Geometrical Descriptors for Human Face Morphological Analysis and Recognition

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Research paper

A mixed reality framework for interpretable and explainable joint replacement assessment

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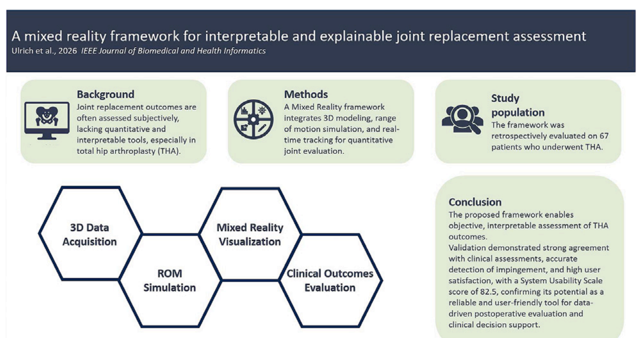
HIGHLIGHTS

- A Mixed Reality framework for objective joint replacement assessment is presented.
- 3D modeling and ROM simulation are used for advanced visualization of prosthesis mechanics.
- Accurate anatomical alignment through MR tracking enables real-time feedback.
- Retrospective and usability analysis are consistent with clinical and literature data.

GRAPHICAL ABSTRACT



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ABSTRACT

Objective: Joint replacement surgery, also known as arthroplasty, is a common procedure that restores mobility and relieves pain in patients with severe joint pathologies. Despite being considered routine, arthroplasties are complex interventions with potential complications and variable clinical outcomes. Accurate evaluation of replaced joint mobility to ensure implant stability within the patient's functional range of motion (ROM) is a major challenge in postoperative care. However, the reliability of current assessment methods is limited due to their lack of standardized and quantitative tools. This study presents a patient-specific Mixed Reality (MR) framework designed to enhance postoperative evaluation in joint replacement with a focus on total hip arthroplasty (THA). *Methods:* The proposed system enables objective quantification and MR visualization of prosthesis biomechanics by integrating ROM simulation and 3D modeling, promoting explainability and interpretability of surgery outcomes. A retrospective analysis of 67 THAs was performed to compare simulated ROM results with clinical assessments and literature benchmarks. Additionally, surgeons evaluated the system's clinical relevance and usability through a preliminary study, including completion of the System Usability Scale (SUS). *Results:* Simulated ROM measurements showed good agreement with both clinical assessments and established literature reference values across ten movements commonly examined in orthopedic practice. The MR tool demonstrated high accuracy, repeatability, and potential to support postoperative decision-making, with usability testing yielding a favorable median SUS score of 82.5, indicating strong acceptance among clinicians. *Conclusion:* The patient-specific MR framework provides a reliable, quantitative, and interpretable method for assessing prosthetic joint

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performance after replacement, supporting its integration into postoperative workflows for improved surgical outcome assessment.

1. Introduction

Joint replacement is a surgical procedure that aims to relieve pain and restore mobility by replacing damaged joints with prosthetic components [1]. It is commonly indicated for treating severe arthritis, trauma, or advanced degeneration, particularly in the hip, knee, and shoulder joints. Recent data show that, in Italy, annual procedures increased from approximately 80,000 in 2000 to over 2,20,000 in 2022 [2], with revision surgeries expected to increase sharply by 2030 due to implant aging and rising patient numbers [3].

Although routine, joint replacements are complex procedures that carry risks of complications and variable outcomes. A primary goal is ensuring implant stability throughout the full range of motion (ROM) required for daily activities, minimizing the risk of dislocation, subluxation, or impingement [4]. Keeping the functional ROM within the implant's mechanical limits significantly reduces these risks [5], making post-operative assessment essential for confirming safe and functional mobility [6].

Arthroplasty clinical evaluation remains challenging due to the lack of quantitative, standardized tools for assessing postoperative mobility [7]. Conventional assessments rely on the execution of control movements under orthopedic supervision, although poor movement execution may hide underlying joint surface conflicts or mechanical limitations, making assessments intrinsically subjective and prone to errors [8–10]. The concepts of interpretability and explainability gain significance in this context. Interpretability is the degree to which a person can comprehend the reasoning behind a choice or result [11]. Explainability, instead, refers to a system's ability to offer concise and intelligible explanations of its procedures, conclusions, or suggestions [12]. These characteristics are essential for integrating cutting-edge technology such as Mixed Reality (MR) into traditional clinical procedures, as the use of interpretable and explainable tools in this context improves decision-making, facilitates multidisciplinary teamwork, and develops stakeholder confidence [13].

