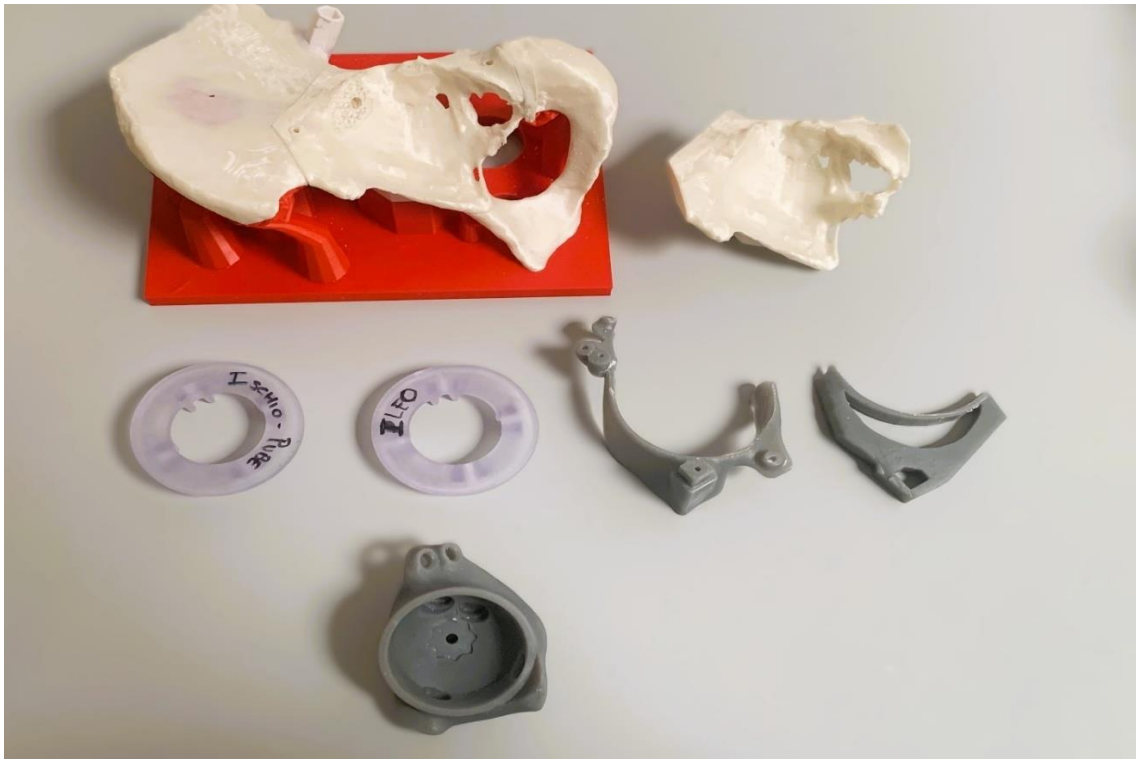


Figure 5: *3D printed phantom and Patient-specific Instruments (PSIs)*

2.3.4 Development of the Augmented Reality navigation system

The AR navigation system was developed using Unity (version 2022) as the platform, with C# as the principal programming language. The Vuforia Software Development Kit (SDK) was incorporated into the system to enable marker-based spatial tracking. The AR application was meticulously optimized for use on the Magic Leap 2 HMD, facilitating real-time visualization and projection of essential surgical components, such as the

patient-specific pelvic anatomy, designated acetabular reaming zones, and pre-established surgical alignment trajectories.

The registration process was conducted using a marker-based method that employed a printed or implanted fiducial marker. This strategy utilized the distinctive anatomical shapes and geometrical characteristics of the pelvic structure to attain accurate alignment between virtual models and the actual phantom. The stable overlay of virtual data onto actual anatomical structures guaranteed that the surgical guidance offered via the headset was precise and therapeutically pertinent, thus facilitating improved spatial awareness and intraoperative decision-making.

2.3.5 Protocol of surgical simulation

The surgical simulation aimed to assess the efficacy and precision of the AR-assisted navigation system during complex acetabular reaming operations. Orthopedic physicians engaged in simulated procedures, employing the AR-HMD to direct the orientation and trajectory of the reamer in alignment with preoperatively established surgical plans. The AR system displayed virtual alignment paths and anatomical landmarks directly in the user's visual field, facilitating accurate instrument alignment with reduced dependence on traditional imaging techniques.

The reaming simulation was organized into two separate phases, intended to mimic the anatomical intricacy commonly found in revision total hip arthroplasty scenarios with significant acetabular bone deficiencies:

Stage 1: Iliac Segment Reaming - Focused reaming of the superior-posterior acetabular area, predominantly affecting the iliac bone.
Stage 2: Ischial Segment Reaming - Targeted preparation of the inferomedial acetabular segment associated with the ischium.

Surgeons modified the reaming angle in real time at each stage, guided by visual feedback via the AR overlay. This input maintained alignment with the specified inclination and anteversion parameters set during preoperative preparation.
Multiple reaming iterations were conducted by surgeons to evaluate the system's resilience and dependability. This facilitated the assessment of procedure repeatability, performance consistency, and any potential variations due to user handling or system latency. The simulation elucidated the clinical viability of AR-assisted navigation in precisely executing surgical plans for complex acetabular defects.

2.3.6 Tracking and accuracy assessment

We employed the NDI Aurora electromagnetic tracking (EMT) system to assess the accuracy of implant placing in the surgical simulation, as it is a recognized method for high-resolution spatial localization. A compact electromagnetic sensor was firmly incorporated into a customized holder within the acetabular implant. This setup enabled real-time monitoring of the implant's spatial orientation and position post-placement.
The EMT approach was utilized to obtain two fundamental parameters critical for evaluating surgical precision:

Angular Alignment: The definitive measurements for acetabular cup inclination and anteversion were documented and compared with the intended surgical parameters. Linear Positional Deviation: The spatial displacement of the implant was quantified along the X, Y, and Z axes in relation to the preoperative digital model, facilitating a thorough assessment of translational inaccuracies.

The NDI Aurora system provides exceptional measurement integrity, featuring an angular resolution of ±0.4 degrees and a positional precision of ±2 mm. These requirements guarantee accurate measurement of angular deviations and positional inaccuracies, thus facilitating an objective evaluation of post-implantation surgical precision.

This monitoring method was efficient for confirming the efficacy of AR navigation and other methods for evaluating performance across each method and surgical variations.

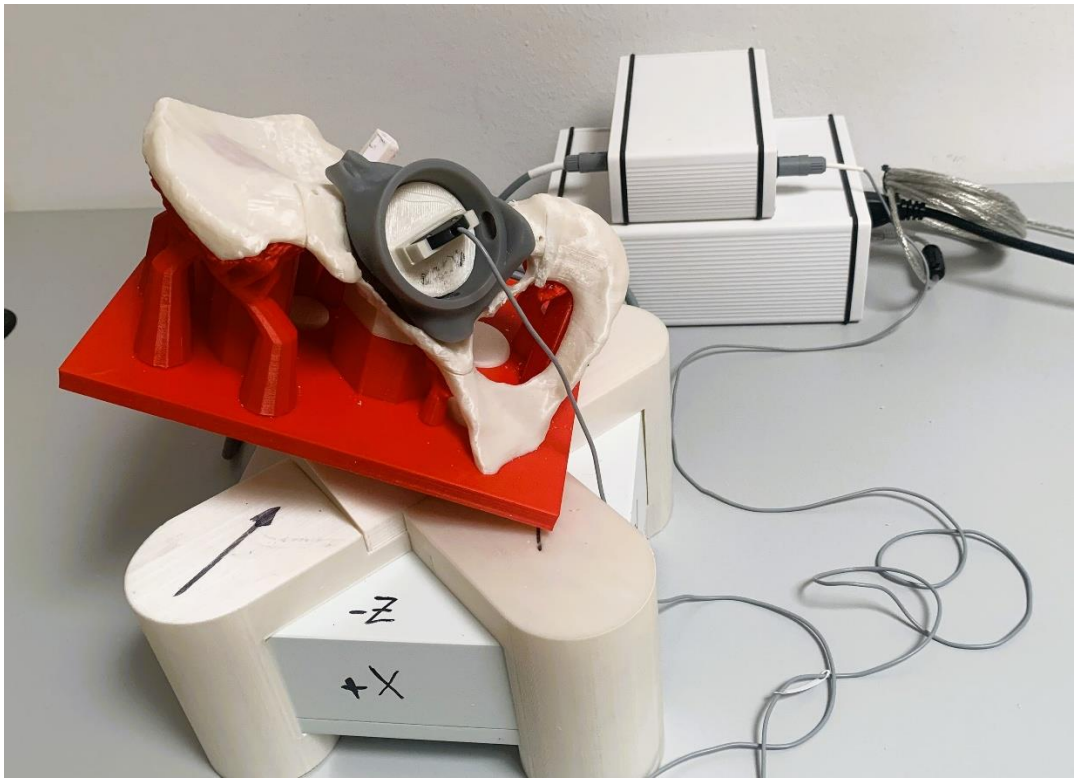


Figure 6: *NDI Aurora Tracking System for post-implantation measurement of inclination, anteversion and displacement along x,y and z axis.*

2.3.7 Intervention and evaluation

All experimental trials were performed by six orthopedic surgeons from our department, each of whom had prior experience with AR technologies. This ensured that the results reflected the performance of the AR system rather than variability due to operator unfamiliarity. Involving multiple surgeons also allowed assessment of inter-surgeon variability while maintaining consistency in overall expertise.

All AR-assisted procedures were conducted using the Magic Leap 2 headset with providence of real-time guidance while allowing surgeons to maintain constant focus on the operative field.

Beyond phantom-based experiments, feasibility of AR implementation in the operating room was also examined. Patient-specific pelvic phantom was used within a simulated clinical environment to replicate intraoperative conditions. This allowed evaluation of workflow integration, ergonomics, and stability of holographic projections under typical surgical lighting and movement.

In this study, outcomes were reported as mean inclination and anteversion angles, across all the experiments comparing it with pre-defined angular parameters (i.e., inclination and anteversion). Together, these metrics provided a comprehensive assessment of AR performance for reaming.

2.3.8 Statistical analysis

A one-sample t-test was employed to determine if the observed means significantly deviate from the expected values. A two-tailed p-value of less than 0.05 was deemed statistically significant. Statistical analysis indicated no significant difference between the intended and actual acetabular cup inclination and anteversion ($p>0.05$).

2.4 Results

The optimal orientation for acetabular cup implantation was established at 50° inclination and 20° anteversion. The AR- assisted reaming utilizing the ML 2 resulted in a mean inclination of 50.17° ± 3.37° and a mean anteversion of 20.43° ± 3.42°. A one-sample t-test indicated no statistically significant variation from the prior plan ($p > 0.05$) for both parameters. The data demonstrate that the AR-assisted system attained angular precision with very less deviation from the intended alignment, indicating superior reproducibility.

Table 6: *presents the mean achieved inclination and anteversion achieved with AR-guided reaming along with standard deviations*

	AR (Magic Leap 2)	
	Inclination	**Anteversion**
Mean	50.17333333	20.43166667
STD	3.374140878	3.424514077

The user-specific deviation analysis for acetabular cup positioning revealed that the AR-ML 2 attained values nearly corresponding to the preoperative plan. Inclination deviations varied from –4.19° to +5.26°, with four of six individuals exhibiting deviations

within ±3°. In a similar manner, anteversion deviations varied from -3.07° to +6.03°, with five out of six users obtaining outcomes within a 3° margin.

Table 7: shows the deviations in inclination across surgeons.

	Inclination					
	User 1	User 2	User 3	User 4	User 5	User 6
AR	-1.39	-0.35	2.90	-1.19	5.26	-4.19

Table 8: shows the deviations in anteversion across surgeons.

	Anteversion					
	User 1	User 2	User 3	User 4	User 5	User 6
AR	-0.70	-2.17	6.03	-0.43	2.93	-3.07

2.5 Discussion

In our study, we recruited a patient with a paprosky type 3 acetabular bone defect to evaluate the precision of AR-assisted reaming by analyzing post-implantation acetabular component's inclination and anteversion. The specified target orientation for

acetabular component placement was set at 50° of inclination and 20° of anteversion, based on preoperative planning parameters aimed at ensuring biomechanical stability and restoring native hip architecture. The accuracy of the AR-assisted technique was evaluated using the ML 2 headset, focusing on the deviation between the planned and actual orientation of the cup during simulated reaming and installation.

Total of six orthopedic surgeons with equal level of expertise performed experiments pre-clinically on patient-specific phantom to access its accuracy.

The minimal standard deviation recorded for both inclination (3.37°) and anteversion (3.42°) indicates a significant level of consistency and repeatability among users. This indicates that the AR interface offered intuitive and dependable navigation throughout the procedure. Despite a low sample size (n = 6), the consistency of results indicates the potential for reproducibility of the system in a wider clinical context.

Furthermore, the results indicate that most users successfully attained target alignment within the very good acceptable error margin of 3°, thereby validating the AR interface's efficacy in facilitating spatial orientation and real-time adjustments during the procedure. Only slight discrepancies were observed, perhaps indicating individual user adjustment to the AR visualization environment rather than constraints of the system itself.

The strong alignment between intended and actual values indicates that AR visualization successfully converts preoperative planning into intraoperative implementation. The integration of 3D hologrrams in the surgical area enhances spatial awareness, aiding the surgeon in accurately positioning the acetabular reamer and implant with little deviation. The precision of the ML 2, along with its portability and user-friendliness, highlights its potential as a significant complement to traditional surgical instruments.

