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Mixed Reality and Artificial Intelligence: A Holistic Approach to Multimodal Visualization and Extended Interaction in Knee Osteotomy

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ABSTRACT Objective: Recent advancements in augmented reality led to planning and navigation systems for orthopedic surgery. However little is known about mixed reality (MR) in orthopedics. Furthermore, artificial intelligence (AI) has the potential to boost the capabilities of MR by enabling automation and personalization. The purpose of this work is to assess Holoknee prototype, based on AI and MR for multimodal data visualization and surgical planning in knee osteotomy, developed to run on the HoloLens 2 headset. Methods: Two preclinical test sessions were performed with 11 participants (eight surgeons, two residents, and one medical student) executing three times six tasks, corresponding to a number of holographic data interactions and preoperative planning steps. At the end of each session, participants answered a questionnaire on user perception and usability. Results: During the second trial, the participants were faster in all tasks than in the first one, while in the third one, the time of execution decreased only for two tasks (''Patient selection'' and ''Scrolling through radiograph'') with respect to the second attempt, but without statistically significant difference (respectively $p = 0.14$ and $p = 0.13$, $p<0.05$). All subjects strongly agreed that MR can be used effectively for surgical training, whereas 10 (90.9%) strongly agreed that it can be used effectively for preoperative planning. Six (54.5%) agreed and two of them (18.2%) strongly agreed that it can be used effectively for intraoperative guidance. Discussion/Conclusion: In this work, we presented Holoknee, the first holistic application of AI and MR for surgical planning for knee osteotomy. It reported promising results on its potential translation to surgical training, preoperative planning, and surgical guidance.

INDEX TERMS Lower limb osteotomy, surgical planning, image segmentation, deep neural networks, extended reality.

Clinical and Translational Impact Statement - Holoknee can be helpful to support surgeons in the preoperative planning of knee osteotomy. It has the potential to impact positively the training of the future generation of residents and aid surgeons in the intraoperative stage.

I. INTRODUCTION

OSTEOARTHRITIS is the most widespread joint disease in adults worldwide [1]. The prevalence of osteoarthritis in the knee affects 37% of subjects over 60 years old and causes stiffness, muscle weakness, and reduced joint range of motion [2], [3]. Knee osteoarthritis is associated with a greater prevalence of cardiovascular diseases (heart failure and ischemic heart disease) [4]. It significantly limits a person's ability to manage other conditions, such as diabetes, and hypertension since the related pain is associated with reduced

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physical activity [4]. Hyaline joint cartilage is the knee structure where osteoarthritis begins [5]. Its diagnosis is based on history, physical, and imaging examination [5]. Osteoarthritis is revealed on conventional radiographs (X-rays). However, symptoms may arise before the damage can be seen in X-rays. For this reason, more advanced imaging examinations should be preferred. Magnetic resonance imaging can detect degenerated cartilage or bone fragments lodged in the joint, while computed tomography (CT) can identify osteophytes (bone spurs) and the ways they affect adjacent soft tissues. Ultrasound can detect synovial cysts that sometimes form in people with osteoarthritis. Treatment of osteoarthritis includes physiotherapy, orthopedic aids and orthoses, pharmacotherapy, and finally surgery and rehabilitation [5]. Surgery is indicated when the more conservative approaches have been unsuccessful [5]. Joint-preserving surgical treatment options are symptomatic (lavage, shaving, and debridement), bone-stimulating (drilling, micro fracturing, abrasion arthroplasty), joint surface restoration (autologous chondrocyte transplantation and autologous osteochondral transplantation), and corrective osteotomy near the joint. Osteotomy is a surgical procedure aiming to correct varus/valgus knee, in particular, deviations of the weight-bearing line to decrease the load in the diseased area, thus reducing pain and delaying the progression of osteoarthritis [6]. There are two types of knee osteotomy. The first, called high tibial osteotomy, is the surgical procedure to fix the varus knee. It consists of shifting the weight-bearing line laterally to offload the damaged medial area. The other one, distal femoral osteotomy, is intended to treat the valgus knee. It consists of shifting the weight-bearing line medially to offload the lateral area. For both procedures two techniques can be employed: closing wedge and opening wedge osteotomy, to respectively remove or open a wedge of bone. Before the execution of osteotomy, a planning phase is necessary to calculate the correction angle required for recovering the alignment between the weight-bearing line, also known as the mechanical axis of the lower limb, and the line formed by the mechanical axes of the femur and tibia [7]. New devices for preoperative planning and intraoperative guidance are available to address the increasing complexity of orthopedic surgery [8]. Such devices show information on 2D screens and need to be placed outside the surgical field [8]. With the emergence of computer-aided techniques 2D surgical planning has been replaced by 3D models from CT scans [9]. Orthopedics has benefited considerably from recent advanced technologies like 3D modeling, 3D printed patient-specific instrumentation, virtual reality (VR), augmented reality (AR), and mixed reality (MR) [8], [10]. VR, AR, and MR are different immersive technologies that fall under the category of extended reality [11]. The launch of cheap see-trough headsets for mixed-reality like Vuzix M400, Toshiba DynaEdge, Epson Moverio BT-300, and Microsoft HoloLens 2 by Microsoft (Redmond, WA, United States) promoted the development of new immersive applications. While all such devices provide the same frame rate at 30 fps for the visualization, Microsoft Hololens 2 provides the greatest field of view (FOV) and the wider display spatial resolution of 2048 × 1080 (Table 1). Several studies on clinical applications in orthopedics using AR and MR were documented by recent reviews [10], [12]. They pertain to osteotomy, arthroplasty, trauma, orthopedic oncology, training, and education. MR represents a cutting-edge evolution of AR seamlessly merging digital and physical objects into a unified environment, enabling dynamic interaction and coexistence between the two realms [11]. When applied to orthopedic surgery, MR would enable the planning of the intervention by displaying the 3D anatomy of the patient, and simulating how to safely cut the bone, how to design the direction and angle of the osteotomy, and how to place the device. In a notable case report, a system was meticulously crafted using the HoloLens 2 technology for planning and simulating a total knee arthroplasty procedure in a 71-year-old patient [8]. Concurrently with the emergence of MR technologies, there have been substantial advances in artificial intelligence (AI) tools, such as convolutional neural networks (CNN), that showcased the potential of greatly automatizing image processing in many different clinical applications, for diagnostic and surgical planning purposes [13]. In orthopedics, CNN models were applied for the segmentation of knee bones and cartilage from magnetic resonance imaging providing invaluable support in the diagnosis of osteoarthritis [14], [15], for the automatic segmentation of bones in knee CT scans for the realization of personalized cutting guides [7], [16], [17], for total knee arthroplasty planning using X-ray radiographs [18], [19], [20]. Some initial studies have explored the potential of integrating AI tools with technologies for extended reality in hip and knee arthroplasty [21]. The authors highlighted the substantial advantage of reducing physicians' "busywork" of data collection and analysis. Likewise, several identified challenges, primarily revolving around the quality of image segmentation and model reconstruction, were emphasized for their direct impact on the surgical planning and execution processes. As a main finding, they suggest the adoption of wide and heterogeneous training data sets and careful cross-validation of the results. In this paper, we described a holistic approach to AI and MR, leading to a new holographic environment to visualize multimodal clinical and