MR offers new opportunities to meet these needs, enabling immersive visualization and interaction with patient-specific models and clinical data [14]. The reviewed literature confirms that MR is a validated and increasingly adopted technology in the orthopedic field, by supporting different tasks including diagnostic processes [15,16], surgical planning [17,18], intraoperative navigation [19,20], patient rehabilitation [21–23], and surgical training [24,25]. Most academic studies emphasize the role of MR in joint surgery, mainly for accurate placement of implants and guide wires, especially in hip and shoulder replacement. For instance, MR-enhanced guidance has been demonstrated to provide more accurate glenoid guide wire positioning over the free-hand method [26–29]. As regards hip surgery, the contribution of MR to customized navigation in total hip arthroplasty (THA) has been described in several works, which emphasized an excellent visualization of the structures, resulting in precise implant fixation and maximized outcomes [30–34]. Furthermore, numerous studies report that MR also improves adherence to preoperative planning, thanks to real-time intraoperative overlay of the surgical plan and patient anatomy [35–37], collectively confirming the ability of MR to link planning and execution with real-time visual feedback [18]. Recent perspectives frame MR as a strategic enabler within advanced engineering and Healthcare 5.0 ecosystems, where patient-specific modeling and digital twins support safety-critical decision-making processes [38]. In this broader context, MR should not be considered just a visualization interface, but an advanced support technology capable of combining biomechanical modeling, simulation, and interactive analysis within a unified environment [39].

Despite the clinical relevance of post-operative assessment in orthopedic surgery, there is still a lack of effective tools to quantitatively evaluate a patient's ROM. This limitation also affects the ability to provide clear and meaningful feedback to patients on procedure outcomes, hindering both the optimization of rehabilitation strategies and the patient's understanding of the intervention results. Even with the growing adoption of MR technologies in healthcare, no studies have yet developed or validated MR-based tools that effectively support clinicians during the post-operative phase of joint replacement procedures.

This work aims to present a novel framework for MR-assisted joint replacement evaluation, designed to provide a more objective and reproducible assessment of prosthesis implant performance, meeting the need for impartial and easy-to-use evaluation tools in orthopedics. Through the integration of advanced visualization methods with spatialized clinical data, the MR framework enables accurate postoperative condition interpretation and provides user-friendly, immersive tools for analyzing biomechanical outcomes, and prosthesis positioning. Additionally, the framework implementation is demonstrated in the context of THA, one of the most common and clinically relevant joint replacement procedures. The system supports orthopedic surgeons in interpreting patient feedback in a more evidence-based way by providing revision scenarios with interactive analysis and quantitative data. This also contributes to improving communication between clinician and patient, simplifying the explanation of complex information, and fostering shared decision-making through clear and interpretable representations of postoperative results.

The remainder of the paper is structured as follows: in Section 2, the framework's conceptual design and a practical application to THA is presented. The obtained results are reported in Section 3, Section 4 discusses the study's limitations and implications, and Section 5 offers final remarks and future directions.

2. Methods

This study presents an MR framework that allows for a quantitative, interpretable, and explainable evaluation of joint replacements, addressing the limitations of traditional assessment methods. The framework can be applied to a variety of joints, as it relies on a general 3D motion analysis approach to simulate joint kinematics, calculate ROM along clinically relevant directions, and identify areas of impingement caused by specific movements, with joint-specific parameters defined according to the anatomical context. These numerical and visual outputs are designed to assist clinical decision-making by offering unbiased data that improves transparency and comprehension of the joint biomechanical behavior. The sequential steps illustrating the general methodology of the framework are shown in Fig. 1.

A 3D model of the joint must be generated for the motion analysis starting from Digital Imaging and Communications in Medicine (DICOM) images, which are usually obtained from Computed Tomography (CT) scans or 3D Brilliance imaging. Image segmentation must be performed to isolate the region of interest (ROI) required for generating the 3D representation of the joint. When DICOM images originate from CT acquisitions, segmentation can usually be performed automatically or semi-automatically due to the higher and more consistent image quality. Dedicated medical image processing software, such as Mimics (Materialise NV, Leuven, Belgium), enables threshold-based and region-growing segmentation workflows that facilitate efficient extraction of bone and prosthetic structures. Conversely, images acquired through Brilliance systems often exhibit lower contrast resolution and greater operator-dependent variability. In such cases, automatic

