Virtual Bone Surgery Cut Alignment with the HoloLens

Daniel Woortmann, Mikkeline Elleby, Philipp Gerstner, Saatushan Sabesan
ETH Zürich

Supervised by: Matthias Rüger (Zurich), Javier Narbona Cárceles (Madrid), Jonas Hein (ETH Zürich)

Abstract

Bone surgeries, particularly osteotomies for deformity corrections, demand high precision but are often performed using traditional tools like calipers and goniometers, which are prone to inaccuracies, prolonged operation times, and increased radiation exposure. Mixed Reality (MR) offers a transformative solution to these challenges. In this work, we present an MR application developed for the Microsoft HoloLens 2 to enhance surgical workflow. The application enables surgeons to place virtual calibrating elements, such as points and planes, on the patient's bone, tracked using QR code-based attachments, to guide osteotomies with minimal reliance on traditional tools. To evaluate the application's usability and impact, we conducted a user study. The study revealed high user satisfaction with the application's intuitive design, suggesting its potential to streamline surgical workflows. Feedback highlighted specific areas for refinement for future iterations, including improving the precision of holographic alignment and enhancing user interactions with the virtual content.

1. Introduction

Bone surgery techniques require precise measurements and cuts (osteotomies) on the patient's bone, and have barely evolved in the last century despite the advent of high-tech medical equipment. During the pre-planning step, surgeons draw planes and angles on top of the bone (e.g. from X-rays), to determine the location and orientation of a deformation. From this, the positions and angles of one or more cuts are determined. Then the cut parameters are enforced during the operation with calipers, goniometers, and wires through the bone. These century-old techniques come with several disadvantages. First, they lack in precision. Second, they are uncomfortable both for the patient and the surgeon. Finally, they need many X-ray checks resulting in a lot of radiation exposure for the patient.

Mixed Reality (MR) presents an opportunity to revolutionize the bone surgery process and overcome these limitations. MR has demonstrated significant potential in enhancing surgical precision, as evidenced by numerous studies [7]. While the use of 3D models (image-guided surgery) is popular for planning osteotomies [13, 14], MR has to the best of our knowledge not found widespread adoption as an intraoperative tool to assist during bone surgeries. In this work, our goal is to facilitate and increase precision for bone surgery techniques with a MR app. Our app is designed to be active on a AR headset during the surgery and allows the surgeon to place virtual calibrating elements on top of a bone, e.g. aligning cuts while tracking the bone position, thereby largely eliminating the need for calipers, goniometers and surgical wires. Moreover, MR has the potential to improve surgical assistance in low-income countries. Specifically, Matthias Rüger hopes that such a system could also be developed as an AR smartphone app instead of a headset.

To assess the efficacy and usability of the proposed AR application, we conducted a user study with participants representing a diverse range of AR experience. The study provided valuable feedback on the system's performance, particularly its intuitive interface and the quality of holographic alignment. This feedback not only underscored the potential of AR in enhancing surgical workflows but also highlighted key areas for further improvement, such as optimizing the precision of registration and enhancing user interaction mechanisms. These findings serve as a foundation for refining the application, guiding its evolution toward a practical and impactful tool for orthopedic surgery.

1.1. Background: Bone Surgeries

To better understand the benefits of MR assistance in our scenario, we give some background regarding the workflow of bone surgeries. Specifically, we focus on bone deformity correction. To illustrate this, Figure 1 shows a typical human anatomical condition caused by bone deformities: the invard-bent knees are due to an incorrectly shaped femur.