TABLE 1. Head-mounted displays technical features. Type: monocular (M) or binocular (B), Mic: microphone presence (Y) or absence (N), Camera: sensor horizontal resolution, Display: holographic screen resolution, OS (operating system) android (A), windows (W).

Name	Type	Mic	Camera	Display	OS	FOV
Vuzix M400	M	Y	4k	640 480	A	17°
Toshiba Dynaedge	M	Y	1080p	640 480	W-Pro	17°
Epson Moverio	B	N	1080p	640 480	A	23°
Microsoft Hololens 2	B	Y	1080p	2048 1080	W-Holo	52°

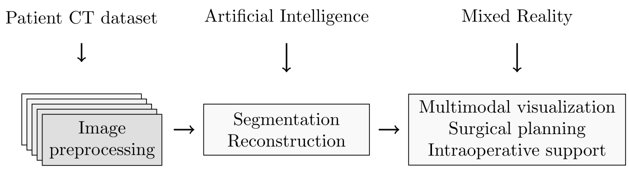

FIGURE 1. Pipeline of Holoknee system.

computer-generated data using the HoloLens 2 device. The holographic environment, called Holoknee, was specifically developed for knee osteotomy, providing specific functions to display and interact with clinical and planning data, patient images, and bone surfaces. Surgical planning and simulation of bone cutting were enabled thanks to specific holographic windows. In addition, Holoknee was extended to gather and display in real-time vital signs thanks to an integrated full-stack client-server web app. Technical functionalities were tested by a group of participants with different levels of experience in orthopedic surgery, executing a set of tasks in the holographic environment. The usability and user perception of Holoknee were finally assessed through questionnaires in the context of its potential translation to clinical practice. The contributions of the paper can be thus summarized as:

- unique holographic environment to integrate multimodal clinical data;
- holographic tools to interactively plan the knee osteotomy;
- interoperability tools to gather vital signs from monitoring equipment and holographic tools to display them in real-time;
- functionality and usability of Holoknee environment to assess the potential translation in clinical practice.

II. METHODS AND PROCEDURES

The pipeline of the whole system is depicted in Fig. 1. It includes the following modules devoted to: a) image preprocessing (Data preparation module), b) automatic AI-based image segmentation and surface reconstruction (SegMentor module), c) Unity-based multimodal visualization, preoperative planning, and intraoperative support running on the HoloLens 2 headset (Holoknee module).

A. ANALYZED DATASET AND DATA PREPARATION MODULE

Two datasets were available for this study. The first one (D1) was devoted to training the segmentation network in the SegMentor module while the second one (D2) was devoted to testing the Holoknee module. The dataset D1 was composed of 700 axial knee CT scans of patients who underwent total knee replacement surgery from 2015 to 2020. They were retrospectively available in anonymized form by Medacta International SA (Castel San Pietro, TI, Switzerland) [22]. The patients suffered from advanced osteoarthritis with different degrees of cartilage defects, femoral osteophytes, and shape abnormalities mainly at the condylar regions of the distal femur and at the tibial plateau. Each scan was associated with the corresponding label mask of the distal femur and proximal tibia. 500 CT scans were used for training and 200 for testing the segmentation network according to the work performed in [22]. Dataset D2 was composed of 12 retrospective patients who underwent osteotomy between 2017 and 2021 at ASST FateBeneFratelli Sacco Hospital in Milan. The dataset was available in anonymized form under the approval of Ethics Committee Area 1 (ASST Fatebenefratelli Sacco Hospital, protocol number: `ORTO_01_2021_JMRF`). Because of differences in scanning equipment, CT scans of both D1 and D2 datasets underwent preprocessing steps to ensure consistency in pixel intensity distribution and spatial dimensions. Firstly, pixels corresponding to the filling background and air were automatically identified in the images using information from the DICOM file header, and their corresponding intensity values were set to zero. The remaining image pixels underwent intensity normalization, which accounted for the different gray scales (Hounsfield map, raw 12 bits, raw 16 bits). All scans first underwent cropping and then patching to extract sub-volumes of size $144 \times 144 \times 144$ pixels to speed up the training of the segmentation network.

B. SEGMENTOR MODULE

SegMentor comprised two submodules, one for image segmentation and the second for 3D surface reconstruction. Automatic CT scan segmentation was attained by adopting the CEL-UNet, a variant of UNet [23], which was proposed by our group in [22] to segment DICOM scans. CEL-UNet adds some new features to UNet [17], namely 1) an additional decoding branch to detect contours, 2) directed connections between contour and region branch progressively at different decoding scales, pyramidal edge extraction in the contour branch to perform multi-resolution edge processing, 3) distance-weighted cross-entropy loss function to increase delineation quality at the sharp edges of the shapes (Fig. 2). The encoder of CEL-UNet consisted of three blocks with convolutional layers, rectifying linear unit (ReLU) activation function, and max-pooling layers. As illustrated in Fig. 2, the decoder was split into two parallel branches, one for region segmentation and the other for edge detection. In the decoder, ReLU was inserted between the Convolutional and Pyramidal Edge Detector layers. Skip connections between the corresponding blocks of region segmentation and edge detection were established to improve segmentation. This enabled the aggregation between edge and region features at progressively increasing spatial scales. One computing cluster, equipped with one A100 graphic processing unit (GPU) by Nvidia (Santa Clara, CA, United States) with 40 GB of memory was used for training the CEL-UNet on dataset D1 (500 cases). SegMentor was trained with the following settings: epochs = 200, batch size = 6, learning rate = 1e-04 (constant). Once trained, the segmentation process was performed by exploiting a Docker environment and TensorFlow Serving. The 3D surfaces in the STL formats were