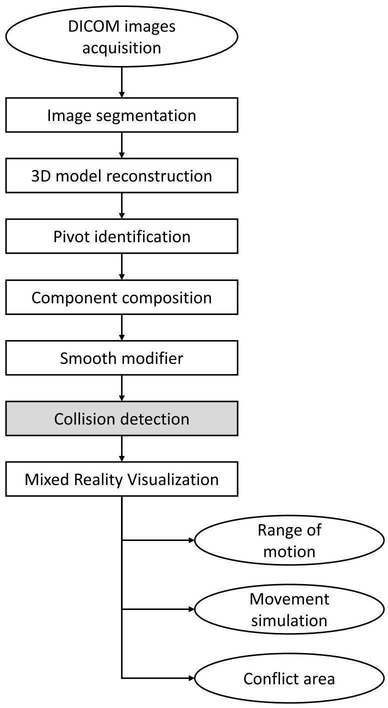


Fig. 1. 3D joint motion analysis framework. The highlighted *Collision detection* step is better detailed in Fig. 4.

segmentation may not be sufficiently reliable, and manual or operator-assisted segmentation is required to ensure geometric fidelity of the reconstructed model. Following segmentation, surface reconstruction is performed to convert the segmented ROI into a triangulated 3D surface mesh suitable for geometric processing and motion simulation. Typically, algorithms like Marching Cubes [40] or Flying Edges [41] are used to carry out this reconstruction, resulting in a triangulated mesh that constitutes the geometric basis for subsequent preprocessing steps. Once reconstructed from the DICOM series, the 3D surface model is exported and imported into Blender (Blender Foundation, Amsterdam, The Netherlands), where geometric preprocessing is performed to prepare the meshes for subsequent kinematic simulation and collision analysis. The model is first divided into two main components: a mobile part that can rotate around a pivot point and a fixed structure. Due to the nature of the mobile component, whether it is a prosthesis or a native bone, and the particular joint under investigation, the exact location of this pivot is not always uniquely defined, as rotational and translational movements are frequently combined in joint motion. The pivot can be determined either automatically or under the supervision of an orthopedist, with the goal of best approximating the actual kinematics of the joint. Once the pivot is established, the obtained meshes are exported and imported within a Python-based computational environment where the kinematic simulation is implemented. A set of movement directions is defined according to the anatomical characteristics of the joint and clinical requirements. These directions represent parameterized rotational transformations applied to the mobile component around the predefined pivot, such that the mesh is incrementally transformed along each specified axis to simulate clinically relevant joint motion. At each step, collision detection is performed using Boolean intersection operations provided by the Visualization Toolkit (VTK, Kitware Inc., Clifton Park, NY, USA). A collision is identified when the intersection between the mobile and fixed meshes yields a non-null geometric result, indicating spatial overlap. To efficiently determine the maximum collision-free rotation angle, movement is applied in discrete steps using an adaptive refinement strategy. Initially, larger angular increments are used to accelerate computation. When a collision is detected, the algorithm reverts to the last valid configuration and progressively reduces the angular step size until a predefined precision threshold is reached. With this approach, a threshold can be defined to adjust the trade-off between processing time and computational accuracy. Following the computation, the simulation results are exported from the computational environment and imported into a MR application. This integration enables interactive visualization, spatial exploration of joint mechanics, and clinician-driven assessment within an immersive environment.

Three primary outcomes are obtained from this process:

1. a dynamic representation of the joint behavior that visually simulates each movement;
2. quantitative values that represent the ROM reached in each tested direction;
3. areas of impingement highlighted on both the fixed and mobile component meshes.

These outputs collectively contribute to the interpretability and explainability of the framework. Interpretability is ensured by the direct geometric correspondence between simulated movements, computed ROM values, and observable anatomical interactions, allowing clinicians to trace quantitative results back to specific spatial configurations of the prosthetic components. Explainability is further supported by the explicit visualization of impingement regions and motion trajectories, which provide transparent, anatomy-based justification for movement limitations rather than relying on opaque or predictive modeling approaches. In addition to the benefit of a more systematic and data-driven approach for the clinical status evaluation, a non-secondary advantage of this tool is the possibility of showing tangible results that can improve the doctor-patient relationship, by facilitating informed consent and supporting shared decision-making through clearer, tangible results.