Preoperative Planning First surgeons need to understand the details of the deformation in a patient's bone in order to

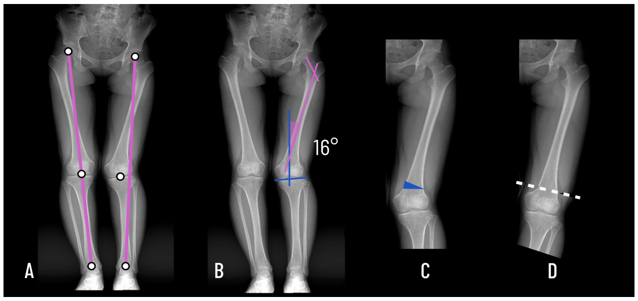


Figure 1. Hip femoral valgus osteotomy. (A) This patient has a left inward-bent knee (valgus) because the center dot is not aligned on the load axis. (B) The malalignment is in the femur, with the correction/malalignment angle. (C) As a result, the blue wedge (that has the same correction angle) will be cut out. (D) The re-aligned bone after the cut, with the "realignment line" marked. X-ray scans kindly provided by Javier Narbona Cárceles.

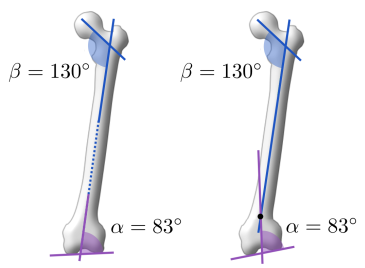


Figure 2. A human femur bone, in normal condition on the left and deformed on the right. When overlaying the same reference lines and angles on the bone, they meet in parallel on the normal bone but meet at an intersection on the deformed bone. From this we get the deformity angle (see also Figure 1 B). Drawing (modified) kindly provided by Javier Narbona Cárceles.

precisely plan the corrective measures needed. To accomplish this, the patient is subjected to X-ray scans of their bone, which are then analyzed.

Typically the CORA (Center of Rotation of Angulation) method is applied for this analysis, a widely used analytical approach, based on identifying the exact point (the CORA) where a bone's alignment deviates. The CORA serves as the geometric center for angular deformities, calculated through the intersection of mechanical or anatomic axes of the affected bone segments. Figure 2 shows these axes on a human femur bone. This method ensures surgeons can accurately determine the location of the corrective cuts.

During Surgery Having determined the cut parameters, it is crucial that the cut parameters are applied and maintained during the operation, to enable the right correction. In practice, this is enforced with calipers, goniometers and K-wires (surgical wires). Figure 3 shows a goniometer in action. In

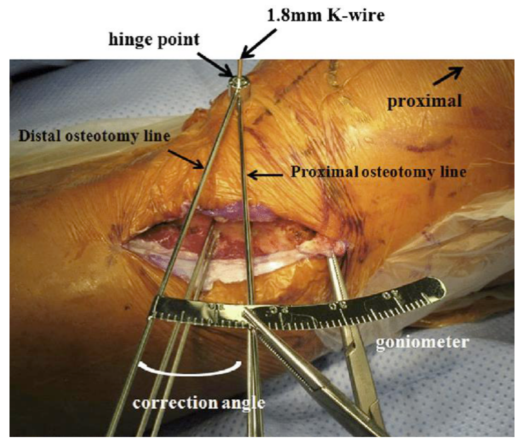


Figure 3. Here a goniometer is used during the procedure to define the correction angle along with the osteonomy cut lines. Inserted wires are needed, seen at the top. Image kindly provided by Javier Narbona Cárceles.

the case of the femur correction example, a wedge will be cut out with a saw blade following the cut lines defined earlier (See Figure 1 C).

1.2. Limitations of the Traditional Approach

Traditional bone surgery methods suffer from precision problems, as manual instruments like calipers and goniometers introduce variability. A study by Howell *et al.* [6] on unrestricted caliper-verified kinematically aligned total knee arthroplasty with manual instruments found that surgeon experience had a negligible effect on accuracy, suggesting inherent limitations in manual tools. These imprecisions can result in suboptimal corrections.

The methods are also uncomfortable for both patients and surgeons. Manual adjustments of surgical tools can prolong operation times, increasing patient discomfort and exposure to anesthesia. Indeed, a study by Costa [2] assessing operative times across multiple surgical specialties found that manual methods contribute to longer durations in the operating room.

Moreover maintaining steady and accurate alignment of these surgical tools during prolonged manual procedures can lead to surgeon fatigue, which may also compromise precision. Research by Ferrari *et al.* [3] doing simulated total hip arthroplasty indicated that manual methods are associated with increased muscle fatigue among orthopedic surgeons, highlighting the physical demands of traditional techniques.