Despite the limited sample number constraining the statistical power of the study, the lack of significant error trends and the restricted variation range collectively suggest a high level of accuracy and dependability for AR-guided reaming. The uniformity observed in trials indicates that the system may proficiently reduce human-induced variability that frequently leads to angular misalignment in freehand procedures.

2.6 Conclusion

In conclusion, AR-assisted reaming using the ML 2 exhibited clinically acceptable accuracy and consistency in attaining the intended acetabular cup position. The majority of users exhibited variances within the range of 3°, hence affirming the system's reliability and user-friendliness. The limited diversity among surgeons underscores its capacity to diminish human error and improve surgical precision. Inspite of the restricted sample size, the findings indicate that AR guidance can proficiently convert preoperative

planning into accurate intraoperative implementation. These findings endorse the incorporation of AR technology as a significant complement in THA procedures.

3 Chapter 3 OBJECTIVE 2

Comparative Analysis of AR-Assisted Reaming with Freehand and Patient-Specific Instrumentation Techniques

3.1 Rationale and Objective

This chapter aims to do a comparative assessment of reaming precision among three different procedures employed in THA: AR-assisted navigation, patient-specific instrumentation (PSI), and the traditional freehand approach. This study employs a defined in-vitro experimental framework to produce reliable and objective data, specifically to assess the clinical relevance of each technique in revision cases with significant acetabular abnormalities.

The study is specifically meant to:

Evaluate the angular and translational precision of acetabular component positioning for each method, referencing preoperative planning metrics, including inclination and anteversion angles, with spatial variation along the X, Y, and Z axes.

Assess the comparative merits and limitations of each procedure, considering variables such as user-friendliness, repeatability, adaptability to anatomical difficulties, and potential for incorporation into standard surgical workflows.

This investigation aims to develop a foundational understanding of the comparison between AR-based navigation and conventional approaches, as well as its potential to improve precision in intricate orthopedic treatments.

3.2 Introduction

THA is a commonly performed and highly beneficial orthopedic operation designed to restore hip functionality and minimize discomfort in individuals with degenerative joint disorders or injuries(63). The precise positioning of the acetabular component is a crucial factor in achieving favorable outcomes in THA. Accurate alignment is crucial for ensuring proper joint biomechanics(64), maximizing range of motion, decreasing the risk of impingement, and reducing the chances of postoperative dislocation or the need for early revision surgery.

Acetabular reaming is a crucial procedure for ensuring accurate orientation of the acetabular component, as it entails preparing the bone bed for the implant(65). The reaming procedure contours the acetabular cavity and establishes the trajectory, depth, and orientation of the ultimate cup positioning. Any departure at this phase; such as improper angulation or misaligned depth, can lead to a mispositioned implant. Such errors may jeopardize joint stability and function, potentially resulting in consequences such as atypical wear patterns, implant loosening, and the necessity for revision surgery.

To tackle these issues, various reaming procedures have been devised and are presently employed in clinical practice:

Freehand Reaming: This conventional technique depends on the surgeon's anatomical expertise, experience, and tactile perception. Although frequently employed for its ease

and adaptability, it is intrinsically subjective and prone to inter-operator variability, particularly in anatomically complex cases or modifications involving bone loss.

Patient-specific instrumentation (PSI) : PSI entails the utilization of custom 3D-printed guides tailored to the unique anatomy of each patient, as determined by preoperative imaging. These guides are designed to restrict and orient the reamer along a specified trajectory, hence enhancing reproducibility and precision(66). Nonetheless, the creation of PSI necessitates extra time for preoperative planning and guide manufacture, and once utilized intraoperatively, these tools exhibit inflexibility for real-time modifications in reaction to unexpected anatomical variations or intraoperative discoveries.

AR-Assisted Reaming: AR technology provides a digital layer of guidance by displaying virtual models and planned trajectories into the surgeon's visual field HMDs. In contrast to PSI, AR facilitates real-time intraoperative feedback, permitting dynamic visual alignment of the reamer with the preoperative plan while preserving the surgeon's manual dexterity. This integration of spatial awareness and adaptation signifies a possible method for improving surgical precision while maintaining workflow and equipment variety.

Comparative examination of reaming techniques in rTHA

Despite the therapeutic significance of precise acetabular reaming, comparative assessments of current technologies are insufficient, especially in revision total hip arthroplasty cases characterized by considerable bone loss or altered anatomy.

Freehand reaming, although common and effective in simple cases, is susceptible to variable results, particularly in complicated surgical situations. The technique is devoid of objective feedback and is mostly reliant on the surgeon's expertise, hence elevating the likelihood of alignment inaccuracies.

Conversely, PSI provides extensive preoperative customization and mechanical guidance, which numerous studies have demonstrated enhances alignment precision(67, 68). Nonetheless, its constraints regarding expense, time-consuming planning, and intraoperative inflexibility impede its broad implementation, especially in environments necessitating intraoperative adaptability.

Recent studies have increasingly established the efficacy of PSI in ensuring precise implant placement during THA surgeries(67, 69)

Chen Xi et al. created a constrained-type patient-specific guidance (PSG) system exclusively for acetabular reaming in a group of thirty THA patients. Their findings demonstrated that the application of PSI markedly improved the precision of implant placement in contrast to the conventional freehand method(70). The guides were constructed using comprehensive preoperative imaging, facilitating accurate alignment and depth regulation during reaming, hence reducing discrepancies from the intended component orientation.

These findings align with the existing literature(71) indicating that PSI can be a

beneficial complement in joint replacement surgery, particularly in intricate anatomical situations. The integration of 3D-printed models and customized guidelines enhances the surgical procedure's intuitiveness and reproducibility, minimizing intraoperative uncertainty and expediting the learning curve for trainee surgeons.

As described in the preceding chapter, multiple studies have evidenced the effectiveness of AR-assisted navigation in total hip arthroplasty (THA). Ogawa et al. developed an augmented reality navigation system to enhance acetabular cup alignment(72), whereas Tanino et al. validated its therapeutic advantages through a randomized controlled experiment, demonstrating greater accuracy than the conventional freehand technique(60). Moreover, comparisons with accelerometer-based systems(61, 62) indicated that augmented reality offers more intuitive, real-time visual input and enhanced intraoperative control, rendering it especially beneficial in complex anatomical situations.

3.3 Materials and Methods

3.3.1 Experimental framework

This study was designed as a controlled in-vitro inquiry employing patient-specific, 3D-printed pelvic phantom that simulated complex acetabular abnormalities, precisely categorized as Paprosky Type III A. This models was chosen to replicate clinically complex situations commonly faced during revision total hip arthroplasty.

The study was categorized into three experimental steps according to the reaming

technique utilized:

Step 1: Freehand reaming, directed exclusively by the surgeon's anatomical expertise and tactile perception.

Step 2: Reaming guided PSI, utilizing customized 3D-printed guides based on preoperative imaging and planning.

Step 3: AR-assisted reaming employs holographic projections to direct the reamer along the predetermined course in real time.

Each procedure was assessed by six independent trials conducted by six orthopedic surgeons possessing prior surgical experience. All procedures were conducted under standardized laboratory circumstances, utilizing a same set of surgical instruments and environmental characteristics to assure methodological consistency and remove external variability.

3.3.2 Reaming Protocol

Each reaming approach adhered to a specified protocol customized for its particular guidance modality:

Freehand Technique: Surgeons executed acetabular reaming solely based on their clinical acumen, anatomical understanding, and assessment of discernible bone landmarks. No external aids or navigation systems were employed, illustrating the

traditional approach typically utilized in standard clinical environments.

Patient-Specific Instrumentation (PSI): Reaming was performed via a customized, rigid guide fabricated via 3D printing, specifically created for each pelvic phantom according to preoperative imaging and surgical planning. The guide physically restricted the reamer, guaranteeing alignment with the predetermined orientation for both inclination and anteversion.

AR Guidance: Surgeons employed the Magic Leap 2 HMD to project a holographic overlay of the intended reaming trajectory onto the patient-specific phantom. Surgeons altered the orientation and depth of the reamer in real-time by aligning it with the virtual guidepath displayed in the headset's field of view, utilizing spatial signals from the AR system.

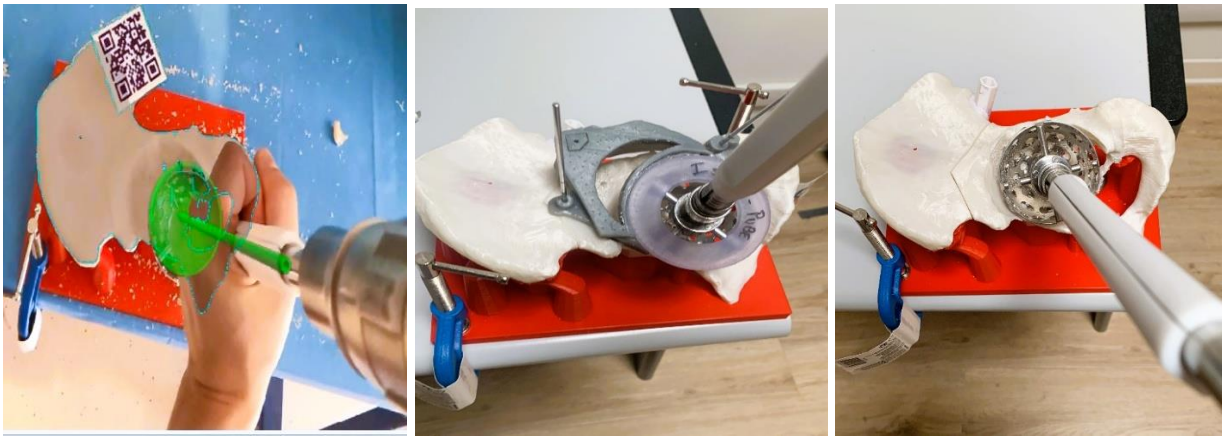


Figure 7: *shows AR guided, PSI guided and Free-hand method reaming on patient-specific phantom*

3.3.3 Phantom and PSI Manufacturing

High-resolution computed tomography (CT) scans were utilized for the segmentation and digital three-dimensional reconstruction of the pelvic anatomy. The reconstructions were utilized to create patient-specific pelvic phantoms utilizing polylactic acid (PLA) using fused deposition modeling (FDM), a prevalent 3D printing method for anatomical modeling as described in previous chapter.

Custom PSI was devised to enhance the PSI-guided reaming process. The PSI's comprised two principal components:

Acetabular Rim Guide: Designed to accurately match the distinct geometry of the acetabular rim, this guide provided secure anatomical fitting and reduced intraoperative displacement.

Reamer Handle Guide: This component is engineered to establish and preserve the desired orientation of the reamer, regulating alignment in accordance with preoperative planning criteria, including inclination and anteversion as well as depth of reaming..

Each guide was customized to the patient's anatomy to guarantee precise alignment, steady fixation during the treatment, and consistency of the reaming trajectory over several trials.

3.3.4 Implant Positioning and Tracking

Upon concluding the reaming process, a customized acetabular implant, crafted to align with the preoperative 3D plan, was implanted into the prepared acetabular cavity of each pelvic phantom. A small electromagnetic (EM) sensor was integrated into a designated slot within the implant structure to enable quantitative evaluation of implant location accuracy. The whole process was repeated as briefly described in previous chapter.

This integrated EM tracking system facilitated the accurate assessment of essential spatial characteristics, including:

Angular orientation: Inclination and anteversion angles, evaluated against preoperative objectives as well as reported for each reaming technique for comparison.

Positional accuracy: Linear discrepancies along the X, Y, and Z axes with relation to the intended implant position for each technique for comparison.

The data obtained from the EM sensor facilitated a precise assessment of surgical precision across various reaming techniques, thereby enabling a comprehensive comparative comparison.

3.3.5 Intervention and Evaluation

All experimental procedures were conducted by six orthopedic surgeons from our department, each of whom possessed prior experience in the use of AR systems. The study was designed in multiple phases to systematically evaluate the role of AR in acetabular preparation during revision THA. In the first phase, the AR-based navigation system was assessed for its capacity to guide reaming procedures with precision. The second phase involved a comparative analysis of three distinct reaming techniques: AR-assisted reaming, patient-specific guide (PSG)-assisted reaming, and the conventional freehand method. Each participating surgeon performed one trial with each technique, thereby ensuring balanced representation across methods. During every procedure, positional data were collected using the NDI Aurora EMT system, a high-fidelity tool capable of capturing angular and translational deviations with sub millimetric accuracy. To enable meaningful comparison, we determined that a 3^0 difference would be clinically meaningful which comparing all three techniques. The data from individual trials were averaged, and absolute error deviations were calculated for each technique. These calculations provided a quantitative measure of accuracy and allowed for a comprehensive evaluation of performance across the three approaches.

The final phase of the study focused on exploring the feasibility of AR-assisted reaming in an OR setting. This assessment was particularly important in establishing the clinical relevance and practical applicability of the proposed system.

All AR-guided trials were performed using the Magic Leap 2 headset, which facilitated real-time overlay of digital content onto the surgical field. Accuracy was evaluated by comparing the achieved implant orientation with the preoperative surgical plan.

Specifically, outcomes were expressed in terms of mean absolute error in inclination and anteversion angles, as well as translational deviations measured along the x, y, and z axes. Collectively, these metrics provided a detailed understanding of the precision, reproducibility, and potential clinical utility of AR-assisted techniques in comparison to established reaming methods.