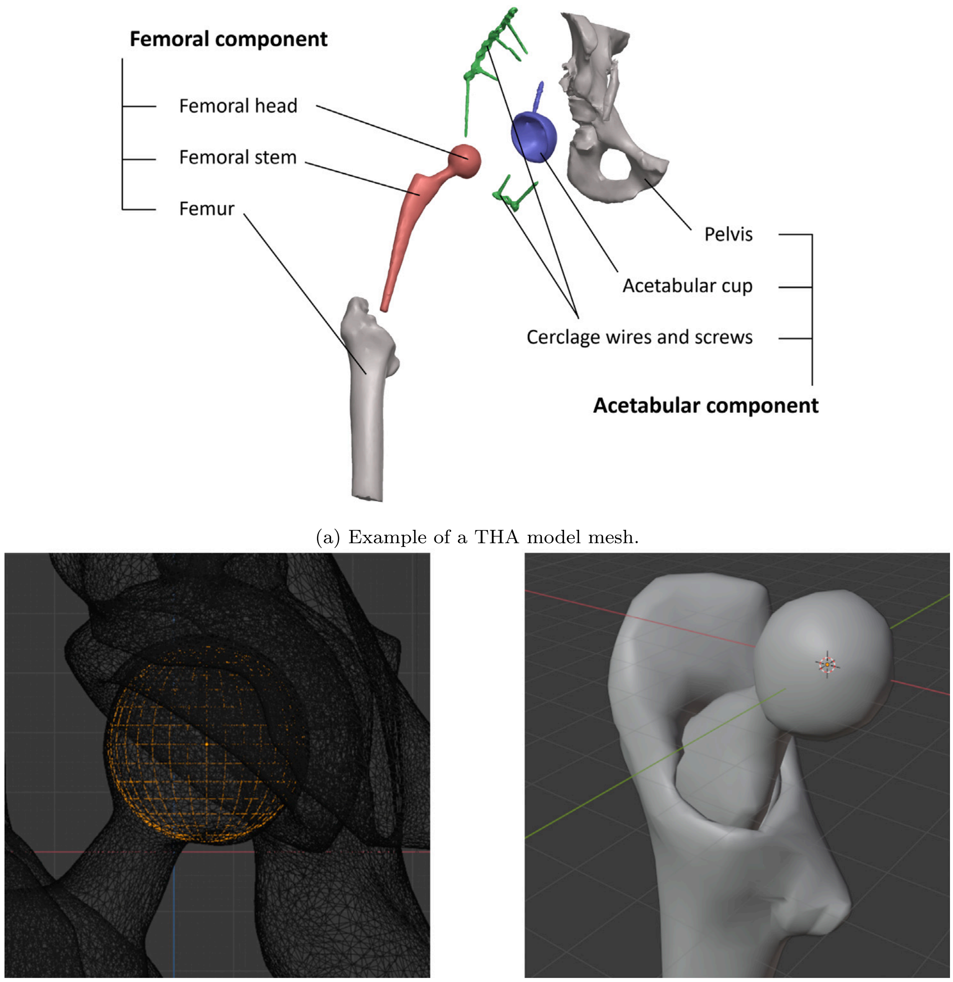
2.1. Case-study: Total Hip arthroplasty assessment

The described methodology was applied to a THA use case, developed in collaboration with the orthopedic team at C.T.O. Centro Traumatologico Ortopedico (Orthopedic Trauma Center), Turin, Italy, demonstrating its efficacy in assessing postoperative implant function and identifying impingement areas. This section details the specific case-study implementation, highlighting the joint-dependent parameterization steps. According to the general methodology, image segmentation is initially performed on each set of DICOM images to isolate the ROI required for generating the 3D representation of the THA. To ensure geometric fidelity, the resulting segmented structures were visually inspected to verify anatomical consistency and correct delineation of prosthetic and bony components prior to surface reconstruction. For the hip joint, each reconstructed 3D model can be decomposed into several distinct meshes, grouped into two functional parts: the acetabular component, which remains fixed during the simulation, and the femoral component, which includes all movable parts considered as a rigid body (Fig. 2(a)).

Subsequently, a human-assisted pivot identification defines the center of rotation of the acetabular component to ensure anatomical and functional accuracy (Fig. 2(b)). Lastly, the smooth modifier is applied to flatten angles between adjacent faces of meshes to improve the accuracy of collision detection computations without increasing vertex count or computational time (Fig. 2(c)). Once the 3D models are processed, the ROM analysis can be performed. Ten movement directions, reported in Table 1, have been identified in literature [42,43], and successively tuned in collaboration with the orthopedic team at C.T.O.

For clarity, the simulated hip movements, corresponding to standard anatomical definitions, can be visualized in Fig. 3.

Flexion refers to forward movement of the femur relative to the pelvis in the sagittal plane, while extension corresponds to backward movement in the same plane. Abduction indicates lateral movement of the



(a) Example of a THA model mesh.

(b) Example of human-assisted pivot identification.

(c) Example of a 3D model of the femoral component ready for the movement simulation.

Fig. 2. Examples of 3D models processing steps.

Table 1
Chosen set of movements for THA motion analysis and corresponding minimum acceptable ROM.