Finally, the traditional approach exposes patients and possibly the surgical staff to considerable amounts of radiation due to repeated X-ray imaging [12]. Indeed, intraoperative (during the operation) scans are often necessary to verify alignment and track progress during the

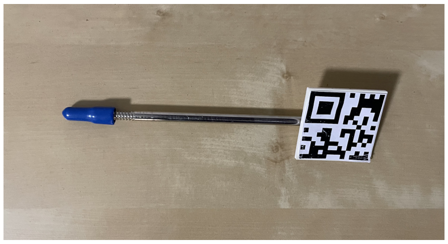


Figure 4. The qr-code tracking rods that should be used for real operations, around 12 cm in length. One end has a surface for the qr code, while the other end has a screw head (protected by a plastic cap here) that should be screwed into the patient's bone being operated.

surgery [5]. Over time, this cumulative radiation poses health risks [4, 12].

2. Material and Methods

2.1. HoloLens & MRTK3

We use the HoloLens 2 device [8] and developed our application with Unity. The app is built on top of MRTK3 (Mixed Reality Toolkit) [9], which is Microsoft's AR/VR toolkit that comes with UI elements, hand tracking/interaction controls and first-class support for the HoloLens.

2.2. Tracking Attachments

The position of the bone on which the osteotomy takes place must be tracked, as it might move during the operation (accidentally or when repositioning the body on the operation table). For this reason, we use a metallic attachment rod with a 3D-printed square for a qr code at the outer end. The other end should be screwed into the bone. This provides a solid, displacement-resistant connection between the bone and the qr code, ready for the OR. On Figure 4 the tracking attachment is displayed with a qr code.

2.3. Bone Models

To facilitate development and provide a case study for our system, we used a femur and a tibia bone model supported by rubber connectors to simulate human leg bones (see Figure 5). Since drilling a hole into these models was not an option, we instead 3D-printed a simple qr code attachment that clamps on the bone, with a screw to loosen/tighten the fit. Clearly, this is not feasible for the OR since the attachment would likely be covered by flesh. Therefore this setup was just used throughout the project, but the tracking rods should be used in a clinical setting.

Figure 5. Left: Human leg bones model with femur and tibia used for development and testing. Right: The qr code clamp used for the bone models, to avoid drilling a hole in them.