3.3.6 Statistical Analysis

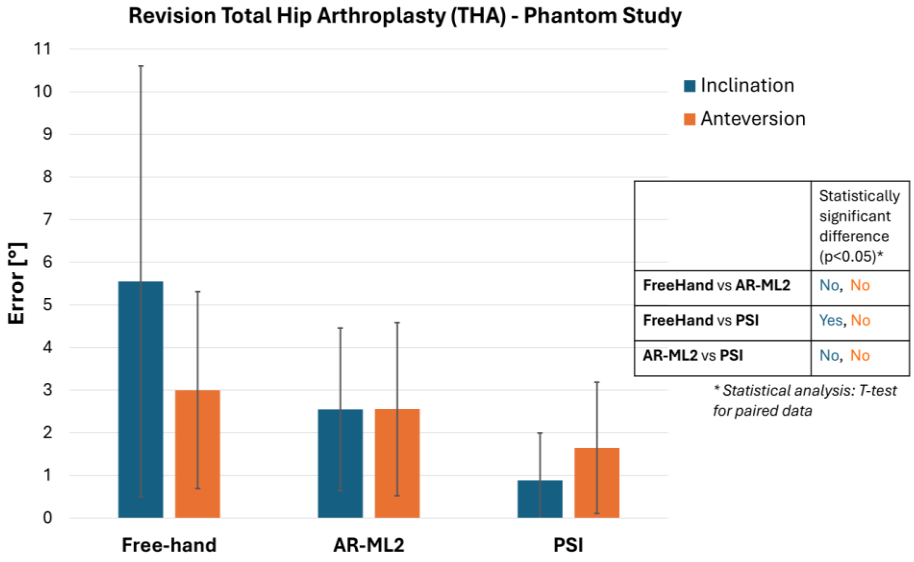
Continuous variables, specifically inclination and anteversion, were reported as absolute mean error values with their corresponding standard deviations and ranges. To determine whether significant differences existed between groups, paired t-tests were applied. A two-tailed p-value of <0.05 was considered statistically significant. In addition to angular accuracy, translational deviations along the x, y, and z axes were also assessed, enabling a comprehensive evaluation of both angular and spatial accuracy across the different reaming techniques.

3.4 Results

The phantom study evaluated the accuracy of acetabular cup placement in revision THA with large acetabular defects using three methods: free-hand, AR and PSIs. The key outcomes focused on orientation errors (inclination and anteversion), and positional errors. All measurements were derived from controlled phantom models, with statistical analyses performed using paired t-tests ($p < 0.05$ indicating significance). The following sections describe the findings.

Angular errors in acetabular cup placement

Bar Graph 1 presents the mean errors in inclination (blue bars) and anteversion (orange bars) for the three methods, along with error bars representing standard deviations (SD). The free-hand method exhibited the highest orientation errors, with a mean absolute inclination error of approximately 5.55° (SD ≈ 5.05°) and anteversion error of approximately 3° (SD ≈ 2.31°). In comparison, the AR-ML2 method showed reduced errors, with mean inclination of 2.55° (SD ≈ 1.91°) and anteversion of 2.55° (SD ≈ 2.03°). The PSI method demonstrated the lowest errors, with mean inclination of 0.88° (SD ≈ 1.11°) and anteversion of 1.65° (SD ≈ 1.54°).



Bar Graph 1: *represents the mean absolute error of inclination and anteversion of three techniques: Free-hand, AR and PSI along with statistical difference between them.*

Absolute Error [°]		
	Inclination	SD
Free-hand	**5.55**	5.05
AR-ML2	**2.55**	1.91
PSI	**0.88**	1.11

Table 9: shows the absolute error mean value of inclination of acetabular cup prosthesis with standard deviation of each reaming technique: Free-hand, AR and PSI

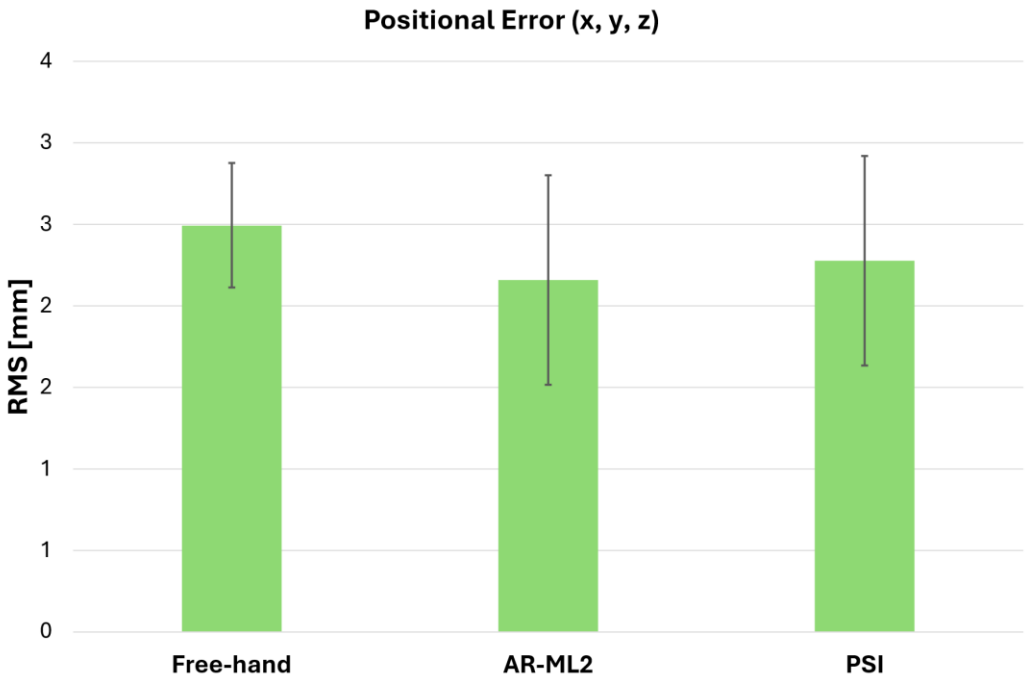
Absolute Error [°]		
	Anteversion	SD
Free-hand	**3.00**	2.31
AR-ML2	**2.55**	2.03
PSI	**1.65**	1.54

Table 10: shows the absolute error mean value of anteversion of acetabular cup prosthesis with standard deviation of each reaming technique: Free-hand, AR and PSI

These results indicate that AR and PSI significantly improved accuracy over free-hand preclinically, however, no statistical significant differences were observed in pairwise comparisons due to small sample size except in PSI versus freehand inclination.

Positional errors in acetabular cup placement

Bar graph 2 illustrates the root mean square (RMS) positional errors across the x, y, and z axes, measured in mm, for the three methods (green bars with SD error bars). The free-hand method had a mean RMS error of approximately 2.5 mm (SD ≈ 0.4 mm). Both AR and PSI methods showed lower errors, with mean RMS values of 2.16 mm (SD ≈ 0.6 mm) for AR and 2.3 mm (SD ≈ 0.6 mm) for PSI. No statistically significant differences were found among the methods.



NO statistically significant differences

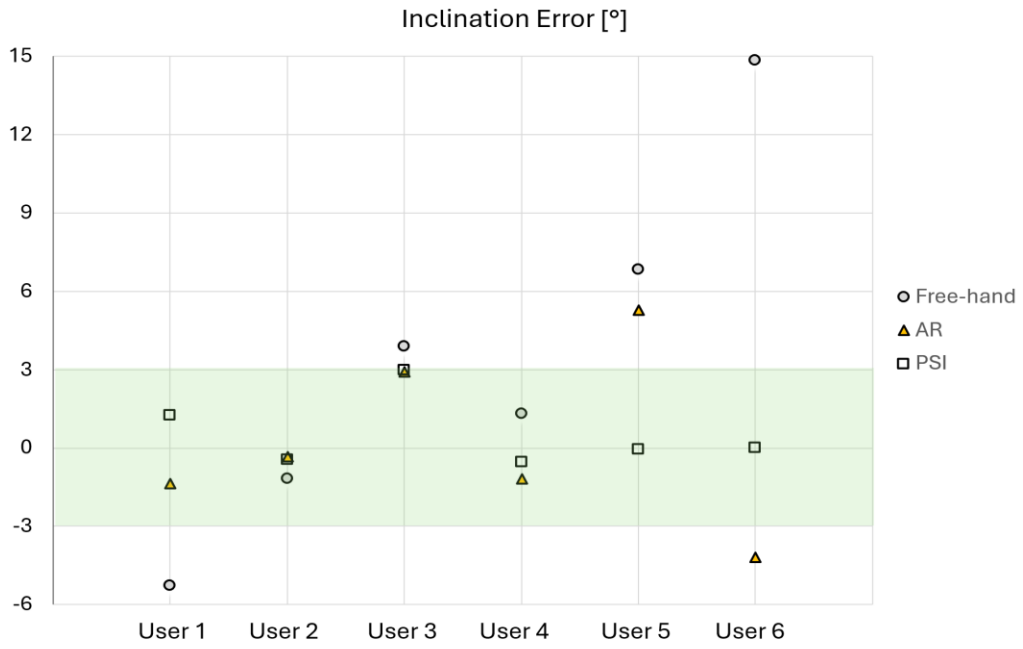
Bar Graph 2*: shows positional errors along x,y and z axis post-implantation with Free-hand, AR and PSI method*

Variability in inclination errors

Scatter plot 1 depicts the inclination errors (in degrees) for six individual users (surgeons) across the three methods: free-hand (circles), AR-ML2 (triangles), and PSI (squares). User-specific errors were identified and depicted across scattered plot. We identified 3° difference as the base value to identify the clinically meaning difference between techniques.

- Free-hand: Ranged from -5° to 15°, with several points outside the 3° zone.
- AR-ML2: Ranged from -4.19° to 5.26°, with most points within or near the safe zone.
- PSI: Ranged from -0.6° to 2.96°, with all points clustered tightly and predominantly within the 3° zone.

This variability underscores user-dependent inconsistencies in free-hand placement, with AR-ML2 and PSI offering more consistent performance across users.



***Scatter plot 1**: depicts the inclination errors across users with each reaming technique*

	Inclination					
	User 1	**User 2**	**User 3**	**User 4**	**User 5**	**User 6**
Free-hand	-5.30	-1.19	3.89	1.29	6.81	14.83
AR	-1.39	-0.35	2.90	-1.19	5.26	-4.19
PSI	1.24	-0.47	2.96	-0.55	-0.08	0.00

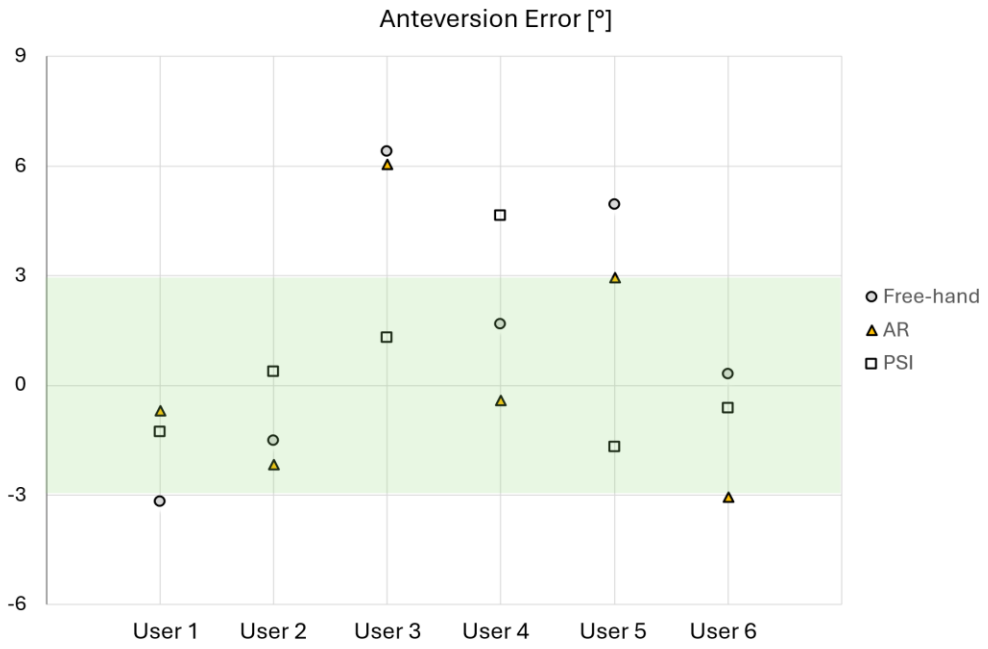
Table 11: presents the inclination error recorded for each participant following the completion of each reaming techniques

Variability in anteversion errors

Scatter plot 2 shows the anteversion errors for the same six surgeons, using identical symbols and 3° as identified clinically significant difference between each technique.

- Free-hand: Ranged from -3° to 6°, with outliers.
- AR-ML2: Ranged from -3° to 6°, with tighter clustering around 0° for several users (e.g., Users 1 and 4 near 0°).
- PSI: Ranged from -1.6° to 4.6°, with most points within 3° zone and minimal spread.

Overall, anteversion errors exhibited less user-to-user variation and errors compared to inclination, with AR and PSI again demonstrating superior accuracy over free-hand.