Movement	Minimum acceptable ROM
Flexion	90°
Abduction	45°
Intrarotation	30°
Intrarotation with 30° Flexion	60°
Intrarotation with 60° Flexion	40°
Intrarotation with 90° Flexion	30°
Intrarotation with 30° Flexion and 20° Adduction	50°
Intrarotation with 60° Flexion and 20° Adduction	40°
Intrarotation with 90° Flexion and 20° Adduction	30°
Extrarotation with 15° Extension	15°

femur away from the body's midline in the coronal plane. Internal rotation (intrarotation) describes rotation of the femur toward the body's midline around its longitudinal axis, whereas external rotation (extrarotation) corresponds to rotation away from the midline. Compound movements (e.g., internal rotation with flexion and adduction) simulate clinically relevant combined positions that may predispose to implant impingement.

The ROM of a given THA along a specific direction is calculated using an *a posteriori* collision detection approach. The system advances the femoral component with a 16.0° step size until detecting implant collision, at which point it retreats to the last valid position and resumes movement with a halved step size. This adaptive refinement process continues until the step size reaches a specified threshold, set at 1.0° (Fig. 4), thus allowing the functional range to be detected with high precision while maintaining computational efficiency.

To maintain clinical feasibility, compound movements are only evaluated if each individual movement meets its minimum ROM threshold. For example, "Intrarotation with 90° Flexion" is only assessed if Flexion reaches at least 90°; otherwise, it is excluded, ensuring only feasible movements are considered. From a computational standpoint, the time required to simulate the complete set of movements for each reconstructed THA on a standard high-performance laptop workstation (Intel i9-12900HK CPU, 32 GB RAM, NVIDIA RTX 3050 Ti GPU) was in the order of seconds, depending on mesh complexity. The collision-based ROM calculations are performed during model initialization in the Python environment, and the resulting movement configurations are subsequently exported to the MR application. As only precomputed movement states are rendered during MR interaction, visualization remains smooth

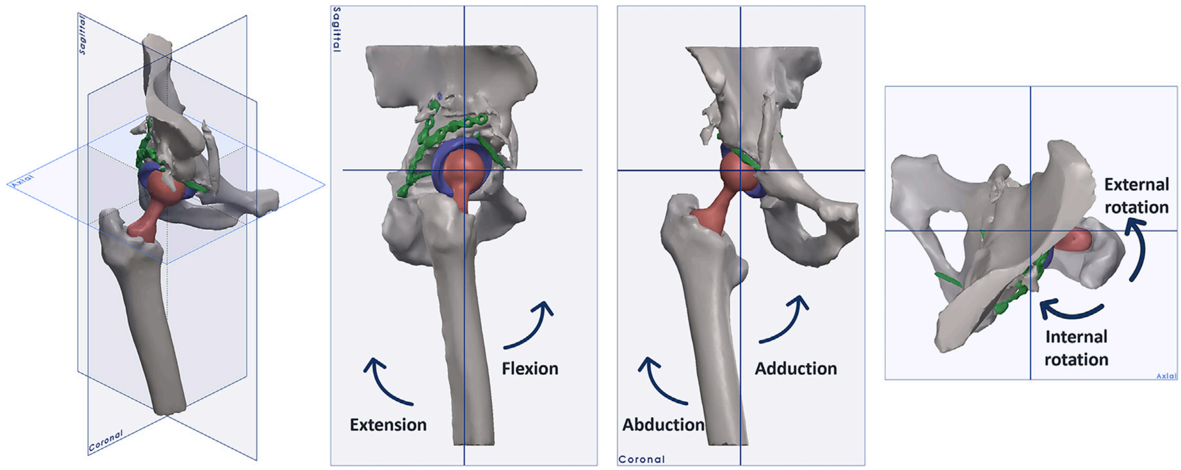


Fig. 3. Anatomical directions of the hip movements simulated in the proposed MR framework. Flexion and extension occur in the sagittal plane, abduction in the coronal plane, and internal/external rotation around the longitudinal axis of the femur.

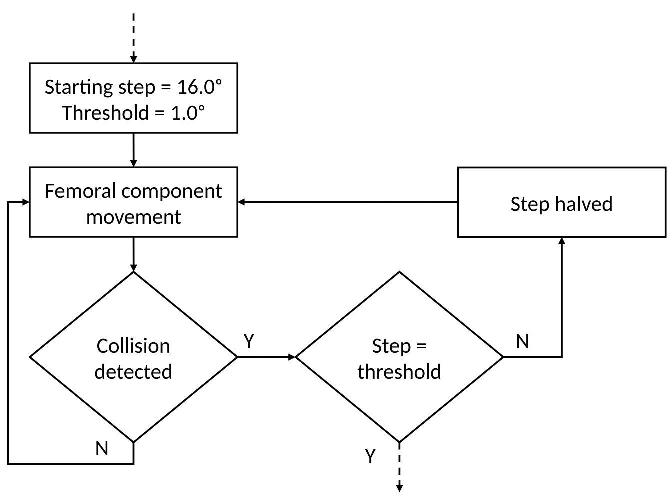


Fig. 4. Flowchart of the iterative *collision detection* algorithm used for femoral component movement.