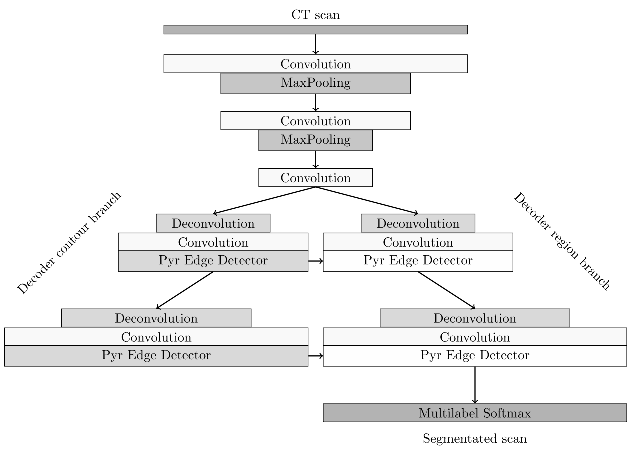

FIGURE 2. Simplified CEL-UNet architecture.

reconstructed automatically by a custom method based on the marching cubes algorithm to provide the final output. Overall, SegMentor was implemented using the following Python libraries: Pydicom (to work with DICOM datasets), Nibabel (to access neuroimaging files like NifTI), Scikit-image (for image processing and computer vision), Pyvista (for meshes), Numpy-stl (for STL files), Numpy and TensorFlow. Training and testing were carried out on a PowerEdge R740 with an Intel Xeon Platinum 8260L CPU and 512 GB RAM. Metrics evaluation was performed to assess both segmentation and surface reconstruction quality. The segmentation quality provided by the CEL-UNet was tested reporting the median and inter-quartile ranges of Jaccard index, recall, and precision, in comparison with two traditional UNet models, trained using either Dice or focal loss. The reconstruction error was reported in terms of root mean squared error (RMSE). In addition, time quantification for each step of the SegMentor pipeline was provided.

C. HOLOKNEE MODULE

Holoknee was developed as an immersive environment devoted to the femur and tibia osteotomy. Overall, it coped with multimodal data visualization, and preoperative planning making vital signs available in the visualization area. It was developed by incorporating:

- a file-manager Python application to manage patient data organization remotely on Microsoft Azure cloud storage;
- Unity-based application, exploiting Mixed Reality Toolkit (MRTK), running on board the HoloLens 2;
- an interoperable client-server application based on OpenICE (Open-source Integrated Clinical Environment) protocol (https://www.openice.info/) for gathering vital signs from in-room medical equipment and delivery in real-time to the holographic visualization.

1) MULTIMODAL HOLOGRAPHIC VISUALIZATION AND PRE-OPERATIVE PLANNING

This function enables the visualization of holographic window panels embedding textual clinical data, x-ray images, CT scans, and planning documents, which are retrieved automatically from Microsoft Azure cloud storage. Thanks to the Segmentor module, it allows fast visualization of accurate proximal tibial and distal femoral surfaces. Interaction with the holograms is ensured by the built-in capture technologies (voice, hand/fingers) on the HoloLens 2. The Holoknee virtual room consists of eight scenes, namely 1) SelectPatientScene to select a specific patient from a dropdown list, 2) DataScene including patient demographic information, X-Ray images, CT images, and planning (Fig. 3), 3) LoadingCTScene to subdivide CT scans into axial, sagittal, and coronal views, 4) CTScene to display the axial, coronal, and sagittal slices for the selected CT volume, 5) 3DModelScene to visualize the 3D surface models of the tibia and the femur and to allow the surgeon to manipulate the models using hand motions to rotate, zoom, and move them, 6) XRayPlannigScene to compute the femur/tibia correction angle to restore the correct mechanical axis of the lower limb by picking the hip, knee, and ankle joint centers, 7) SimulationScence to simulate eight different surgical scenarios by considering the combination of the right/leg, tibia/femur bone, and anatomical medial/lateral side, and closing/opening type of operation. In the previous scene, the bone wedge is obtained by tilting and translating two virtual cutting planes (red and green, see Fig. 4), which are to be properly set to cope with the planned correction angle. A video showing the surgical planning steps integrated into Holoknee is provided as a Supplementary file.

2) INTRAOPERATIVE SUPPORT TO REAL-TIME MONITORING AND VISUALIZATION OF VITAL SIGNS

Intraoperative support in Holoknee is enabled to interoperate with different in-room medical devices. Vital signs can be gathered in real-time and conveyed to the HoloLens 2 for visualization. This function was conceived to provide live access to the patient status in the unique virtual room of the Holoknee. The developed application was based on the client-server full-stack paradigm implemented in Javascript. The server was implemented in Express.js, an open-source framework to develop RESTful APIs in Node.js, an open-source runtime environment enabling server-side Javascript execution. The client consists of a web application called OpenICE2Web for the aggregation and visualization of the data. OpenICE2Web connects to the server and receives real-time information from a Python module and a Java-based OpenICE client (Fig. 5). One prototype test of the intraoperative support was performed by simulating the acquisition of cardiovascular signals using the Finometer (Finapres, The Netherlands) equipment, which was interfaced via OpenICE to the client. The acquired blood pressure signals (finger and brachial artery) were encoded in the server and transmitted to the OpenICE2Web page. Along with blood pressure raw signals, heart rate and blood oxygen saturation could be gathered from the Finometer and visualized in real-time (Fig. 5). Performances of the full-stack application were tested with Autocannon and Lighthouse for, respectively,