Scatter plot 2: *depicts the anteversion errors across users with each reaming technique*

	Anteversion					
	User 1	**User 2**	**User 3**	**User 4**	**User 5**	**User 6**
Free-hand	-3.21	-1.52	6.39	1.65	4.94	0.29
AR	-0.70	-2.17	6.03	-0.43	2.93	-3.07
PSI	-1.30	0.36	1.28	4.62	-1.69	-0.63

Table 12: *presents the inclination error recorded for each participant following the completion of each reaming techniques*

3.5 Discussion

Precise acetabular reaming constitutes one of the most critical steps in revised THA specially with large acetabular defects, as it ensures that the acetabular prosthesis is implanted in accordance with the preoperative plan. Proper reaming not only guarantees a stable and congruent bone bed for the cup but also reduces the likelihood of malpositioning, which is one of the major contributors to postoperative complications and poor clinical outcomes. For this reason, the surgical community continues to investigate advanced methods and technologies that can optimize acetabular preparation.

In the present study, we compared three reaming modalities: PSI reamers with guides, and the conventional freehand technique. Each technique was assessed for its ability to achieve accuracy relative to the planned acetabular orientation, with the aim of identifying strengths and weaknesses in terms of reproducibility, clinical feasibility, and precision.

Numerous studies have sought to overcome the challenge of ensuring consistent accuracy in acetabular preparation. Tanino et al., in a prospective randomized controlled trial, demonstrated that accelerometer-based navigation significantly improved the accuracy of cup placement when compared to the conventional freehand method(73). In contrast, Pagkalos et al. reported that navigation-assisted reaming did not significantly enhance accuracy compared with the conventional freehand approach, indicating that the added time and complexity of such systems may not always provide clinically meaningful benefits(74).

The present study demonstrated clinically relevant improvements in post-implantation acetabular cup placement accuracy, achieving mean inclination and anteversion errors of less than 3° with both AR-assisted and PSI-assisted reaming techniques. Whereas, with freehand reaming the absolute mean error angles are more than 3°.

The drawback of many conventional navigation systems lies in their reliance on intraoperative imaging, particularly fluoroscopy, which exposes both patients and surgical teams to repeated doses of ionizing radiation. In response, the development of portable navigation systems has been prioritized as a means of reducing radiation exposure while maintaining or improving accuracy. This is the context in which AR-based navigation has emerged as a highly promising alternative, combining intuitive visual overlays with intraoperative flexibility and reduced dependence on radiation(73, 75).

Two parameters, namely inclination and anteversion are universally recognized as pivotal in determining the quality of THA. Malposition in either of these parameters predisposes patients to dislocation, instability, and implant impingement. Excessive inclination may lead to under-coverage of the hip component, mimicking iatrogenic developmental dysplasia of the hip (DDH). Conversely, insufficient inclination increases the risk of femoroacetabular impingement syndrome (FAI) during abduction.

Clinically, an inclination range between 40° and 45° has been proposed as the optimal target(76).The generally accepted “safe zone” for anteversion is between 15° and 20°. These parameters collectively define the Lewinnek safe zone, which has long served as a benchmark for cup orientation. However, recent studies have questioned its absolute

validity, highlighting variability in patient-specific anatomy and pelvic mobility specially in complex cases such as large acetabular defects.

Advances in robotics and 3D planning have significantly contributed to the refinement of acetabular preparation techniques. Walker et al. pioneered the use of minimally invasive robotic reaming systems to create an optimal hemispherical bone bed, reporting improved accuracy relative to manual reaming(65).In subsequent studies, the same group recommended robotic burring systems over both robotic reaming and conventional freehand approaches, citing superior control and precision in preparing the acetabulum(77)

Similarly, randomized controlled trials evaluating 3D preoperative planning combined with PSI have demonstrated superior accuracy in achieving target acetabular anteversion compared to conventional freehand techniques(66). PSI offers the advantage of constraining reaming trajectories using custom guides, ensuring that the final implant closely aligns with preoperative planning. However, PSI is limited by logistical challenges, for instance, the production of a guide for a single patient often requires 3 to 8 weeks, which reduces its practicality in cases requiring urgent revision surgery.

AR-assisted navigation offers a hybrid solution that integrates the strengths of preoperative planning with the flexibility of real-time intraoperative adaptation. AR overlays allow the surgeon to visualize the planned reaming trajectory and depth directly on the surgical field via a head-mounted display, such as the Magic Leap 2. AR maintains full manual control of the reamer while providing continuous digital guidance.

This facilitates immediate intraoperative adjustments and preserves natural surgical ergonomics.

Another study demonstrated the use of CT_based AR naviagtion for cup placement and pelvic motion. Naito et al. demonstrated that AR-based navigation significantly improved acetabular cup placement accuracy, even under conditions of progressive pelvic motion in the lateral decubitus position, which typically complicates intraoperative alignment(78). Such findings underscore the adaptability of AR systems to real-world intraoperative challenges.

While this study did not assess the impact of pelvic tilt due to its preclinical nature, it is well established that intraoperative changes in pelvic position can profoundly affect acetabular orientation. AR has the potential to mitigate these variations by providing continuous visual guidance relative to anatomical landmarks. Moreover, the integration of advanced tracking systems, such as the NDI Aurora electromagnetic tracker, enables high-fidelity measurement of inclination and anteversion angles in real time, providing both navigation support and quality control.

3.6 Conclusion

In summary, the phantom study results highlight that both AR and PSI methods reduced orientation and positional errors relative to free-hand. Eventhough, we are short of to get statistical significant results due to small small size but we can see the clinical significant results by achieving mean absolute error of less than 3°. Individual user data

further reveal reduced variability with technology-assisted methods, suggesting potential for improved reproducibility in clinical settings.

4 Chapter 4 OBJECTIVE 3

Comparative evaluation of HoloLens 2 and Magic Leap 2; using Patient-specific Phantom in the context of Orthopedic Oncology.

4.1 Rationale and Objectives

Orthopedic oncology is a specialization that continually confronts the dual problem of maintaining significant oncological margins while maximizing functional preservation. Attaining this challenging equilibrium is especially vital in pelvic and extremities bone cancers, where complex 3D anatomy impacts both preoperative planning and intraoperative implementation. Despite advancements in imaging and navigation, a significant risk of positive margins and subsequent local recurrence remains. Emerging technologies like AR provide the potential to close this gap by incorporating preoperative imaging data directly into the operating environment.

Various AR devices, like the Microsoft HoloLens 2 and Magic Leap 2, have been launched for surgical navigation. Although HoloLens 2 has been more thoroughly examined in medical literature, the Magic Leap 2 is a more recent technology that provides an expanded field of view, enhanced optics, and superior hardware, potentially rendering it more appropriate for surgical malignancies applications. Nonetheless, a thorough and direct comparison between these two devices is absent.

The major aim of this study was to conduct a direct comparison between Magic Leap 2 and HoloLens 2 using patient-specific phantom models in orthopedic oncology. The study specifically aimed to evaluate the precision of AR-assisted surgical resections and to examine ergonomic parameters pertinent to intraoperative application. This study aimed to generate standardized patient-specific phantoms using clinical data to yield

reproducible insights on the performance of each device in a controlled experimental environment.

4.2 Introduction

In surgical context, AR is characterized by the real-time blending of digital information, such as 3D reconstructions, anatomical overlays, and surgical guides, into the user's actual surroundings. In contrast to virtual reality (VR), which fully immerses the user in a digital environment(79), AR augments the surgeon’s inherent perception by superimposing computer-generated models over actual anatomy. The technology has progressed from initial smartphones and tablet-based AR to advanced HMDs that feature gesture detection, eye tracking, and interactive holographic visualization(80).

The primary benefit of AR in surgery is its capacity to convert preoperative planning into intraoperative assistance. Surgeons can concentrate on patient-specific anatomy, surgical margins, and trajectories within the operational field, eliminating the need to divert attention to external monitors, as is typical with navigation systems.

Consequently, AR has been swiftly integrated into numerous surgical specialties, with significant applications in neurosurgery(81), urological surgery(82), cardiovascular surgery(83), spine surgery(84), breast surgery(85), gastrointestinal and hepatic surgery(86, 87), as well as orthopedic surgery, and cranio-maxillofacial surgery(57).

In neurosurgery, AR has been utilized to visualize cortical and subcortical regions within the operative area, facilitating tumor resections, aneurysm clipping, and functional

mapping procedures(88). In urological surgery, AR has enabled minimally invasive procedures, such as robot-assisted partial nephrectomy, where accurate identification of renal malignancies in relation to vascular anatomy is essential for nephron-sparing techniques(89). Cardiovascular surgeons have utilized this technology to strategize and perform complex congenital heart repairs, where holographic representation of patient-specific anatomy has demonstrated significant value(90). The spinal surgeons have used it, especially for pedicle screw placement, showing enhanced precision relative to conventional fluoroscopy-guided techniques(91) . In breast surgery, AR has facilitated tumor localization and oncoplastic resections(92), whereas in gastrointestinal and hepatic surgery, AR-based overlays of vascular systems and parenchymal lesions have enhanced the safety of resections and increased oncologic clearance(93). In cranio-maxillofacial surgery, AR aids with orthognathic operations, trauma reconstruction, and tumor resections, where precision to the millimeter is essential(94).

Orthopedic surgery, particularly orthopedic oncology, is a domain where augmented reality may possess significant potential. Bone cancers frequently occur in anatomically intricate areas, such as the pelvis or proximal femur, where obtaining oncologically safe boundaries while maintaining limb functionality is very difficult. The principal oncological issue in these resections is the potential for positive surgical margins, which has been consistently associated with increased rates of local recurrence and poorer long-term survival (95). Conventional intraoperative methods for margin management depend significantly on the surgeon's anatomical expertise, tactile perception, and fluoroscopic validation; yet, even among skilled practitioners, these techniques possess intrinsic limits.

Meticulous preoperative planning is required to mitigate these problems(96). Latest software facilitates the segmentation of tumors from CT and MRI scans, the generation of patient-specific 3D models, and the virtual construction of osteotomy planes. Nonetheless, converting these meticulously designed virtual designs into practical application is not simple. AR technology, particularly HMDs, have the capacity to function as a direct conduit, offering real-time intraoperative guidance that overlays projected tumor borders, resection planes, and anatomical landmarks immediately within the surgeon's visual field.

Numerous innovative studies have investigated the use of AR in orthopedic oncology, revealing feasibility and encouraging precision. Molina et al. utilized the Augmedics XVision system to assist with osteotomy and pedicle screw placement for a patient with lumbar chondroma, demonstrating enhanced spatial orientation during resection(84). García-Sevilla et al. emphasized the efficacy of augmented reality in pelvic tumor resections with the Microsoft HoloLens 2, wherein augmented reality visualization aided in the identification of safe margins and placement of PSI in an area characterized by complicated three-dimensional anatomy (97). Moreta-Martínez et al. expanded their research to a patient-specific phantom model of Ewing's sarcoma, assessing the precision of the AR-assisting intervention and indicating its role in resections aligned more closely with the preoperative plan than traditional techniques(98). Pose-Díez-de-la-Lastra et al. did a comparative evaluation of HoloLens 1 and HoloLens 2 in the context of tumor resections of the upper and lower extremities. Their findings indicated enhancements in visualization quality and surgeon ergonomics with the second-generation technology(80).

Regardless the increasing advancements in AR technologies, the majority of the current literature in orthopedic oncology has concentrated on the Microsoft HoloLens. Although the second-generation HoloLens has been validated in surgical research, it possesses specific limitations that may hinder its wider clinical application.

Recent head-mounted displays, including the Magic Leap 2, have been engineered to address certain constraints. Preliminary results indicate that this device may enhance visualization and increase user comfort, potentially rendering it more appropriate for surgical environments that need high precision and prolonged focus. However, thorough comparison analyses of the HoloLens 2 and Magic Leap 2 in orthopedic oncology are limited.

This study aimed to provide a direct comparison between Microsoft HoloLens 2 and Magic Leap 2, employing patient-specific phantom of pelvic bone tumor as a validated model for preclinical surgical assessment. Pelvic phantoms were selected due of the pelvis's well-known anatomical intricacy, its frequent location during oncological resections, and the critical need of obtaining negative margins in this area.

Our experimental design concentrated on three primary aspects. Initially, we evaluated surgical precision, characterized as the discrepancy between preoperatively planned osteotomies and the actual resections performed by surgeons utilizing AR guidance. Secondly, we assessed the technical differences of both devices. This was accomplished by quantifying the discrepancy between various technical aspects required for the system’s robustness to perform complex surgical tasks. Thirdly, we also

conducted an ergonomic survey among participating surgeons, assessing headset weight, comfort, range of view, visualization clarity, eye strain, and ease of intraoperative engagement. The study sought to deliver a thorough assessment of each device's therapeutic appropriateness by integrating both objective accuracy measurements and subjective usability evaluations.

In conclusion, augmented reality has exhibited considerable potential across several surgical fields, with its use in orthopedic oncology being particularly encouraging due to the critical need for precision in tumor excisions. Prior research has confirmed the viability of AR-guided surgery with the HoloLens series; nevertheless, these technologies still exhibit limitations. The advent of the Magic Leap 2 necessitates an evaluation of its capacity to address current issues and offer a more dependable platform for AR integration in orthopedic oncology. This research aims to provide inaugural systematic evidence for the therapeutic application of AR technologies in oncologic bone surgery by directly comparing Magic Leap 2 with HoloLens 2 in a controlled phantom-based investigation as well as technical differences.