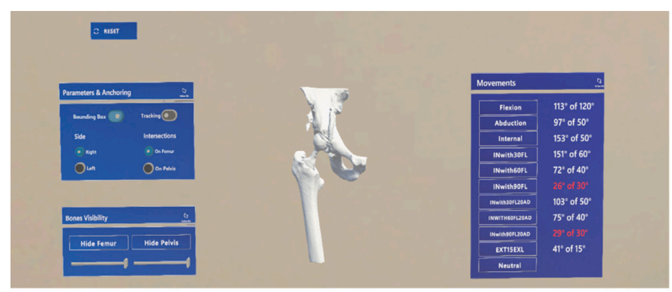
without perceptible latency, thereby supporting the practical feasibility of integrating the framework into routine postoperative clinical workflows.

2.2. MR-based solution

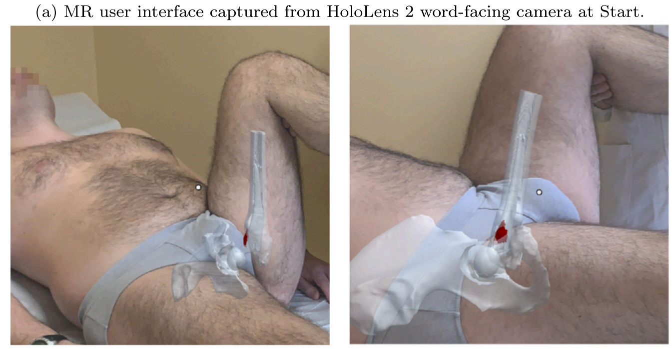
A Microsoft HoloLens 2 MR solution has been further developed and improved from a previous version using the suggested approach [44] within the cross-platform game engine Unity (Unity Technologies, San Francisco, CA, USA). The Mixed Reality Toolkit (MRTK) has been integrated to support advanced user interactions within the application.

The goal of the MR application is to provide an innovative solution for objective post-operative assessment of THA using patient-specific 3D imaging to represent hip kinematics and implant position that the orthopedist can manually interact with, using hand gestures, gaze, and head movements, allowing for an immersive visualization experience by looking around the holographic scene to examine different joint angles and perspectives.

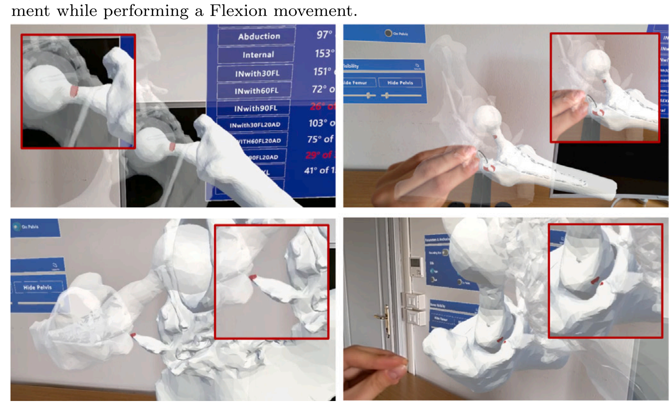
A user interface, reported in Fig. 5(a), has been implemented to allow the orthopedic surgeon to individually select the visualization and simulation of chosen movements (Fig. 5(b)).



(a) MR user interface captured from HoloLens 2 word-facing camera at Start.

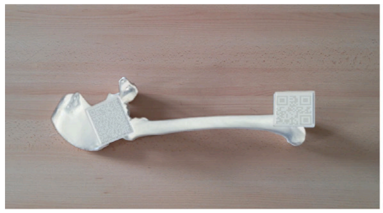


(b) MR visualization of a THA overlaid on the patient's body during clinical assessment while performing a Flexion movement.

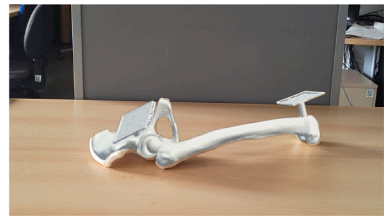


(c) Visual representation of the area of impingement on the femur and pelvis 3D models, generated upon collision detection on different movements.

Fig. 5. MR application views.



(a) Front view.



(b) Side view.

Fig. 6. Simulated example of the real-time tracking system used to register the position of 3D virtual model on a 3D-printed replica of the patient's hip.