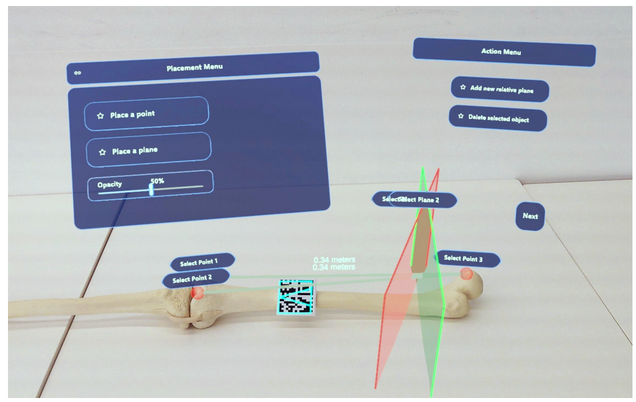


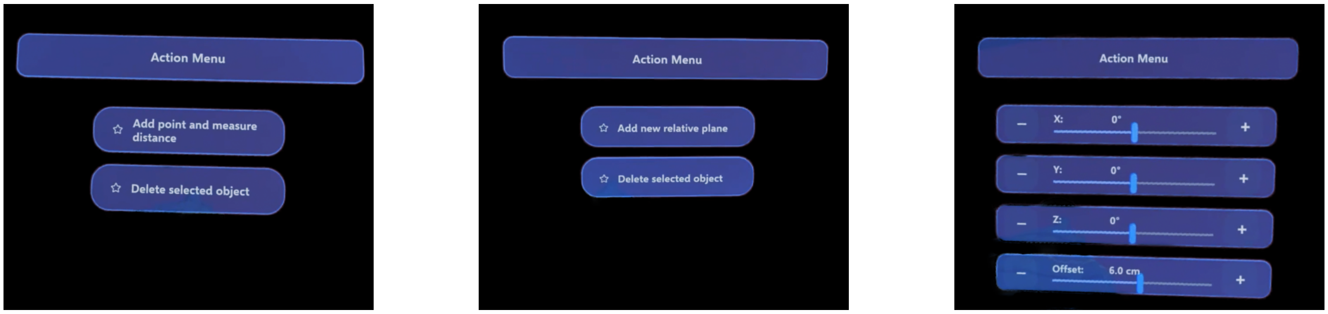
Figure 6. This MR screenshot of our app shows its full capabilities, with the placement menu (on the left) and action menu (on the right), qr code tracking of our bone model, points, planes, and distance measurement.

3. Proposed Solution

We provide surgeons with a mixed reality app used to precisely overlay virtual calibrating elements (points and planes) on top of the patient's bone. The app can then be used while performing the osteotomy to, for example, serve as a cut guide for a saw blade, ideally eliminating the need for measurement tools and wires. To make the virtual objects robust against movements of the operated bone, it is tracked with a qr code as described in the previous section. A screenshot of the full solution is shown in Figure 6.

3.1. App UI structure

The UI is structured as follows: there is a *placement menu* window to place virtual objects, which has buttons to place points and planes. Each virtual object can be placed freely and has a *label* next to it in virtual space. Clicking on the label selects or deselects the object. Moreover, there is an *action menu* allowing to perform certain actions depending on what virtual objects are selected (see Figure 7).



(a) (b) (c)

Figure 7. Action menu, changing dynamically depending on what objects are selected. 7a When selecting a point, we can add another point and measure the distance between them. If instead 2 points were selected it would directly say ”measure distance” (not shown here). 7b When selecting a plane, we can add a relative plane to it. 7c Selecting a relative plane allows precise positioning controls, with euler angles and offset relative to the parent plane.

3.2. Distance Measurement

We implemented distance measurement between 2 virtual points. When activated, a line annotated with the distance between the points is drawn, as shown in Figure 6 and 8. The HoloLens takes care of the mapping between real distance and virtual distance, so that distances in virtual space (should) match distances in real space. To use distance measurement, there are 2 options: either a point is selected, followed by clicking ”Add point and measure distance” (see Figure 7a) or 2 points are selected followed by clicking ”measure distance” in the action menu.

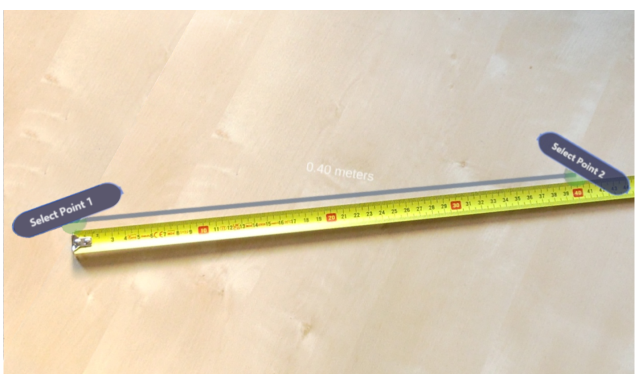


Figure 8. Two virtual points are placed 40cm apart. The measured distance displayed by our application is 0.40m, exemplifies the accuracy of the hololens distance mapping

3.3. Planes & Relative Planes

Virtual planes are crucial to define the bone cut lines and angles or to define calibrating lines. We can add a new virtual plane by selecting the option in the placement menu, and then place/orient it freely with the hand, leveraging MRTK’s gesture controls. We can add more planes this way or we can add *relative planes*. By selecting a plane U, we can click ”place a relative plane” on the action menu (Figure 7b). This will spawn a new plane whose position and orientation is anchored to the parent plane U: moving the parent plane will move the child plane. Moreover, selecting a child plane brings up precise controls in the action menu (Figure 7c). We can rotate the plane using euler angles around 3 axes, and offset the plane relative to the parent plane’s normal direction. We can also add a child plane to a child plane and so on, using the same procedure as above. This feature allows positioning of calibrating elements relative to some ”origin” parent element, based on predefined distances and angles (see the CORA method, Section 1.1). As a result, the surgeon only has to worry about the placement of the origin element, with the child element then respecting the predefined offsets/orientations.