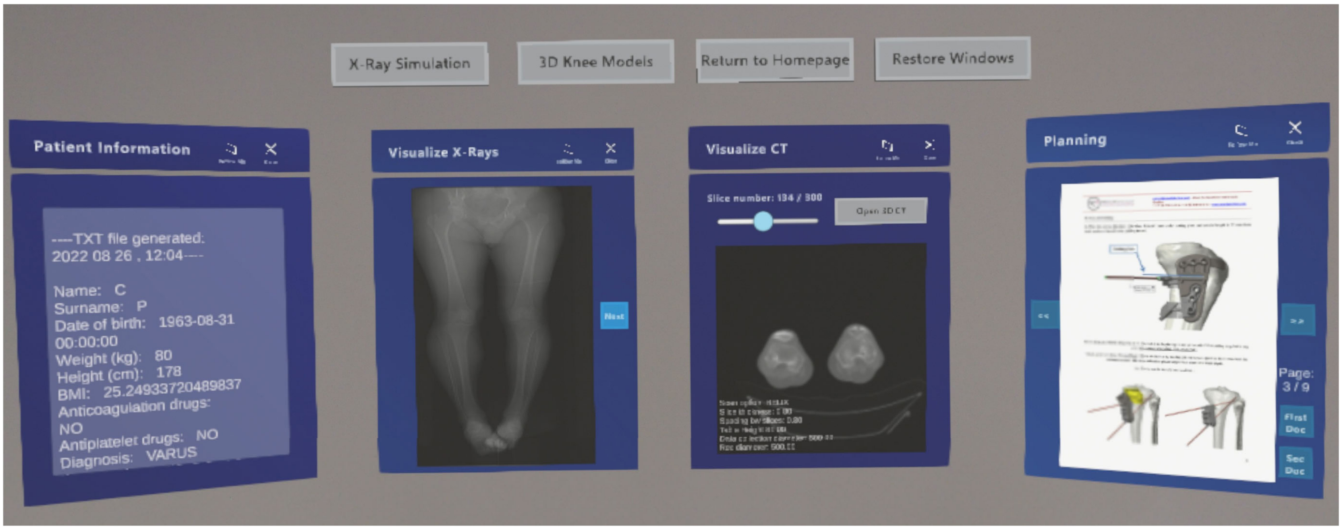

FIGURE 3. **Holoknee DataScene. Once the user selects the patient, the main holographic view can be browsed. It is composed of four main windows, including patient clinical information, the radiographic images, the CT scan, and the document describing osteotomy surgical planning.**

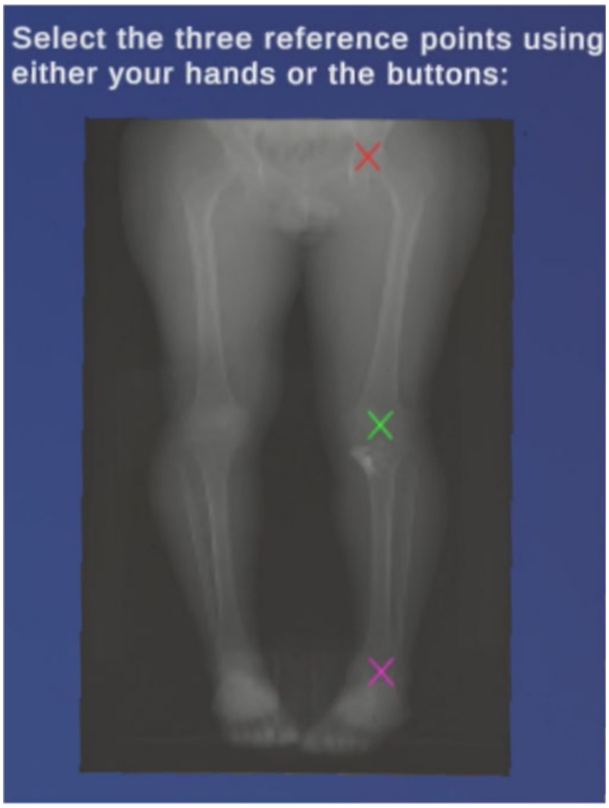

FIGURE 4. **Holoknee PlanningScene. This scene enables the user to pick the hip, knee, and ankle joint centers to draw the deviation of the femur and tibial mechanical axes from the lower limb mechanical axis.**

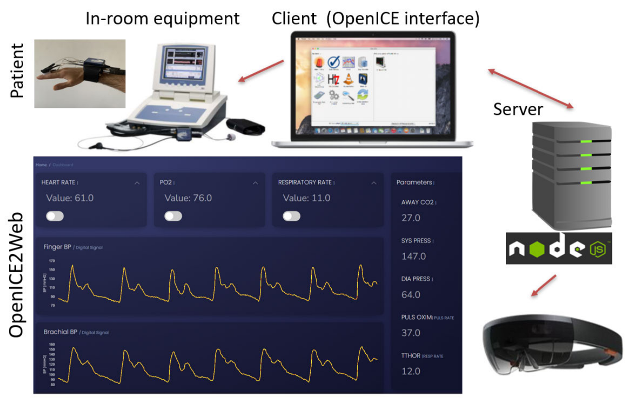

FIGURE 5. **Architecture of Holoknee intraoperative support for monitoring and visualization of patient vital signs. Interoperability was ensured by OpenICE protocol. The present test reports blood pressure, heart rate, and SpO2 recorded by the medical-certified Finometer system.**

server and client sides. The server was assessed in terms of the number of requests handled per second (throughput), the response time of the server to each request (latency), how it manages multiple requests at the same time (concurrency), high load (stress), and the maximum load (load capacity).

D. CLINICAL TESTING

1) STUDY DESIGN

A cohort of 11 participants (one medical student, one surgical resident in orthopedics, and nine expert orthopedic surgeons) from Fatebenefratelli Sacco Hospital in Milan tested Holoknee. The participant group included two females and nine males. The surgeons had a mean of 17.4 ± 13.0 years of experience. The test sessions were conducted in the hospital and in the CartCas laboratory at Politecnico of Milano in Milan. The subjects executed three times the first six tasks described in Table 2. In the first session, the participants performed two trials on the same day to assess possible improvements in user performance. Feedback from the users was gathered concurrently. For instance, one main criticism was about the scarce sensibility of hand gesture tracking. All issues were analyzed and modifications were quickly performed (it took some working days) on the system

TABLE 2. List of tasks executed by the study participants.