The collision detection algorithm's output is then highlighted on both the pelvis and femur 3D models, allowing for the sites of impingement to undergo close examination on both bones by selecting the optimal visualization mode (Fig. 5(c)). Angular excursion values are also shown, indicating whether movement is restricted below physiological thresholds.

In addition, the app features real-time automatic tracking to register virtual 3D models' positions with actual joint movements, enabling live ROM comparisons during assessments and real-time feedback of simulation results. This also enables accurate data collection on the patient's hip joint movements performed by healthcare personnel, enabling detailed monitoring and identification of potential problems, as this information can be saved and associated with information such as patient-reported pain. Real-time registration of the virtual model is achieved by optical tracking of two 80 mm square targets, using the world-facing HoloLens camera, thus excluding the need for an external tracking system (Fig. 6).

A pelvic target is positioned on the skin, in correspondence with femoral head's center, with the patient lying supine. A second target is then positioned in correspondence with the center of the patella so that the mechanical axis of the femur can be determined, and the hip joint coordinate system can be established. A solution exploiting the `Microsoft.MixedReality.OpenXR.dll` assembly has been developed to enable the recognition of two custom QR code, combining fiducial tracking with instant patient data access. QR codes indeed provide superior pattern recognition while efficiently encoding patient-specific clinical information, including biographical details, CT scan date, surgery history, and prosthesis specifications. In addition to the automatic registration procedure, manual fine-tuning of model alignment is also supported, thus providing them with more flexibility and control over the positioning of the model during procedures. Notably, anchoring the 3D model to the patient's anatomical district is not mandatory, allowing visualization and interaction with the model regardless of the patient's physical presence, thus further facilitating postoperative evaluation by the surgeon.

3. Results

A preliminary evaluation of the proposed framework for THA was performed to assess the clinical relevance for orthopedic surgery, as well as surgeons' perceptions on the application's integration into the existing clinical workflow, its usability, and user experience.

3.1. Clinical trial results

A retrospective review was conducted on the medical records of patients who underwent either primary or revision THA and received a postoperative CT scan at the authors' institution between January 2013 and November 2019. All data were fully anonymized prior to analysis, with no personal identifiers or sensitive information included. No direct contact or intervention with patients was carried out. The study was approved by the Ethics Committee of the A.O.U. Città della Salute e della Scienza di Torino under protocol DB-2021, approved on 3 September 2021, and informed consent was waived. Of the 183 patients initially identified, 128 were discarded due to conditions such as dislocation (61 patients), peri-prosthetic fractures (46) patients, or polyethylene wear affecting the hip rotation center (21 patients). In the end, the study involved 55 patients, 12 of whom had undergone bilateral PTA and had both hip CT scans available, for a total of 67 hips. Each complete DICOM series corresponding to a single hip was processed independently for 3D reconstruction and simulation.

Table 2
Results of ROM for patients who reported satisfactory outcomes following THA, reported as mean ± standard deviation.

Movement	Mean	Std.Dev
Flexion	99°	28°
Abduction	52°	18°
Intrarotation	107°	35°
Intra, 30° Fl	78°	39°
Intra, 60° Fl	47°	18°
Intra, 90° Fl	30°	17°
Intra, 30° Fl, 20° Add	72°	32°
Intra, 60° Fl, 20° Add	45°	23°
Intra, 90° Fl, 20° Add	23°	15°
Extra, 15° Ext	34°	18°

The studied population counted 17 (30.9%) male and 38 (69.1%) female subjects with a mean age of 72 ± 12. 43 (78.2%) subjects had a unilateral THA, while bilateral THA was observed in 12 (21.8%) subjects. The right side was replaced in 31 (46.3%) cases and the left side in 36 (53.7%). All 67 hip arthroplasties were cementless, while 23 (34.3%) were revision THA and 44 primary THA (65.7%).

The hip ROM to impingement and dislocation was evaluated, and the aggregated results, expressed in degrees, are reported as mean and standard deviation in Table 2.

61 (91.0%) cases reported acceptable results expected after THA, with hip flexion >90°, abduction >45°, internal rotation >30° and 15° extension with a combined 15° of external rotation. The simulated ROM values were further validated through clinical correlation by re-evaluating the postoperative CT scans of each patient. Based on implant positioning, cup inclination and anteversion, femoral stem orientation, and the presence of potential bony abnormalities like heterotopic ossification, an experienced orthopedic surgeon independently assessed the expected functional limitations of the joint. The simulated ROM restrictions and identified impingement regions were found to be consistent with these imaging-based clinical interpretations, supporting the clinical validity of the proposed framework. ROM analysis allowed the identification of 6 (9.0%) cases at high risk of premature impingement and consequent hip dislocation. Each of these cases, whose ROM values are presented in detail in Table 3, had a unique type of impingement, which was confirmed through postoperative CT evaluation.