3.4. Bone Tracking with QR Code

As discussed in Section 2.2, we use a qr code to keep track of the bone location. To track the qr code in our app, we use the OpenXR QR tracker, which is part of MRTK3 [11]. It turns out that the tracking seems to only apply updates every couple of frames in case the qr code is moved. As such, the virtual elements do not smoothly move with the bone in real-time. Instead, they only update their position every couple of frames, introducing lag. For this reason, smoothing was implemented, which somewhat mitigates the lag.

4. User study

To assess our app, a user study was conducted. Participants were provided with a tutorial that guided them through the process of placing points and planes for a surgical procedure on a misaligned femur shown in Figure 2. Following step-by-step instructions displayed on a dedicated panel, participants were tasked with placing virtual calibration objects on the human leg model shown in Figure 5, similar to the procedure described in Figure 1.

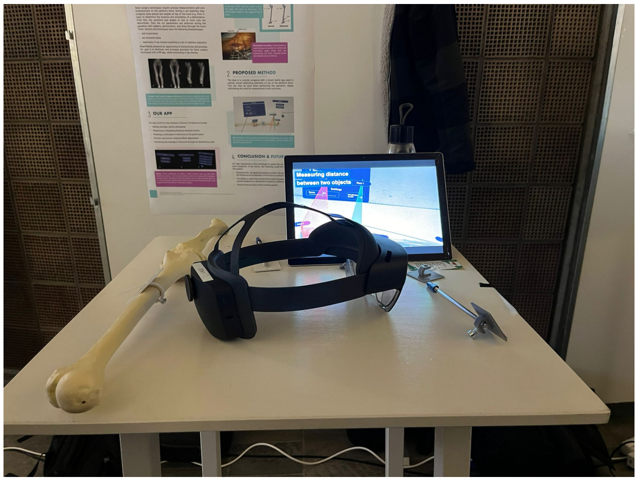


Figure 9. For the user study, the participants were first introduced to our app with a demo video on a tablet. Afterwards we explained the users what they are going to do in the tutorial before they wore the HoloLens and started the tutorial, in which they were guided on placing points and planes on top of the human leg bone model.

4.1. Participants

A questionnaire exploring the user's experience and challenges was designed, along with some background information on the user. In total 16 people participated, aged between 20 and 35. Among them, only 3 participants had prior experience using the HoloLens, whereas 6 participants had some familiarity using other AR/VR headsets. The remaining 7 participants had no experience working with any mixed reality headset. 10 participants wore either glasses or contact lenses.

4.2. Results

The majority of participants found the the tutorial very helpful in giving them an insight on the purpose and capabilities of our app. While most users were able to complete the tutorial with ease, some experienced some difficulties with the hand-tracking system of the HoloLens, citing issues with its gesture recognition and accuracy.

Figure 10 provides an overview on some feedback regarding the functionalities of our app. Overall, the placement of points and planes felt easy and straightforward for the participants. The UI controls were considered responsive and user-friendly, and many participants found the application intuitive to use. However, the most critical feedback we received, was that only a few participants could envision using the headset for an extended period of time (more than one hour). This could be a crucial disadvantage against our application when comparing it to the traditional approach of using a goniometer. Moreover, users could submit as free text any other feedback they may have had. Through this, we noted that several users reported troubles with the hand tracking system of the HoloLens, for example the device not recognizing a ”click” action.

5. Discussion

Our findings indicate that mixed reality can provide transformative benefits for bone surgery. The ability to overlay virtual calibration objects simplifies surgical workflows, reduces reliance on traditional tools, and could minimize the need of intraoperative X-ray imaging. However, several limitations must be addressed for broader clinical adoption.