	Requested Task	Abbreviation	Evaluation Method	Requested Interactions
1	Open Holoknee application from the homepage	AC	Time to complete the task	Open home page, press button
2	Select a patient from the initial menu and read a specific parameter from the Patient Information window ("select the '20170608varmm' folder and read out loud the height of the patient")	IN	Time to complete the task	Selection from the dropdown, press button, read data
3	Read specific information from the surgical planning in the Planning window ("bring the window closer to you using your hand or the dedicated button, go to the second page and read me the distance in the figure")	PL	Time to complete the task	Move window, press button, read data
4	Load the CT images and scroll through them ("press the button 'Load CT images', wait until all the images are loaded and then scroll through them")	CT	Time to complete the task	Move window, press button, read data
5	Access the 3D CT of the knee and slide the axial, coronal, and sagittal slices ("press the button 'Load 3D CT', wait until the page is loaded, then press 'Visualize 3D CT' and scroll the different planes of the CT")	3D	Time to complete the task	Press button, move slider, move, scale, and rotate object
6	Scroll through all the radiographs in DataScene	XR	Time to complete the task	Move window, press button
7	Perform a cutting angle simulation in the XRaySimulationScene	-	Capability to complete the task	Press button, move objects
8	Open 3D models of the patient and open the SimulationScene	-	Capability to complete the task	Press button, move, scale, and rotate objects

accordingly. With the updated system, the user repeated (third trial) the test one week later. During all test sessions, a tutor was present to provide participants with instructions on using HoloLens 2 device and Holoknee application. The time to complete each exercise of Holoknee was used as a metric for assessment. A statistically significant difference was assessed for statistically significant difference ($p<0.05$).

2) USABILITY AND USER PERCEPTION

At the end of each session, all participants answered a questionnaire to evaluate Holoknee in terms of usability and user perceptions. The first one concerned Health Technology Assessment (HTA), a framework evaluating healthcare technologies with a multi-disciplinary approach [24]. In particular, the authors decided to evaluate clinical efficacy and effectiveness, safety, and organizational impact among the dimensions of impact proposed by the HTA Core Model® provided by the European Network for Health Technology Assessment (EUnetHTA) [25]. Being Holoknee a prototype, it was possible to conduct HTA only at an early stage, and these dimensions were considered the most suitable for this aim. The participants were asked to evaluate these dimensions through closed questions with a 5-point Likert scale, ranging from Strongly Disagree to Strongly Agree, or with options to select. The second survey was administered to doctors after the second session to assess the usability of Holoknee.

III. EXPERIMENTAL RESULTS

A. SEGMENTOR MODULE PERFORMANCE

The median values on Jaccard, precision, and recall for the tibia and femur exceeded respectively 0.95 and 0.92 (Fig. 6). In particular, CEL-UNet architecture outperformed D-UNet and F-UNet, variants of the traditional UNet, trained respectively with dice loss and focal loss, respectively. These outcomes were supported by a statistical comparison, performed with a Kruskal-Wallis test, that stated the superiority ($p<0.001$) of the CEL-UNet for the three indexes. The reconstruction results of the tibia and femur surfaces were below 1 mm, with higher accuracy for the reconstructed tibia shapes (Fig. 7). Again, statistical analysis confirmed the superiority of the CEL-UNet with respect to traditional UNet ($p<0.001$). Overall, the computational cost, from image preprocessing to 3D reconstruction of tibia and femur surfaces, was quantified (Table 3). The segmentation process required the highest time with a median value of 2.5 s, while the reconstruction of the femur was slower than the one of the tibia (2.1 vs 1.6 s, respectively) since the distal femur is usually larger than the proximal tibia in the cropped CT scans. With a median time of 7.8 s for the whole process, SegMentor was able to provide at the same time both an accurate and fast approach that could provide support for the preoperative planning procedures (Table 3).

TABLE 3. Time metrics of the SegMentor pipeline as median and inter-quartile range values.

Operation	Time [s]
CT Preprocessing	1.4 (1.1-1.8)
CT Segmentation	2.5 (1.8-3.4)
Tibia Reconstruction	1.6 (1.2-2.1)
Femur Reconstruction	2.1 (1.5-2.8)
Overall	7.8 (5.9-10)

B. OPENICE2WEB TESTS

During the throughput test, the average value of latency ranged from 19.9 ms to 1,373.9 ms for respectively 10 and 500 connections. During the latency test, the average value of latency varied between 32.5 ms and 958.4 ms for respectively 10 and 500 connections. During the concurrency test, the average value of latency rose from 17.8 ms to 1,103 ms

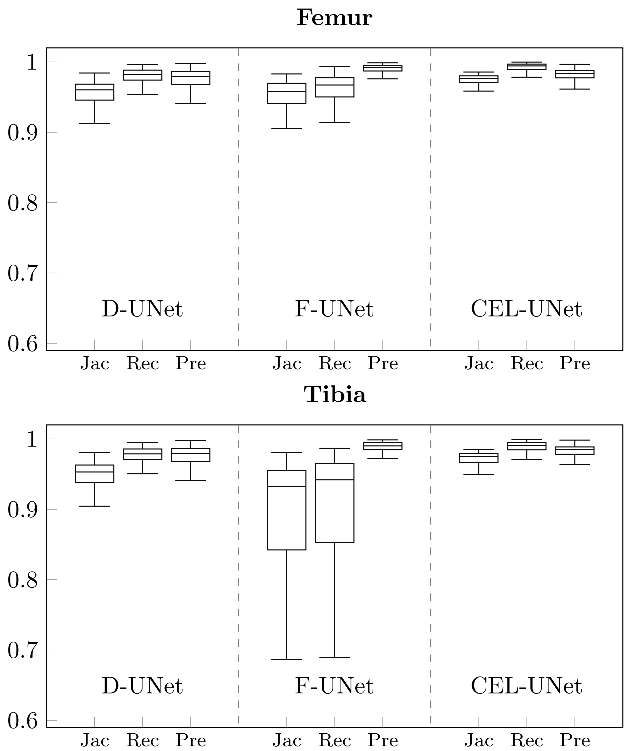

FIGURE 6. Boxplots of Jaccard, Recall, and Precision results computed on the test set comparing the three different networks for the femur (upper plot) and tibia (lower plot). D-UNet (trained with dice loss) and F-UNet (trained with focal loss).