4.3 Materials and Methods:

4.3.1 Patient selection and their clinical data:

This study focused on clinical case of patient diagnosed and treated for malignant bone tumor at the Department of Orthopedics, IRCCS Azienda Ospedaliero-Universitaria di Bologna. The selection of this patient was determined by precise criteria: a confirmed

diagnosis of primary bone malignancy, tumor placement inside the pelvis necessitating complex surgical excision, and eligibility for preoperative imaging and three-dimensional (3D) reconstruction (elective surgery).

To maintain patient confidentiality, participant was allocated a distinct anonymized case identification. All identifying information, including name, hospital identifier, and personal health data, was eliminated prior to data processing. Ethical issues were meticulously adhered to, with the study protocol sanctioned by the Institutional Review Board and Ethics Committee of the hospital. Informed consent was secured from patient before inclusion, in accordance with the principles established in the Declaration of Helsinki (1975, updated 2013). The permission process encompassed comprehensive elucidations of the study aims, the utilization of anonymized clinical data, and the creation of patient-specific 3D printed phantoms solely for research reasons.

The demographic and clinical information of the patient participating in the trial is displayed in Table 13. Patient age, gender, anatomical site, and tumor dimensions were documented. This data was deemed crucial for comprehending the complicated anatomy of the resections and for creating representative phantoms for experimental assessment.

The patient exhibited an chondrosarcoma affecting the ilium, requiring extensive resection to secure negative surgical margins. For that, preoperative computed tomography (CT) imaging provided the foundation for digital segmentation and phantom construction, which underpinned the AR evaluation process.

The study attempted to establish realistic surgical settings, allowing for rigorous testing and comparison of the two HMD's under investigation using AR-based guidance.

Table 13: *Clinical data of patient from Orthopedic Department*

Age	Sex	Type of tumor	Anatomical Region	Tumor Size
48 y	F	osteosarcoma	Iliac	9.1 cm × 2 cm × 5.5 cm.

4.3.2 Process of Data acquisition and Phantom Development

The creation of patient-specific surgical phantoms for this investigation adhered to a systematic approach that commenced with the procurement of high-resolution medical imaging data. Preoperative computed tomography (CT) scans were acquired, utilizing a slice thickness of 0.5 mm to guarantee optimal information for future segmentation. The thin-slice capture facilitated the generation of precise 3D models, essential for reproducing the complex anatomical structures.

The DICOM data from the CT scans were imported into Mimics 20.0 software (Materialise, Leuven, Belgium), where segmentation of bony structures and neoplastic lesions was conducted. Segmentation entailed the extraction of pertinent anatomical regions from adjacent tissues by a synthesis of thresholding, region growth, and manual editing techniques. This stage was crucial for generating a realistic digital depiction of

both the natural bone and diseased tissue, establishing the basis for later modeling and surgical planning.

Subsequent to segmentation, the reconstructed 3D models were exported as stereolithography (STL) files, a conventional format for 3D printing and computer-aided design (CAD) processes. The STL files underwent additional processing in 3-Matic software (Materialise, Leuven, Belgium), where enhancements like smoothing, mesh correction, and the incorporation of surgical planning tools were executed. Surgical planes corresponding to the intended resection margins were developed within the CAD environment. Furthermore, virtual surgical guides were developed, tailored to conform accurately to the patient's osseous structure. These guides were designed to emulate intraoperative instruments that offer reference during bone cutting procedures, hence simulating authentic surgical techniques within the phantom model. For preclinical study like this, surgical guides with groves of 1mm, 2mm and 3mm was designed to access the accuracy AR assisted simulated resection for both devices.

QR-code-based markers were integrated into the workflow to enhance AR navigation through automatic registration and tracking. Marker-based registration was chosen for its reliability when utilized with hard bony structures, which offer stable reference points for both phantom evaluation and prospective clinical application. The markers were structured with uniform size (5cmX5cm) to guarantee reliable recognition by AR devices. A customized holder was employed to affix the tracking marker directly onto a designated region of the phantom's osseous surface. The surgical team established the precise location of marker placement, considering the operating strategy, patient

positioning, surgical angles, and the necessity of maintaining an unobstructed line of sight for the surgeon utilizing the AR headset.

Upon completion of virtual planning, the finalized digital models, encompassing both tumorous bone segments and patient-specific surgical guidance, were exported for additive manufacture. Phantoms were constructed via Formlabs 3 stereolithography printers (Formlabs Inc., Somerville, MA, USA) with a photopolymeric white resin. This material was chosen for its superior resolution and mechanical stability, enabling accurate reproduction of intricate anatomical details essential for surgical simulation. The phantoms were designed just for in-vitro experimental study, thereby eliminating the necessity for biocompatible resins like BioMed resin and the implementation of sterilization procedures.

The combination of CT imaging, sophisticated segmentation, CAD modeling, and 3D printing facilitated the development of very realistic phantoms that mirrored patient anatomy and surgical situations. These models established the basis for assessing the projection accuracy of AR overlays, offering a controlled and reproducible setting for the direct comparison of the two examined HMD's through simulated resection lines markings.

4.3.3 Development of AR application

The development phase of the AR application adhered to a systematic methodology aimed at guaranteeing functionality, usability, and repeatability across the examined HMD platforms. The application was developed utilizing Unity (version 2022.3.9f1, Unity

Technologies, San Francisco, USA), a prevalent platform for augmented reality and virtual reality innovation. The programming was executed in C#, facilitating modular coding and the integration of interactive features specific to surgical needs. The project was meant to ensure interoperability with both the Magic Leap 2 and Microsoft HoloLens 2, facilitating a systematic comparison of device performance under identical testing conditions.

The Vuforia Engine 10.20 (PTC Inc., Boston, USA) was included into the Unity environment for tracking and registration purposes. Vuforia is a computer vision-oriented software development kit (SDK) that facilitates the detection of specified visual markers, namely a unique QR-code pattern. This marker-based methodology enabled the AR system to consistently recognize and align the patient-specific phantom with the relevant virtual representations. Registration between the virtual and physical realms was accomplished via pre-determined spatial coordinates, guaranteeing precise alignment of holographic content with the anatomical surfaces of the phantom. This marker-based tracking was chosen for its durability, repeatability, and appropriateness for bone-related applications, where solid and stable structures reduce the likelihood of misalignment.

The AR interface was deliberately crafted to furnish surgeons with a transparent, intuitive, and interactive environment. The application facilitated the visualization of numerous critical components, including (i) the defined normal bone, (ii) the tumor volume with a defined contour to highlight margins, and (iii) the pre-established resection planes. Each element can be toggled independently, granting the user

complete control over the displayed visual information. This targeted visualization aimed to replicate actual intraoperative requirements, wherein surgeons must concentrate on particular structures devoid of visual distractions.

Interaction with the holographic components was facilitated via gesture-based controls included into the HMD systems. The surgeon utilized basic hand gestures to maneuver through menus, choose anatomical layers for display, and modify visualization settings instantaneously. This hands-free contact was essential for preserving sterility and enabling the surgeon to operate without disruption during the experimental assessment.

The application provided the display of resection lines projected directly into the phantom model, in addition to static overlays. The holographic lines provide real-time direction, enabling the surgeon to adhere to the predetermined trajectory with accuracy. This technique duplicated the desired therapeutic benefit of augmented reality in oncological bone surgery, where precise delineation and compliance with resection margins are critical in minimizing the likelihood of positive margins and recurrence.

4.3.4 Evaluation of AR

The implementation of AR in surgical disciplines requires rigorous evaluation to establish its feasibility, reliability, and precision in replicating complex surgical maneuvers. In orthopedic oncology, accuracy is paramount to ensure that osteotomies align with preoperative plans, thereby minimizing complications and enhancing surgical outcomes. To assess the performance of the developed AR system, we designed an in-vitro study employing patient-specific pelvic phantoms and 3D-printed templates. This

methodology enabled controlled evaluation of AR-guided osteotomies in terms of reproducibility and accuracy.

To evaluate accuracy of both devices, three osteotomy planes; right, left, and horizontal were defined for iliac tumor (Fig. 7). These planes represented the critical resection lines required to perform oncologic resections or corrective osteotomies with precision. Each planned cut was subsequently superimposed onto the pelvic model to create reference templates for surgical execution.

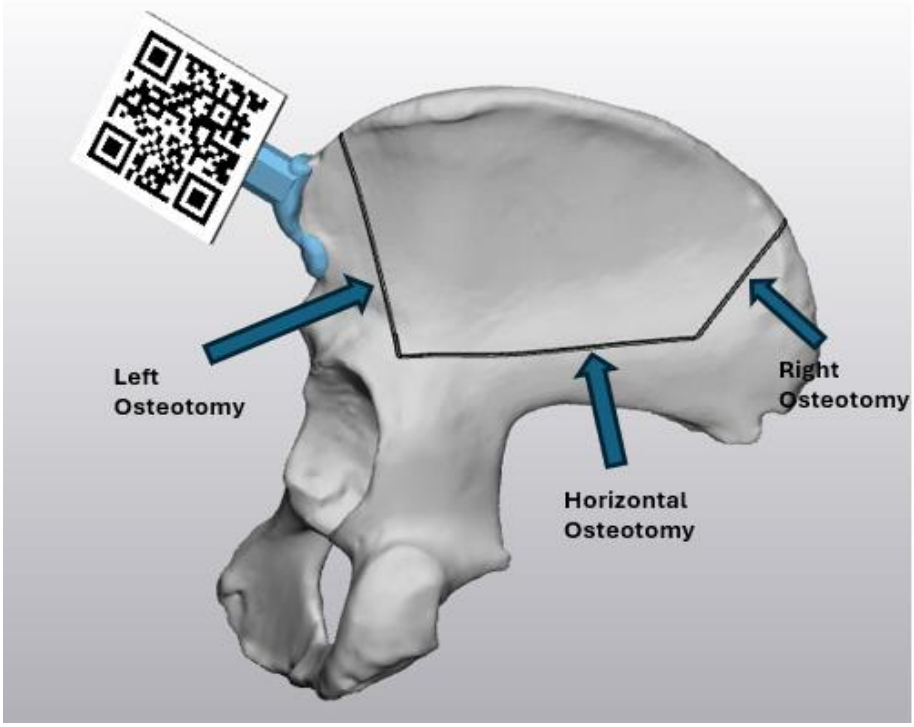


Figure 7: *Three osteotomy plane; right , left and horizontal for iliac tumor*

To validate accuracy, a grooved template was designed (Fig. 8). This template incorporated predefined grooves along the osteotomy planes, serving as a benchmark for assessing the deviation of AR-guided cuts from the ideal trajectory.

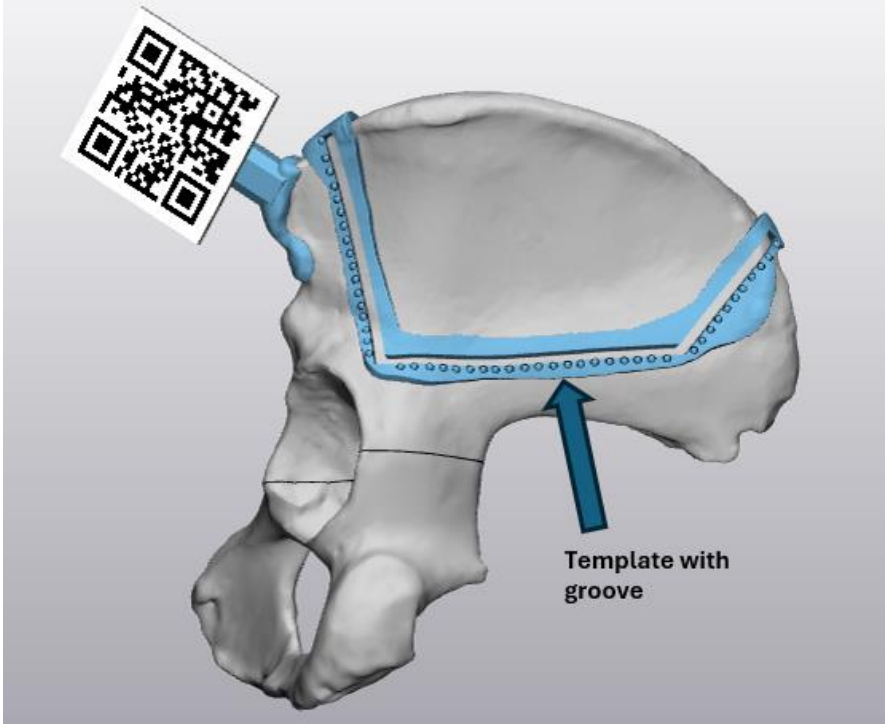


Figure 8: *Template groove to assess accuracy*

The validation templates were 3D printed, with grooves of varying widths; 1 mm, 2 mm, and 3 mm (Fig. 9). These different groove widths allowed evaluation of three accuracy thresholds, enabling quantification of the both AR devices ability to guide osteotomies with progressively tighter tolerances. The templates provided a reproducible and objective tool for measuring the degree of alignment between planned and executed cuts.