Headset comfort and usability: Feedback from our user study highlighted the need for a lighter, more ergonomically designed headset. Extended use may currently be impractical.

Hand-Tracking robustness: HoloLens' hand-tracking system still has some issues in terms of accuracy. These inaccuracy can lead to annoyance and frustration during a surgical procedure, if the surgeons' actions are not properly registered. This could be mitigated by ensuring optimal conditions for the hand-tracking system, such as optimal lighting.

Bone-Tracking robustness: While the qr code tracking worked effectively in tracking the bone, lag during dynamic movements needs improvement. Future iterations should explore alternative tracking systems, such as optical markers or infrared-based trackers, for higher accuracy and responsiveness.

While our prototype demonstrates promise, further refinements are necessary to fully align with the needs of clinical practice.

6. Conclusion

Our app represents a first mixed reality prototype to guide surgeons during bone surgeries. It illustrates the potential to revolutionize bone surgery by providing precise virtual overlays for guiding osteotomies. The integration of real-time bone tracking (through qr codes) and intuitive virtual object manipulation reduces reliance on traditional tools. While promising, challenges related to hardware comfort, tracking latency, and clinical adaptability must be addressed. The insights gained from this work lay a strong foundation for future innovations in MR-assisted surgeries.

7. Future work

An important feature would be the incorporation of surgical tools into the system. By applying trackers on them, the app could tell the distance and orientation of the tool to a virtual (cut) line or plane. This would ensure the correct placement of, for example a saw blade and further improve

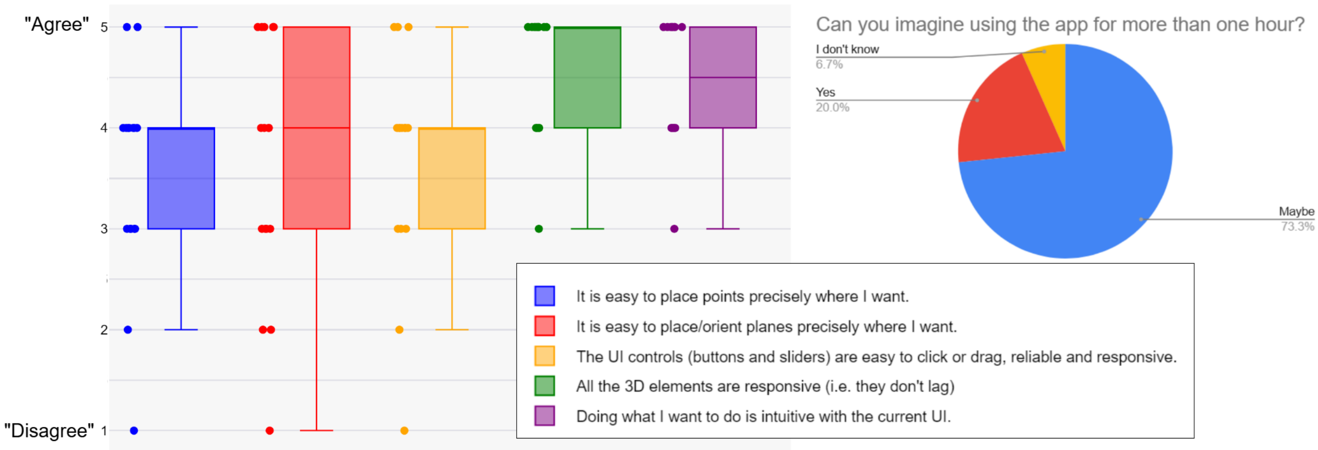


Figure 10. Results of the user study. Usability questions had to be answered on a scale from 1 (Disagree) to 5 (Agree). Boxplots along with the data points show answers to these usability questions, indicating a generally positive trend. The pie chart shows whether users are inclined to use the application for a prolonged time.

precision of the cut. In addition, the ability to share the information overlaid between several surgeons or assistants could improve collaboration. This could be accomplished by, for example, leveraging the HoloLens' spatial anchor feature [10]. Moreover, one could explore using a different tracking system such as Vuforia's multitarget box tracking [1] to improve the robustness and latency of tracking the bone being operated and allow it to be tracked from various viewpoints. Finally, it is important to do a user-study with actual surgeons in a clinical setting to get more valuable information on the benefits and disadvantages of using MR for bone surgery.