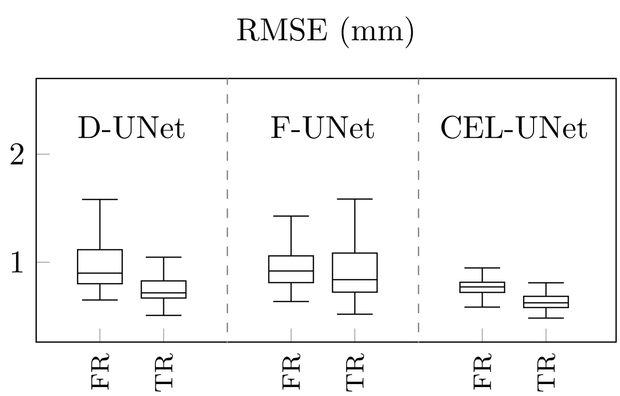

FIGURE 7. Boxplots of global RMSE reconstruction (mm) computed on the test set comparing the three different networks. *FR*: Femur RMSE; *TR*: Tibia RMSE. D-UNet (trained with dice loss) and F-UNet (trained with focal loss).

for respectively 10 and 500 connections. During the stress test, the average value of latency increased from 17.9 ms to 1,220 ms for respectively 10 and 500 connections. During the load capacity test, the average value of latency ranged from 17.7 ms to 1,134 ms for respectively 10 and 500 connections. The Dashboard page achieved a score of 99, 98, 92, and 100 on, respectively, performances, accessibility, best practice, and search engine optimization. The Monitor page obtained slightly lower scores than the Dashboard one in terms of performance (86), accessibility (97), and the same on best practice (92), and search engine optimization (100). Finally, the Parameters pages reached 98 on performance, 91 on accessibility, 92 on best practice, and 100 on search engine optimization.

C. CLINICAL TESTS: QUANTITATIVE PERFORMANCE

The time to complete the tasks during the three trials (two in the I session and one in the II session) is reported in Table 4. During the second trial of the I session, the participants were faster in all tasks than in the first one with a statistically significant difference in all tasks with the exception of IN ($p = 0.13$) and 3D ($p = 0.96$) tasks. In the third trial, the time of execution decreased only for two tasks with respect to the second trial, i.e. IN and XR tasks. There was no statistically significant in any task between the second and third trials.

D. CLINICAL TESTS: QUALITATIVE EVALUATION

1) TRAINING

All participants from orthopedics strongly agreed that MR can be effectively used for surgical training (Table 5). For eight orthopedic surgeons (72.7%) the greatest concern during surgical training is related to technical issues (e.g., Internet connection, and battery out of charge). Concerning the organizational impact, for six participants (54.5%) users would take little time to use correctly the technology.

2) PREOPERATIVE PLANNING

For all participants, MR can be effectively used inside the preoperative phase, while for 10 (90.9%) the system can help the surgeon to perceive the anatomy of the patient in a better way (Table 6). The main concern during the preoperative phase when using the system is related to technical issues (e.g., Internet connection, and battery out of charge) for eight subjects, followed by the lack of reliable information technology infrastructure for three of them. For eight participants (72.7%) HoloLens 2 could help to have access to clinical data of the patient during the operation.

3) INTRAOPERATIVE PHASE

Results of the first survey on the intraoperative stage are reported in Table 7. For eight participants (72.7%) MR can be used effectively in the operating room, while for 10 (90.9%) the developed system would increase the accuracy of surgical performance. For seven (63.6%) Holoknee would reduce the stress of the surgical team. Concerning safety, for seven (63.6%) the use of HoloLens 2 would not impair the surgeon attention. For nine of the interviewed subjects (81.8%), the major concern is represented by technical issues (e.g., Internet connection, and battery out of charge). For seven participants (63.6%) using voice commands to manage the Holoknee is better than hand gesture commands. For nine (90.9%) the developed technology would not increase the size of the surgical team.

E. ASSESSMENT ON USABILITY

All participants with the exception of the medical student participated in the second test session, at the end of which

TABLE 4. Time (in seconds) to complete the six tasks (see Table 1 for task description) across the 11 subjects (one did perform the third trial).

	First trial						Second trial						Third trial					
	AC	IN	PL	CT	3D	XR	AC	IN	PL	CT	3D	XR	AC	IN	PL	CT	3D	XR
Subject 1	40	20	41	120	80	30	20	15	15	30	60	25	50	11	29	73	40	10
Subject 2	30	11	60	60	25	39	12	10	10	20	42	20	22	10	40	50	39	11
Subject 3	40	15	50	70	37	20	20	25	22	58	30	15	33	12	31	46	30	15
Subject 4	31	19	50	60	45	30	2	10	10	45	20	18	26	11	24	56	27	7
Subject 5	60	23	58	60	60	12	33	16	52	55	30	10	24	8	80	60	30	14
Subject 6	44	18	80	80	30	15	30	15	55	50	24	12	22	17	40	71	37	20
Subject 7	80	13	55	90	40	30	15	13	40	50	30	18	25	10	15	60	32	4
Subject 8	60	16	45	90	15	11	45	10	30	50	13	10	26	12	52	57	60	10
Subject 9	31	7	50	60	30	15	60	9	25	40	28	15	32	10	55	76	36	12
Subject 10	39	9	36	16	29	8	25	7	28	11	45	7	–	–	–	–	–	–
Subject 11	48	22	72	93	58	7	34	13	16	66	26	7	28	10	25	48	35	6
Mean	45.7	15.7	54.3	72.6	40.8	19.7	26.9	13.0	27.5	43.2	31.6	14.3	28.8	11.1	39.1	59.7	36.6	10.9
St. Dev.	15.4	5.3	12.9	26.8	18.8	10.8	16.1	4.9	15.7	16.7	12.9	5.7	8.3	2.4	19.1	10.6	9.2	4.7

TABLE 5. Health technology assessment of Holoknee (training phase).

Domain	Statement	Answer
Efficacy and effectiveness	MR can be used effectively for surgical training	Strongly agree (n=11)
Safety	What would be your greatest concern during the training of new surgeons due to the use of the visor?	Technical issues (e.g., internet connection, battery out of charge) (n=8); Adverse symptoms such as nausea, headache, or vertigo (n=1)
Organizational impact	It would take a lot of time to train the employees to correctly use the technology	Agree=1, strongly agree=1, disagree=6, strongly disagree=1, neutral=2

TABLE 6. Health technology assessment of Holoknee (preoperative planning).