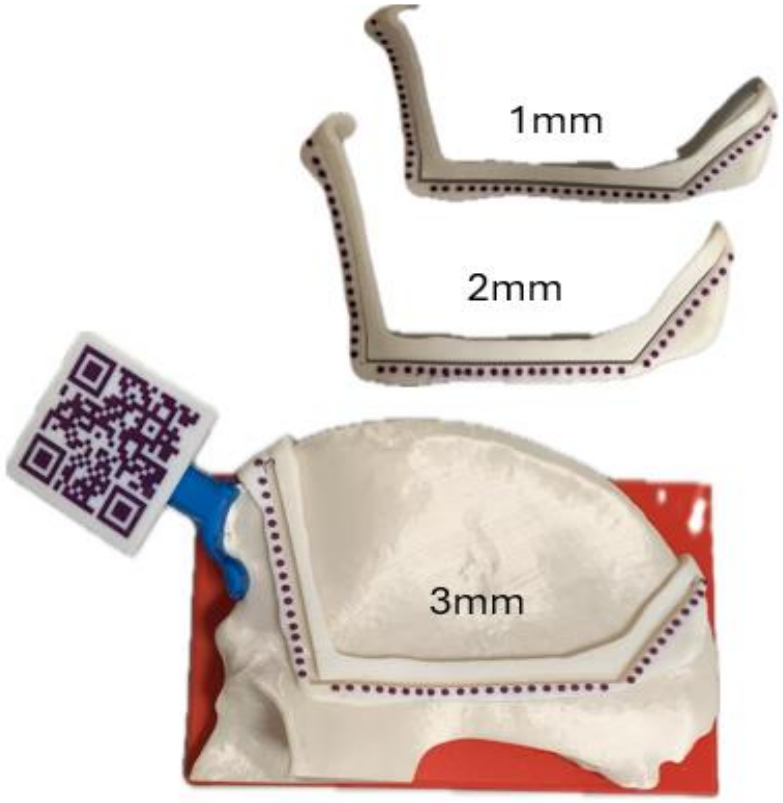


Figure 9: *Template grooves with varying widths; 1mm, 2mm and 3mm*

4.3.5 Experimental Protocol

To evaluate the surgical accuracy of both devices; HoloLens 2 and Magic Leap 2, the authors conducted a power test involving 30 simulated procedures, where participants performed selected simulated osteotomies on 3D-printed phantoms. This study engaged 10 participants in total; five experienced surgeons and five engineers, balanced by demographics with five females and five males, all aged between 25 and 50 years. Each participant repeated the procedure three times on the same phantom to ensure consistent conditions and reliable data collection.

The experimental protocol was structured into three sequential stages (Fig. 10):

1. Superimposition of Planned Osteotomies:

   The preoperatively defined osteotomy planes were projected onto the phantom model using both AR headsets. A fiducial marker i.e., QR code was fixed to the model, allowing precise registration between the digital plan and the physical phantom.

2. Execution of AR-Guided Osteotomies:

   Surgeons and engineers performed the osteotomies while wearing the AR headsets alternatively, aligning their instrument (marking pencil) with the holographically projected cutting planes. The AR overlay provided continuous visual feedback, guiding the trajectory and orientation of each osteotomy.

3. Accuracy Assessment:

   Following completion of the osteotomies, the resected models were fitted with the grooved templates. Deviations from the grooves were documented, with the tolerance levels (1 mm, 2 mm, 3 mm) serving as thresholds for quantifying the precision achieved.

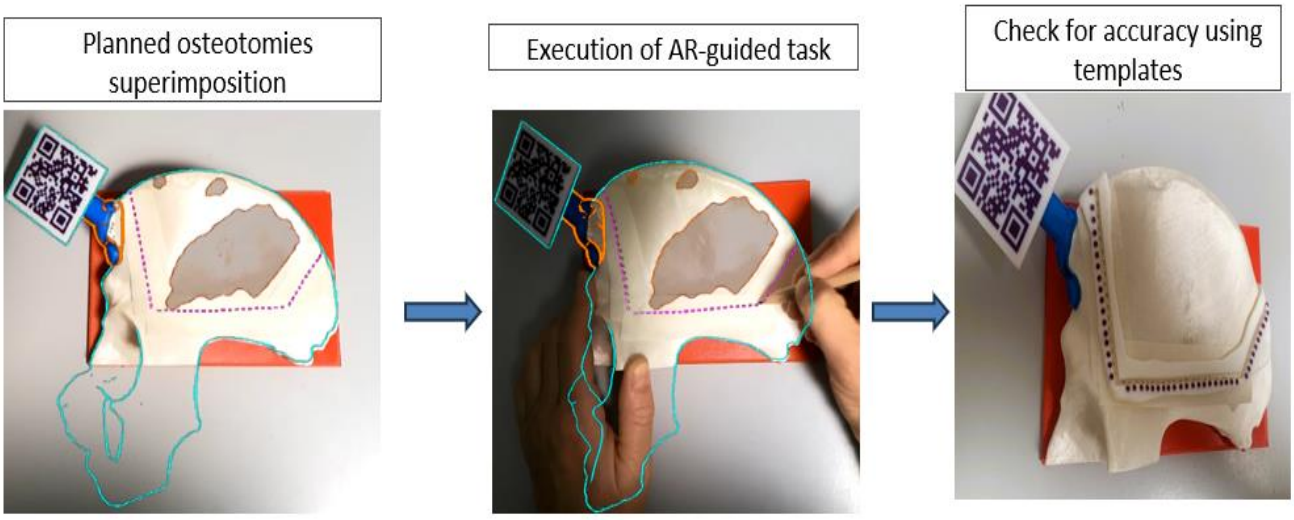


Figure 10: Workflow of performing AR-assisted osteotomy

4.3.6 Technical differences between Magic Leap 2 and HoloLens 2

Table 14: shows technical differences between Magic leap 2 and HoloLens 2

	Magic Leap 2	**HoloLens 2**
Release Date	September 2022	November 2019
Processor	AMD Zen 2 Quad-core + Custom Co-processors	Qualcomm Snapdragon 850 + Custom HPU 2.0
GPU	AMD RDNA 2 @ 1.1 GHz, 1SA, 4WGP (8 CU), 2RB+, 1MB L2 Cache	Integrated Adreno 630

OS / Platform	Lumin OS (Android-based custom OS)	Windows Holographic (Windows 10-based)
Display Type	Waveguide with LCoS displays	Waveguide with laser-based MEMS
Resolution	1440 x 1760 per-eye	1440x936 per-eye
Field of View (FoV)	70° diagonal field of view	52° diagonal field of view
Refresh Rate	Up to 120 Hz	60 Hz
Eye Tracking	Yes	Yes
Hand Tracking	Yes	Yes
Voice commands	Yes (custom voice commands)	Yes (Microsoft Cortana)
Sensors	IMU, Depth, Ambient light, World cameras, Eye tracking	IMU, Depth sensor, IR, Ambient light sensor
Focal Planes	Multiple focal planes (dynamic dimming zones): default setting of 37cm (adjustable to 25cm minimum) to infinity	Single fixed focal plane (2 meters)
SLAM	Yes – Enhanced (optimized for dynamic environments)	Yes – Advanced (via sensors + HPU 2.0)
RAM/Storage	16GB LPDDR5 5500/256 GB	4 GB LPDDR4x / 64 GB
Weight	260 g headset (with external compute pack)	566 g (fully integrated)

Battery life	3.5 hours typical use (7 hours in sleep mode)	2–3 hours of active use
Developer SDK	Magic Leap SDK, Unity, Unreal	MRTK, Unity, Unreal
Price (Launch)	$3,299	$3,500

4.3.7 Ergonomics survey comparison between HoloLens 2 and Magic Leap 2

AR-HMDs like the Microsoft HoloLens 2 and Magic Leap 2 have become revolutionary tools in domains such as medicine and engineering, facilitating immersive visualisation and interaction with digital holograms superimposed on the physical environment. The ergonomic design of these devices is crucial for their practical adoption, especially during extended use in high-pressure settings. Components including comfort, fit, weight distribution, interaction quality, and tiredness can profoundly influence user performance, satisfaction, and long-term usage.

This sub-chapter discusses the findings of an empirical ergonomics survey aimed at comparing the HL 2 with ML 2. The survey assesses critical ergonomic characteristics pertinent to clinical and engineering tasks, utilizing subjective user feedback to identify strengths and problems related to both devices. This investigation quantifies user views using a Likert-scale, offering insights into the alignment of these gadgets with user-centered design principles. The results highlight the significance of ergonomics in the

advancement of AR technology and provide guidance for subsequent versions or future work on these devices.

The survey comprised of a comprehensive investigation into AR-assisted processes, concentrating on users with clinical expertise. The analysis demonstrates uniform patterns in user preferences, influencing device choices in clinical contexts.

Total of 10 paticipants, consisting of 5 surgeons and 5 engineers, chosen to represent end-users in medical and technological fields where AR integration is becoming increasingly pertinent. All participants had varying degrees of prior experience to AR systems, as evaluated through an initial screening questions.

5-point Likert scale (1 = worse, 5 = best) was employed to rate ergonomic attributes. Nine core questions targeted device-specific factors. Those factor questions are tabulated as below:

Table 15: Survey- Comparing HoloLens 2 and Magic Leap 2 for Clinical Applications

Section	Question	HoloLens 2	Magic Leap 2
General Information	Have you had any prior experience with augmented reality (AR) vision systems in general?	- Yes - No	- Yes - No
		- Yes - No	- Yes - No

	Have you used both HoloLens 2 and Magic Leap 2 for clinical applications?		
Comfort and Wearability	2. How would you rate the adjustability and fit of the device for extended use?	- Poor - Fair - Good - Very Good - Excellent	- Poor - Fair - Good - Very Good - Excellent
	3. How comfortable is the device to wear during clinical tasks?	- Poor - Fair - Good - Very Good - Excellent	- Poor - Fair - Good - Very Good - Excellent
	4. How would you rate the weight of the device on your head during prolonged use?	- Too Heavy - Heavy - Slightly Heavy - Just Right - Lightweight	- Too Heavy - Heavy - Slightly Heavy - Just Right - Lightweight
Hologram Quality and Interaction	5. How would you rate the quality of holograms and their integration into the real world?	- Poor - Fair - Good	- Poor - Fair - Good

		- Very Good - Excellent	- Very Good - Excellent
	6. How intuitive and realistic is the interaction with holograms?	- Not Intuitive - Slightly Intuitive - Moderately Intuitive - Very Intuitive - Extremely Intuitive	- Not Intuitive - Slightly Intuitive - Moderately Intuitive - Very Intuitive - Extremely Intuitive
	7. How would you rate the response speed of the device during interactions?	- Slow - V. Slow - Moderate - Fast - Very Fast	- Slow - V. slow - Moderate - Fast - Very Fast
Recognition and Field of View	8. How accurate and reliable is the hand recognition feature on devices?	- Poor - Fair - Good - Very Good - Excellent	- Poor - Fair - Good - Very Good - Excellent
	9. How would you rate the field of view (FOV) on both devices?	- Too Narrow - Slightly Narrow - Adequate	- Too Narrow - Slightly Narrow - Adequate

		- Wide - Very Wide	- Wide - Very Wide
Fatiguability	10. Have you experienced fatigue after wearing the device for extended periods?	- Total fatigue/Exhaution - V. fatigue - Moderate Fatigue -Little fatigue - No fatigue	- Total fatigue/Exhaution - V. fatigue - Moderate Fatigue -Little fatigue - No fatigue
Additional Feedback	11. Do you have any additional comments or observations about the HoloLens 2 or Magic Leap 2 in clinical settings?	Open-ended response	Open-ended response

4.3.8 Statistical Analysis

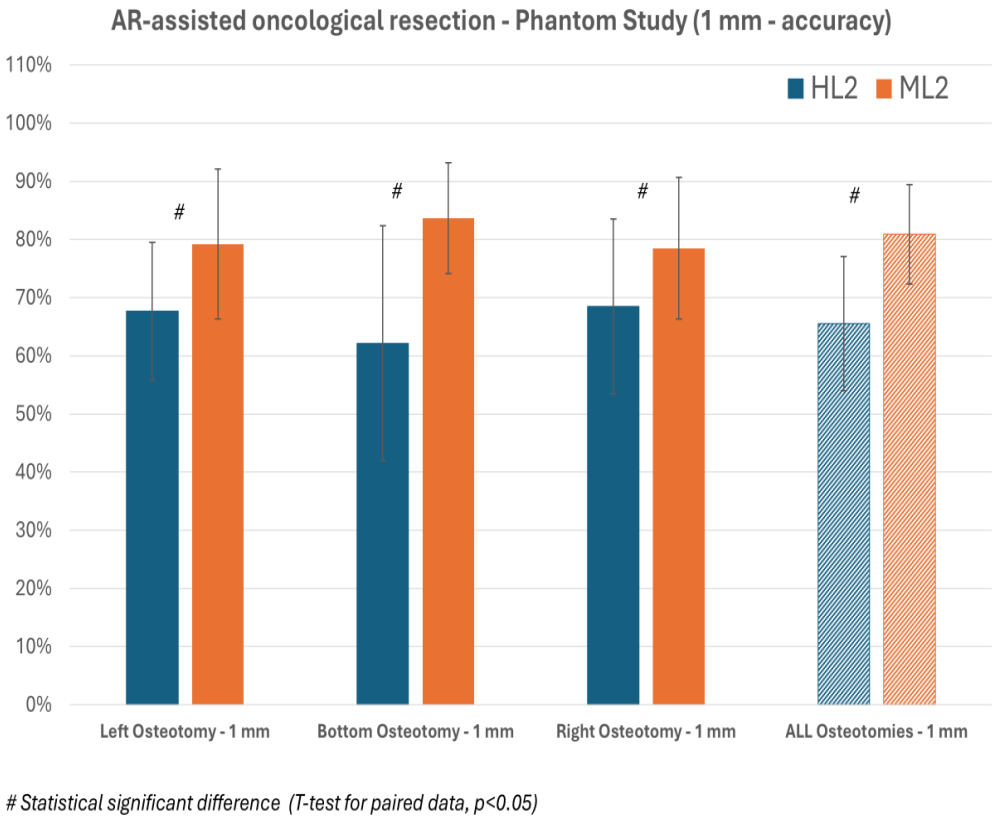
Paired t-tests were conducted to compare accuracy between HL 2 and ML 2 for each osteotomy site and margin, with statistical significance defined at $p < 0.05$. Significant differences were observed at the 1 mm and 2mm margin across all osteotomies (left, bottom and right).