References

[1] Multi Targets — Vuforia Library — developer.vuforia.com. https://developer.vuforia.com/library/objects/multi-targets. [Accessed 04-01-2025]. 6

[2] Altair da Silva Costa. Assessment of operative times of multiple surgical specialties in a public university hospital. *Einstein*, 15:200 – 205, 2017. 2

[3] Elisabetta Ferrari, Mariam Khan, Jack Mantel, and Robert Wallbank. The assessment of muscle fatigue in orthopedic surgeons, by comparing manual versus automated broaching in simulated total hip arthroplasty. *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine*, 235:1471 – 1478, 2021. 2

[4] Richard T. Griffey and Aaron Sodickson. Cumulative radiation exposure and cancer risk estimates in emergency department patients undergoing repeat or multiple ct. *American Journal of Roentgenology*, 192(4):887–892, 2009. PMID: 19304691. 3

[5] D. Hambright, Michael Hellman, and Robert Barrack. Intraoperative digital imaging: assuring the alignment of components when undertaking total hip arthroplasty. *Bone Joint Journal*, 100-B:36–43, 01 2018. 3

[6] Stephen M. Howell, Alexander Johannes Nedopil, and Maury L. Hull. Negligible effect of surgeon experience on the accuracy and time to perform unrestricted caliper verified kinematically aligned tka with manual instruments. *Knee Surgery, Sports Traumatology, Arthroscopy*, 30:2966 – 2974, 2022. 2

[7] Lukas Jud, Javad Fotouhi, Octavian Andronic, Alexander Aichmair, Greg Osgood, Nassir Navab, and Mazda Farshad. Applicability of augmented reality in orthopedic surgery–a systematic review. *BMC musculoskeletal disorders*, 21:1–13, 2020. 1

[8] Microsoft. Microsoft hololens. https://www.microsoft.com/en-us/hololens/. Accessed: October 6, 2024. 3

[9] Microsoft. Mixed Reality Toolkit 3 Developer Documentation - MRTK3 — learn.microsoft.com. https://learn.microsoft.com/en-us/windows/mixed-reality/mrtk-unity/mrtk3-overview/. [Accessed 30-12-2024]. 3

[10] Microsoft. Spatial anchors. https://learn.microsoft.com/en-us/windows/mixed-reality/design/spatial-anchors, 2023. Accessed: October 6, 2024. 6

[11] Microsoft. Qr code tracking overview. https://learn.microsoft.com/en-us/windows/mixed-reality/develop/advanced-concepts/qr-code-tracking-overview, 2024. Accessed: October 6, 2024. 4

[12] Ankur S. Narain, Fady Y. Hijji, Kelly H. Yom, Krishna T. Kudaravalli, Brittany E. Haws, and Kern Singh. Radiation exposure and reduction in the operating room: Perspectives and future directions in spine surgery. *World Journal of Orthopedics*, 8:524 – 530, 2017. 2, 3

[13] K. Stokbro, E. Aagaard, P. Torkov, R.B. Bell, and T. Thygesen. Virtual planning in orthognathic surgery. *International*

Journal of Oral and Maxillofacial Surgery, 43(8):957–965, 2014. 1

[14] Max J. Zinser, Hermann F. Sailer, Lutz Ritter, Bert Braumann, Marc Maegele, and Joachim E. Zöller. A paradigm shift in orthognathic surgery? a comparison of navigation, computer-aided designed/computer-aided manufactured splints, and "classic" intermaxillary splints to surgical transfer of virtual orthognathic planning. *Journal of Oral and Maxillofacial Surgery*, 71(12):2151.e1–2151.e21, 2013. 1