Domain	Statement	Answer
Efficacy and effectiveness	MR can be effectively used inside the preoperative phase	agree=1; strongly agree=10
	With Holoknee technology, the surgeon would be able to perceive the anatomy of the patient in a better way	agree=1; strongly agree=9; neutral=1
Safety	What would be your greatest concern during the planning surgery due to the use of the visor?	Technical issues (e.g., internet connection, battery out of charge) (n=8)); Lack of reliable information technology infrastructure (n=3)
Organizational impact	It is easy and already sufficient for the surgeon to have access to clinical data of the patient during the operation	strongly agree=1; disagree=4; strongly disagree=4; neutral=2

they answered a questionnaire to assess the usability of Holoknee technology (Table 8). Overall, according to six subjects (60.0%), the Holoknee technology would reduce the length of a surgical operation. More specifically patient education and preoperative planning are the phases that would benefit the most according to all interviewed. The presence of a dedicated technician to manage possible technical issues would be suggested by all participants. During the second

TABLE 7. Health technology assessment of Holoknee (intraoperative phase).

Domain	Statement	Answer
Efficacy and effectivness	MR can be effectively used inside the operating rooms	agree=6; strongly agree=2; disagree=1; neutral=2
	Holoknee technology could improve the timeliness in the operating rooms	agree=3; strongly agree=2; disagree=2; neutral=4
	Holoknee technology would increase the accuracy of surgical performance	agree=5; strongly agree=5; neutral=1
	Holoknee technology would shorten the surgical duration	agree=4; strongly agree=1; disagree=3; neutral=3
	Holoknee technology would reduce the stress of the surgical team	agree=5; strongly agree=2; disagree=2; neutral=2
Safety	The use of HoloLens device by the surgeons would result in adverse symptoms such as nausea, headache, and vertigo	agree=3; disagree=3; strongly disagree=4; neutral=1
	The use of HoloLens device would impair the surgeon's attention	agree=4; disagree=5; strongly disagree=2
	The use of HoloLens device would overwhelm the surgeon's cognitive load	agree=5; strongly agree=2; disagree=2; strongly disagree=1; neutral=1
	The use of HoloLens device would put the patient's life at risk	disagree=1; strongly disagree=10
	What would be your greatest concern during surgery due to the use of the visor?	Technical issues (e.g. Internet connection, battery out of charge) (n=9)
Organizational impact	Holoknee technology would improve the communication between the surgeon and the surgical team	agree=5; neutral=6
	It would take a lot of time to implement the Holoknee technology in the operating rooms of the hospital (concerning the IT-infrastructure)	agree=2; disagree=5; strongly disagree=1; neutral=3
	Using voice commands to manage Holoknee technology is better than using hand gesture commands	agree=2; strongly agree=5; disagree=2; strongly disagree=1; neutral=1
	The introduction of Holoknee technology would require more people to perform a surgical operation	agree=2; disagree=5; strongly disagree=4

TABLE 8. Usability of Holoknee system.

Statement	Answer
Do you think Holoknee could improve the timing of the surgical process?	Agree=2; strongly agree=4; disagree=2; neutral=2
At what stages of the intervention would Holoknee improve the timing?	Patient education (n=10); preoperative planning (n=10)
In your opinion, is Holoknee helpful in making patients better understand what operation they are about to undergo?	Agree=3; strongly agree=6; neutral=1
Do you think it would be useful to have a specialized Holoknee technician within the operating room to handle possible technical issues? If so, would you be more inclined to use the technology?	Agree=5; strongly agree=5
Could the use of Holoknee impact the number of actors involved in the preoperative phase?	Agree=5; strongly agree=1; disagree=2; neutral=2
Could the use of Holoknee impact the number of actors involved in the intraoperative phase?	Agree=2; strongly agree=2; disagree=1; strongly disagree=1; neutral=4
How do you rate the experience with the HoloLens 2 compared to last week? Has your opinion changed? Do you feel more confident with the technology?	More comfortable (n=8)

test session, eight interviewed (80.0%) felt more comfortable wearing the HoloLens 2 than during the first one.

IV. DISCUSSION

Complex orthopedic surgical procedures, such as corrective osteotomies, necessitate precise preoperative planning and intraoperative guidance [10]. Computer-based technologies have driven significant advancements in visualizing anatomical structures for both preoperative planning and intraoperative procedures, and orthopedics is no exception to these transformative developments [26]. In recent years, AR applications have spread quickly in orthopedics. An AR navigation system for total knee arthroplasty was developed to display the varus/valgus angle and posterior slope angle superimposed on the surgical field on a smartphone screen [27]. When tested on 10 patients, a difference lower than 1.0° was found between the reported angles and the preoperative CT measurements [27]. An AR planning and navigation system for osteotomy in spine surgery showed encouraging results when tested on a patient [28]. Another system consisting of a camera-augmented C-arm overlaying panoramic X-rays onto the surgical video was tested on 25 cadavers with either varus/valgus knees [29]. The AR system reported a strong Pearson's correlation (0.98) with CT scan on axis deviation [29]. In addition to AR, orthopedics has been benefitting also from the rapid advances of AI. CNNs achieved prediction accuracies of 88.2% and 86.3% for femoral components and tibial components, respectively [19]. In another study CNNs, trained on 6,149 radiographs, reported a mean absolute error of 0.8° on femoratibial angle prediction [20]. In another study on 1,842 knees X-ray images, the error obtained by CNNs on hinge point, surgical point, and Fujisawa point was, respectively 2.06±1.16 mm, 2.71±1.45 mm, and 2.01±1.30 mm [30]. In this work, we presented Holoknee, the first application combining AI and MR for preoperative planning in knee osteotomy. The prototype was tested by 11 participants, featuring different levels of experience in orthopedic surgery, who executed six out of the eight designed tasks of Holoknee. The main findings favored the proposed technology thanks to its ability to enhance overall clinical awareness through the immediate accessibility of multimodal data (text and images) within a unified visualization framework, in the planning stage and potentially also in the surgical stage. The advanced 3D simulation underscored the potential of the holographic view for interacting with and manipulating anatomical bone surfaces. Becoming proficient in the effective use of Holoknee requires a learning curve, especially in managing the complexity of holographic manipulation using hand and finger gestures. In particular precise tracking of hand and finger movements is crucial for expediting tasks and reducing cognitive fatigue. Voice commands were recognized as a valuable alternative to hand gestures in certain operations, effectively reducing physical fatigue. Furthermore, all participants strongly supported the capability to access the patient's vital signs within a unified visualization framework. The specific findings showed substantial variability concerning execution time among participants (see. Table 4). The observed performances may be related to differences between the expert surgeons and younger participants in terms of digital literacy, adaptability to new technologies, spatial awareness, perception of extended reality technologies, and attitude toward innovation [21]. Comparison on time of execution among tasks of the Holoknee application is not feasible as some tasks require fewer interactions, and consequently less time, than others. The results of the questionnaires showed that Holoknee has been generally well received by the orthopedic group which recognizes its effectiveness, safety, and organizational impact at the level of training, preoperative planning, and intraoperative guidance. According to some interviewed experts, Holoknee offers advantages in surgical training. First, while there is the chance for expert surgeons to skip some steps while explaining surgical procedures, with Holoknee surgical trainers can review all the steps of a procedure, without missing critical ones. Another important aspect highlighted by orthopedic surgeons is the potential ability to increase accuracy and reduce procedural time using Holoknee in surgical simulation and training. The use of AR in training for orthopedic surgery is largely unexplored [31]. However, the evolution of surgical education has proven that the introduction of novel technologies, like VR surgical simulators, had a positive impact on the effectiveness of training in terms of time and, more importantly, reduction of errors during surgery on real patients [32]. For this reason, we are of the view that AR and MR will expand their range of applications in orthopedic surgery, including education, following the paradigm of VR simulators. Advancements in VR simulation led to mission rehearsal, enabling surgeons to simulate the procedure with patient-specific data before performing the actual procedure on a real patient [33]. The integration of AI into VR surgical simulators had the potential to streamline the segmentation and reconstruction of 3D anatomy for mission rehearsal. This agrees with our findings demonstrating that the SegMentor module in the Holoknee system is capable of completing the entire pipeline (from preprocessing to tibia and femur reconstruction) in less than eight seconds. This signifies a remarkable breakthrough compared to the conventional 3D planning system in orthopedic surgery, which typically demands the manual expertise of radiologists (involving manual delineation in axial image slices, often taking several tens of minutes). Moreover, immersive technologies like AR and MR would allow several users, wearing a headset like HoloLens 2, to share the same simulated scenario, with the potential to make surgical training more efficient, where the surgical trainer can supervise concurrently multiple trainees. However, as with any new generation of surgical simulators, those based on extended reality and AI will need to be thoroughly validated before their integration into the surgical curriculum.