4.4 Results

1- Surgical Accuracy

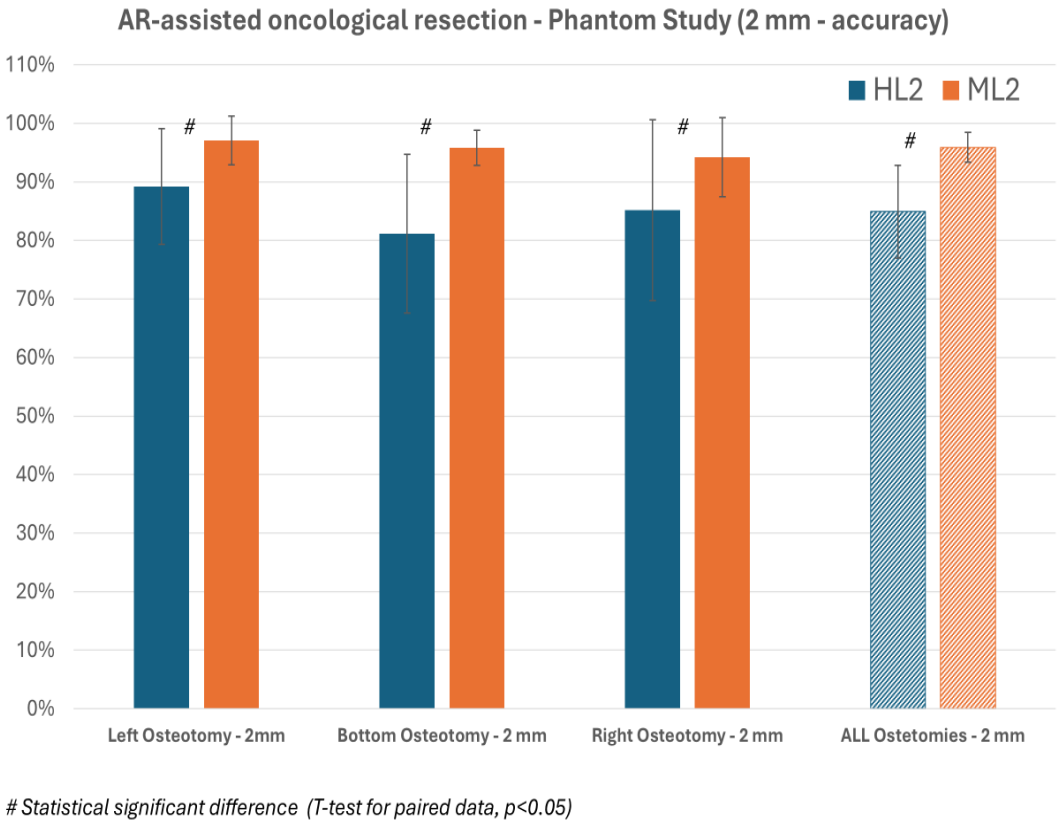
The comparative evaluation of AR-assisted oncological resections (osteotomy lines) using the HL2 and ML2 demonstrated progressive improvements in accuracy across varying osteotomy margin thresholds (1 mm, 2 mm, and 3 mm).

At the 1 mm margin (Bar graph 3) the accuracy achieved with ML2 was consistently higher than that of HL2 across all osteotomy sites (left, bottom, right), as well as in the pooled analysis of all osteotomies. For instance, ML2 yielded accuracy levels approaching 80–85%, whereas HL2 performance ranged around 65–70%. The difference between the two devices was statistically significant across all comparisons ($p<0.05$), indicating the superior precision of ML2 in executing fine-margin resections.



Bar Graph 3: *Accuracy Comparison of HL2 and ML2 Navigation in AR-Assisted Oncological Resection-Phantom Study at 1 mm Margin*

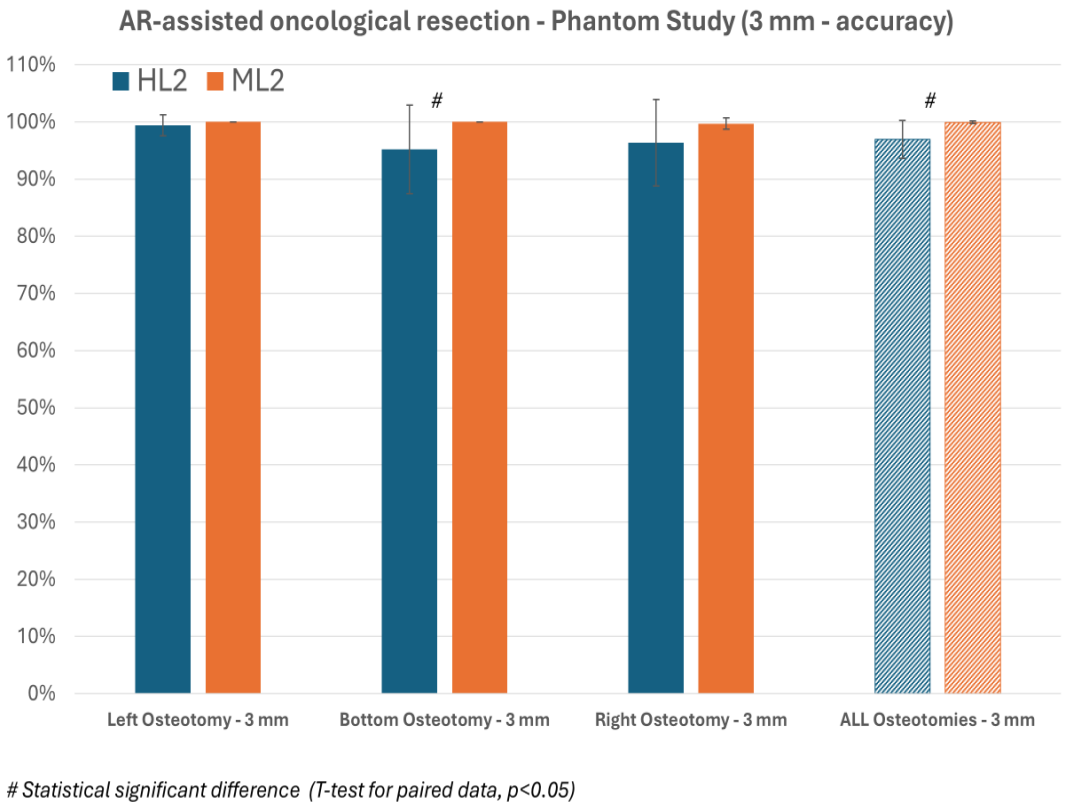
At the 2 mm margin (Bar Graph 4), both devices demonstrated notable improvements in performance relative to the 1 mm margin. ML2 continued to outperform HL2 across all individual osteotomies and in the overall pooled data, with accuracy exceeding 90–95% compared to HL2's 80–85%. Statistical significance was maintained for all osteotomies (p<0.05), reinforcing the advantage of ML2 in achieving higher precision at clinically relevant margin widths.



Bar Graph 4: *Accuracy Comparison of HL2 and ML2 Navigation in AR-Assisted Oncological Resection-Phantom Study at 2 mm Margin*

At the 3 mm margin (Bar Graph 5), both HL2 and ML2 achieved near-optimal accuracy, with performance consistently approaching or exceeding 95–100% across all osteotomies. The margin of difference between the two devices narrowed considerably, reflecting convergence in performance at larger margin thresholds. While ML2 retained a slight edge in accuracy, the statistical differences were reduced. The statistical difference was noted in only bottom osteotomy and overall all osteotomies, highlighting

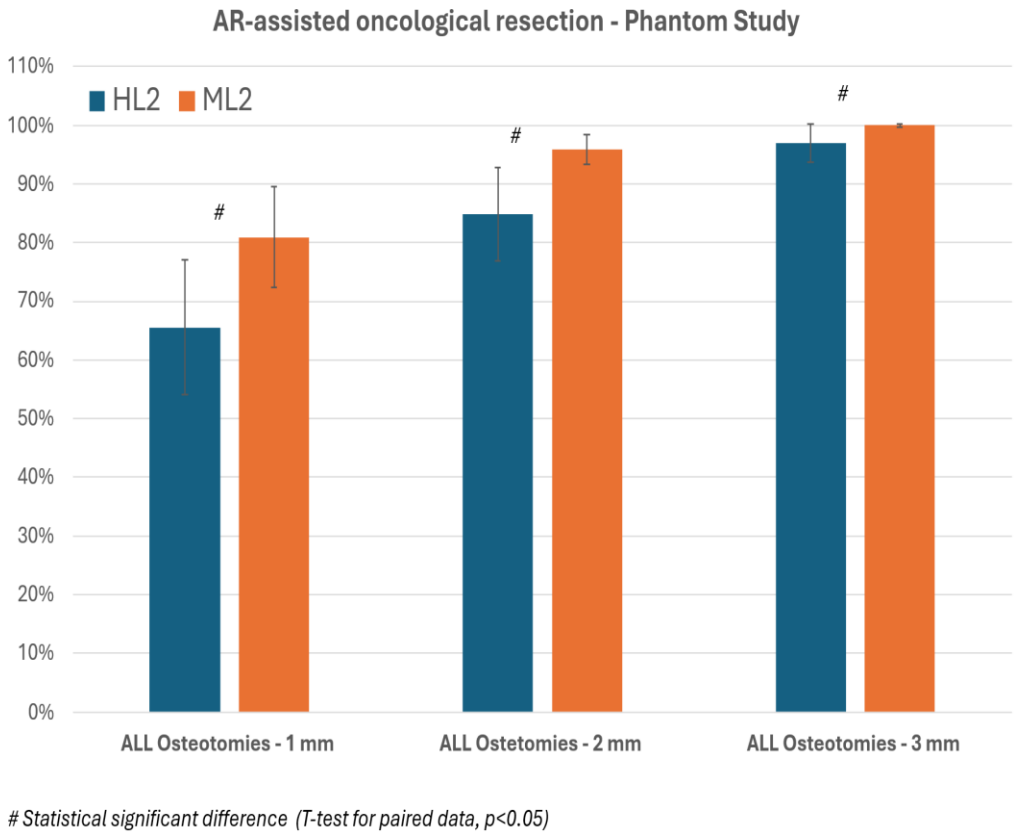
that both devices are capable of achieving highly reliable resections when broader safety margins are employed.



Bar Graph 5: *Accuracy Comparison of HL2 and ML2 Navigation in AR-Assisted Oncological Resection-Phantom Study at 3 mm Margin*

Overall, the results clearly indicate that ML2 provides superior accuracy compared to HL2, particularly at narrower margin thresholds where surgical precision is most critical (Bar graph 6). As the margin increased, the performance of both devices improved, with differences between them almost diminishing at the 3 mm threshold. These findings

emphasized the clinical relevance of AR guidance, especially in scenarios requiring maximal preservation of healthy tissue and precise resection margins.



Bar Graph 6: *Accuracy Comparison of HL2 and ML2 Navigation in AR-Assisted Oncological Resection-Phantom Study at All Margins (1mm,2mm and 3mm)*

2- Technical differences

The technical comparison of ML 2 and HL 2 reveals significant disparities in technology and user experience that influence their appropriateness for surgical applications. Launched in September 2022, ML 2 is a more sophisticated device than the HL 2, which

was released in 2019. ML2 incorporates a robust AMD Zen 2 quad-core processor paired with an RDNA 2 GPU, 16 GB of RAM, and 256 GB of storage, whereas HL2 utilises a Qualcomm Snapdragon 850 with an Adreno 630 GPU, featuring merely 4 GB of RAM and 64 GB of storage, highlighting significant performance differences.

The display quality is superior in ML2, with a resolution of 1440 1760 per eye, a 70° diagonal field of view, and refresh rates of up to 120 Hz, whereas HL2 has a resolution of 1440 936, a 52° field of view, and a refresh rate of 60 Hz. Significantly, ML2 features several adjustable focus planes and improved SLAM tailored for dynamic settings, while HL2 employs a single fixed focal plane at around 2 meters with advanced yet less adaptable SLAM.

Both devices provide eye, hand, and voice tracking; however, ML2 has customized voice command functionality, whilst HL2 is integrated with Cortana. From a design perspective, ML2 is considerably lighter (260 g with an external compute pack) than HL2 (566 g fully integrated), enhancing its ergonomics for extended use. Nevertheless, the external computing pack may impede its utilization in the operating room over sterility concerns.

The battery life of ML2 is marginally superior at 3.5 hours, in contrast to HL2, which lasts between 2 and 3 hours. The distinctions in processing power, display quality, range of view, focal flexibility, and ergonomics demonstrate that Magic Leap 2 offers enhanced

technical performance and user comfort, rendering it more appropriate for accurate and prolonged intraoperative surgical guidance.

3- Ergonomics differences

An ergonomic evaluation comparing HL 2 and ML 2 was performed with ten participants (5 surgeons and 5 engineers) to examine user comfort, device performance, and usability after prolonged use. Magic Leap 2 exhibited enhanced ergonomic performance across all metrics in comparison to HL 2. Regarding adjustability and fit, ML 2 got an average score of 4.0, surpassing HL 2's score of 3.3, signifying superior comfort for extended use. Comfort during clinical tasks and device weight received higher ratings for ML 2 (3.4 and 4.0, respectively) compared to HL 2 (3.1 and 3.2), underscoring enhanced balance and less tiredness.

Participants evaluated the quality and integration of holograms significantly higher for ML 2 (3.8 compared to 2.8), indicating improved visual clarity and spatial stability. Likewise, engagement with holograms (4.0 vs 3.1) and reaction velocity (4.1 versus 2.9) were markedly superior in ML 2, indicating enhanced and more instinctive system reactivity. The hand identification feature in ML 2 was enhanced (3.0 vs. 2.3), however both systems exhibited possibilities for further optimisation. The FOV was wider and more comfortable in ML 2 (3.9 compared to 3.3), aligning with its expanded optical projection area. Finally, the assessment of fatigability with continuous use was

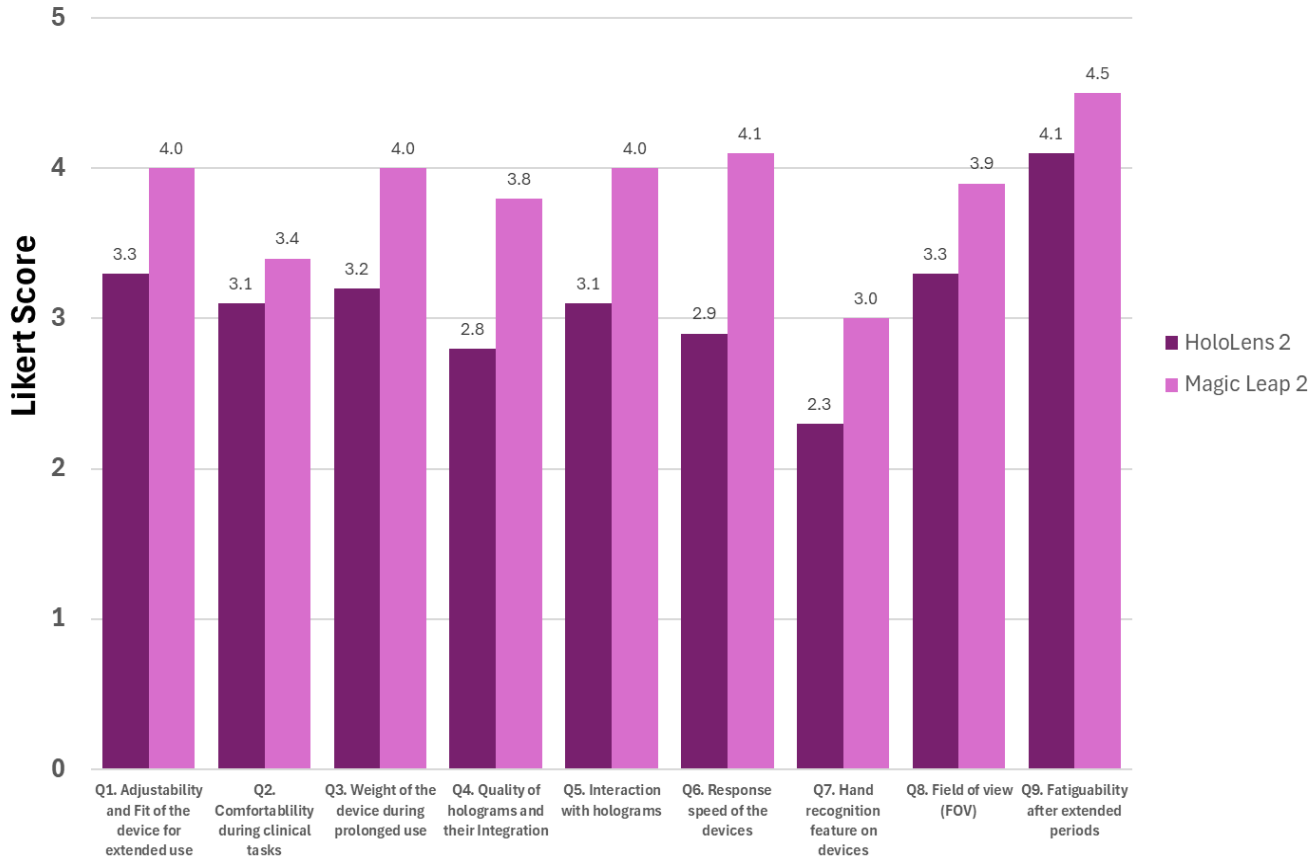
marginally superior for ML 2 (4.5 compared to 4.1), suggesting less strain during longer tasks with both devices.

Participants regarded Magic Leap 2 as the more ergonomically sophisticated and technically proficient gadget, especially concerning visual quality, responsiveness, and extended usability; factors essential for surgical and clinical augmented reality applications. Table below shown the survey comparison of both devices on Likert scale.

Table 16: Comparison of devices on Likert Scale

	HoloLens 2	Magic Leap 2
Q1. Adjustability and Fit of the device for extended use	3.3	4.0
Q2. Comfortablility during clinical tasks	3.1	3.4
Q3. Weight of the device during prolonged use	3.2	4.0
Q4. Quality of holograms and their Integration	2.8	3.8
Q5. Interaction with holograms	3.1	4.0
Q6. Response speed of the devices	2.9	4.1
Q7. Hand recognition feature on devices	2.3	3.0
Q8. Field of view (FOV)	3.3	3.9

Q9. Fatiguability after extended periods	4.1	4.5



Bar Graph 7: *representation of the survey results using a Likert scale*

4.5 Discussion

This study conducts a direct comparative assessment of two advanced AR HMD's HL 2 and ML2, within the realm of orthopedic oncology, utilizing patient-specific pelvic bone phantoms as a controlled experimental model. The results indicate that both devices can effectively enable precise AR-assisted resections; however, ML 2 consistently surpassed HL 2 in precision, visualisation quality, and user ergonomics, especially at narrower surgical margins where accuracy is clinically paramount.

The quantitative analysis demonstrated that ML2 attained superior accuracy at all osteotomy locations and margin thresholds. At the 1 mm and 2 mm resection margins, ML2 consistently demonstrated superior alignment between the planned and conducted osteotomies, reaching accuracies of 85–95%, whereas HL 2's performance ranged from 65–85%. Statistical analysis validated the importance of these differences ($p < 0.05$), highlighting ML2's superior accuracy in replicating complex resections.

At the 3 mm threshold, both devices exhibited near-optimal accuracy (95–100%), with the disparity between them significantly diminishing. This convergence indicates that although both devices are sufficient for broader oncologic margins, ML 2's superiority is particularly apparent under high accuracy requirements, such as those present in limb-sparing resections or pelvic tumour excisions where millimeter-level precision is essential.

These findings validate other studies highlighting the clinical efficacy of AR in enhancing spatial orientation and intraoperative confidence during bone tumor resections. The

higher accuracy of ML 2 can be ascribed to its broader field of view (70° compared to 52° in HL2), higher display refresh rate (120 Hz vs 60 Hz), and advanced depth perception using dynamic focal planes, all of which augment holographic stability and visual fidelity. These features diminish perceptual discontinuities and alignment inaccuracies, resulting in enhanced fidelity of intraoperative guidance.

The technical comparison of the two headsets further elucidates the performance disparity. The ML 2's AMD Zen 2 processor and RDNA 2 GPU provide markedly superior computational performance compared to the HL 2's Snapdragon 850 platform, facilitating enhanced real-time rendering and improved tracking responsiveness. The augmented RAM and storage capacity (16 GB / 256 GB compared to 4 GB / 64 GB) facilitate the management of larger datasets and higher-fidelity 3D models, which are essential for executing complex pelvic reconstructions.

The optical system constitutes a significant development in ML 2. The multi-focal plane waveguide display and adaptive dimming zones reduce the vergence-accommodation conflict, a recognised constraint of HL 2's fixed focal depth (about 2 meters). This yields a more authentic depth perception of holograms, enabling surgeons to sustain accurate alignment between the virtual and physical anatomies. The ML 2 necessitates an external compute pack, potentially raising minor sterility issues in clinical settings; nonetheless, this design choice significantly reduces the headset weight (260 g compared to 566 g), enhancing comfort during extended surgical procedures.

The ergonomic assessment corroborated the objective results, indicating a distinct user preference for the Magic Leap 2. Participants assigned superior ratings to ML2 across all nine assessed categories on the Likert scale, encompassing comfort, fit, visual clarity, and interaction responsiveness. The enhanced adjustability, less fatigue, and exceptional holographic quality noted by users align with its sophisticated optical and mechanical build. The expanded field of view and improved hand tracking (though can be improved more) augmented user immersion and work efficiency, factors essential for clinical adoption where cognitive load and situational awareness are critical.

Notably, although ML2 offers enhanced comfort, certain users emphasised the practical difficulty associated with its external computing pack, indicating that while it has technical benefits, its incorporation into sterile environments necessitates further adjustments to workflow. Overall feedback suggests that ML2 provides a more sophisticated and therapeutically versatile user experience, enhancing sustained focus during extended tasks. Conversely, many users encountered displacement of holograms during surgical procedures with HL 2. Some observed the flickering of superimposed holograms. Several individuals expressed dissatisfaction with the device's slow speed, slow registration process, and hand motion detection compared to ML 2.

From a clinical perspective, our findings highlight the advancing potential of augmented reality technologies in orthopaedic oncology. ML 2 capability to project stable, high-resolution holograms directly onto patient anatomy with enhanced spatial precision highlights its effectiveness in facilitating complex tumour resections, particularly in

scenarios where the preservation of vital neurovascular and muscular components is crucial. Improved precision at narrow margins may help decrease positive resection rates and enhance functional results, thus addressing an important constraint in musculoskeletal oncology.

Moreover, the utilization of patient-specific phantoms offered a reliable and consistent paradigm for evaluating AR-guided precision, facilitating the transition from preclinical validation to clinical application. The technique developed in this study may function as a standardized foundation for future comparative assessments of new AR platforms, including their integration with navigation systems.

This work offers extensive insights, although certain limitations must be recognised. The experiment was initially performed on in-vitro phantoms, which, although anatomically accurate, fail to recreate all intraoperative variables, including tissue deformation, haemorrhage, and post-operative functional outcomes. Future research should prioritise in-vivo validation, integrating actual surgical situations to assess performance under operative settings. The incorporation of augmented reality with intraoperative imaging and haptic feedback help signifies the forthcoming advancement towards a completely intelligent, surgeon-directed navigation system.

4.6 Conclusion

In conclusion, this comparative investigation reveals that ML 2 outperforms HL 2 in technical performance and user ergonomics, providing superior precision in AR-guided phantom resections and enhanced comfort over extended usage. The integration of augmented processing capabilities, expanded field of vision, increased optical clarity, and lightweight construction makes ML 2 a more sophisticated and functional platform for intraoperative augmented reality application despite few limitations confined to it. These findings provide significant evidence endorsing the incorporation of next-generation AR devices in orthopaedic oncology and establish a foundation for practical implementation in precision-guided bone tumour surgery and other orthopedic surgeries.

5 Chapter 5 Conclusions

5.1 Conclusions

This thesis systematically evaluated the role of AR on enhancing surgical precision and consistency in acetabular reaming during THA and orthopedic oncological procedures. The results combined indicate that AR-assisted surgical guidance, specifically with the Magic Leap 2, signifies a substantial technical progression capable of improving accuracy, consistency, and intraoperative vision.

The findings of this study validate that AR-assisted reaming utilizing ML2 attained clinically acceptable precision, with mean deviations in inclination and anteversion maintaining within 3° of the intended orientation. This result demonstrates that AR systems can proficiently convert preoperative designs into intraoperative implementation, thus reducing human error and enhancing component placement precision. The uniformity of outcomes among many users, despite a constrained sample size, demonstrates the system's robustness and independence from human variability. This consistency highlights AR technology's ability to reduce inter-surgeon variability, a significant drawback of conventional freehand techniques, and to enhance uniform surgical results.

The comparative phantom study demonstrated that both AR and PSI techniques significantly diminished angular and positional deviations relative to traditional freehand reaming. Despite the limited statistical power due to the small sample size, the results attained clinical significance, as indicated by a mean absolute error of under 3°. The data indicate that technology-assisted methods improve accuracy and decrease intra

and inter-operator variability, hence revealing significant potential for reproducibility in practical clinical settings.

The comparison analysis of ML 2 and HL 2 highlighted the higher performance of ML2 regarding surgical and technical precision, ergonomics, and user comfort. The ML2 exhibited superior computational power, an expanded range of view, and higher optical clarity; elements that jointly enhance the surgeon's experience during extended procedures. These developments render ML2 a more efficient and versatile AR platform for intraoperative guidance and surgical navigation.

This collection of work presents compelling evidence for the incorporation of AR-based systems in orthopedic surgery, especially for procedures necessitating accurate spatial orientation, such as acetabular reaming and bone tumor resections. The findings underscore the practical feasibility of AR technology as an adjunct rather than a substitute for current navigation techniques, providing a harmonious blend of precision, usability, and efficiency. Ongoing technical enhancement and validation via extensive clinical trials suggest that AR-guided surgery, has the potential to revolutionize orthopedic surgical practices by facilitating increased precision, safety, and reproducibility.

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