Holoknee system was designed and developed taking into account not only the surgical planning but also the use in the operating room. As showcased, it provides functionalities to interface with medical equipment enabling the surgeons to visualize and interact with, in the holographic view, clinical data and vital signs of the patients. As such, by virtue of an ad-hoc full-stack web app based on the OpenICE interoperability paradigm, Holoknee overcomes traditional 3D visualization software by displaying real-time patient data, directly gathered by in-room equipment. This would be particularly helpful in the intraoperative phase to those members of the surgical team like anesthesiologists, who generally monitor the trend of vital signs. In fact, with Holoknee they can view the surgical scene and vital signs in the same device. The results of this study emphasized that the server exhibits exceptional performance at medium to low connection rates, showcasing its efficiency and capability to display the same information to multiple users concurrently. However, it is important to note that limitations became evident when the number of connections to a single server reached a significantly high level. Under such circumstances, the server faced challenges in handling concurrency, load capacity, stress, and throughput, leading to degraded performance. Therefore, while the server excels in moderate and low connection scenarios, careful consideration should be given due to its limitations when dealing with a large number of connections (multiple users). Immersive technologies hold potential also in preoperative surgical planning, as exemplified by Invision by PrecisionOS (Vancouver, BC, Canada), a VR patient-specific planning tool for orthopedics capable of showing on Oculus Quest 2 the 3D reconstructed models from CT scans. It has recently received clearance from the Food and Drug Administration (FDA). In this regard, Holoknee enhances the user experience of VR solutions by providing surgeons with an interactive environment where virtual content merges with real information thanks to MR. Additionally, the preoperative functionalities of Holoknee can be translated easily into the real operating room in terms of both hardware (HoloLens 2 headset is a commercially available holographic visor) and software (SegMentor module provided accurate

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computer-generated data with a computational cost compatible with the clinical practice). According to the findings of the present work, most participants agreed on the improvements brought by Holoknee to the efficacy and effectiveness in the preoperative planning phase. This agrees with previous studies suggesting that AR can improve the efficiency of the preoperative planning phase and allow the surgeon to better perceive the patient's individual anatomy [34], [35]. Most of the interviewed surgeons agreed on the potential that 3D images can provide valuable information about the patient's anatomy compared with conventional 2D images. When comparing Holoknee with conventional 3D software for preoperative planning, the interviewed surgeons agreed that the main advantage of Holoknee is to enable gesture-based handling of digital data in 3D that is not available in the other tools due to the 2D screen. In summary, the test questionnaires have revealed that Holoknee holds significant potential to influence various aspects of surgery, including preoperative planning and intraoperative procedures. Additionally, the consensus among clinicians suggests that Holoknee may also have an impact on the timing of surgical processes. Notably, many operating rooms face constraints related to limited physical space, making it challenging to accommodate additional equipment such as external monitors. In this regard, Holoknee offers a promising solution by providing the surgical team with a single, compact device that can display diverse information, encompassing medical images and real-time vital signs. This study has some limitations. First, Holoknee was tested by a small and heterogeneous group of participants. Second, the tests on usability and user perception depended strictly on the stability of the Internet connection, with a slow connection in the hospital setting. Some efforts should be addressed before the translation of Holoknee into clinical practice. Future developments include the design of surgical simulation tasks, the integration into the intraoperative phase, and improving the stability of the network. However, the most important step concerns the validation of the system in the operating room to see if Holoknee leads to better patient outcomes.

V. CONCLUSION

In this work, we presented Holoknee, a holistic solution based on AI and MR for the preoperative planning of knee osteotomy. Starting from a CT scan of a real patient, Holoknee allows quick segmentation thanks to CEL-UNet and visualization of clinical and computer-generated data on HoloLens 2. The system allows also displaying of vital signs thanks to a full-stack web app, consisting of a server sending the signals to a client which shows the data on a web interface, which in turn is rendered on HoloLens 2. Holoknee was tested by 11 subjects (8 orthopedic surgeons, two residents in orthopedics, and one medical student) on six different tasks, executed three times. The results have shown that their performances in the usage and holographic interaction improved over trials. Holoknee was also assessed by the participants in terms of usability and user perception of surgical training, preoperative planning, and intraoperative guidance on osteotomy. The findings reported encouraging results. Future research will target extended validation of Holoknee in clinical settings.

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VI. CONFLICT OF INTEREST

The authors declare no conflict of interest.

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