Movements marked as "–" were not assessed because prerequisite single-motion thresholds were not met, as described in Section 2.1, while extreme ROM values should be interpreted as abnormal excursions caused by abnormal implant orientation, where impingement occurs preferentially in other directions rather than indicating physiologic joint

Table 3
Results of ROM for patients presenting a unique type of impingement following THA.

Movement	1st	2nd	3rd	4th	5th	6th
Flexion	113°	66°	125°	115°	49°	74°
Abduction	35°	103°	42°	85°	28°	50°
Intrarotation	119°	75°	148°	113°	66°	80°
Intra, 30° Fl	112°	46°	157°	102°	19°	47°
Intra, 60° Fl	38°	10°	71°	80°	–	18°
Intra, 90° Fl	20°	–	41°	53°	–	–
Intra, 30° Fl, 20° Add	94°	36°	143°	67°	38°	107°
Intra, 60° Fl, 20° Add	40°	11°	75°	41°	–	56°
Intra, 90° Fl, 20° Add	12°	–	38°	31°	–	–
Extra, 15° Ext	5°	113°	6°	12°	13°	20°

mobility. 1st case reported a limited ROM in abduction (35°) and in extension (5°) due to the acetabular cup excessive horizontal placement. 2nd case reported a limited abduction of 28° with a combined 49° limited flexion and 13° extension. In this case, the femoral component was excessively deepened in the femoral canal, leading to premature bone impingement between the pelvis and the femur. 3rd case showed a similar misposition of the acetabular component as the case 1st, with suboptimal abduction (42°) and extension (6°). 4th case presented a combined limited hip flexion (74°) and internal rotation (80°), which was confirmed by clinical data. Although the implant was correctly placed, our solution revealed a heterotopic ossification, which led to premature contact between the femur and the pelvis. 5th case showed limited extension (12°), which was explained by the acetabular component's excessive anteversion. The 6th case was characterized by an excessively vertical and posteriorly positioned acetabular cup. In this configuration, limited flexion (66°) was observed due to heterotopic ossification in the anterior acetabular region. Conversely, the high extension value (113°) does not represent physiological hip mobility but reflects the absence of early implant-to-implant or bone impingement in that specific simulated direction. Since the framework computes ROM up to the first detected collision at the femoral-acetabular interface, abnormal cup orientation may shift the primary impingement to other directions, resulting in apparently large excursion values.

3.2. Mixed reality solution assessment

34 subjects among orthopedic surgeons, residents, and students at Turin's CTO (Orthopedic Trauma Center), with little to no prior experience in the use of MR technologies, were asked to assess the usability of the proposed solution. Each participant filled out a demographic questionnaire and an informed consent form and then received a thorough briefing on the goals of the study. Participants were familiarized with MR interaction by completing the Learn Gestures by Microsoft training module to guarantee that the MR system was used consistently, while the Microsoft Eye Tracking Calibration tool was used to adjust the system to each user's gaze behavior. As part of the evaluation, participants interacted with the virtual content during a full THA session assessment, determining the timing and duration of the session at their own discretion.

At the end of the session, participants were asked to complete the System Usability Scale (SUS) questionnaire, a widely adopted standardized questionnaire for determining perceived usability [45]. Respondents were required to rate their degree of agreement or disagreement with ten items on a 5-point Likert scale, with 1 representing "Strongly Agree" and 5 representing "Strongly Disagree". According to [46], participant's scores were analysed and aggregated into a new, unique value between 0 and 100, with a SUS score of 68 or higher regarded as above average [47]. Table 4 reports the questionnaire items and collected results in terms of median, minimum, and maximum values to show the central tendency and the dispersion of responses among participants to a single item.

Table 4
User testing questions for the SUS assessment. The aggregate questionnaire findings are presented in terms of median, minimum, and maximum values.

#	Questionnaire item	Min	Med	Max
1	I think that I would like to use this system frequently	1	4	5
2	I found the system unnecessarily complex	1	1	5
3	I thought the system was easy to use	3	4.5	5
4	I think that I would need the support of a technical person to be able to use this system	1	2	5
5	I found the various functions in this system were well integrated	2	4	5
6	I thought there was too much inconsistency in this system	1	1	4
7	I would imagine that most people would learn to use this system very quickly	2	4	5
8	I found the system very cumbersome to use	1	1	4
9	I felt very confident using the system	3	4	5
10	I needed to learn a lot of things before I could get going with this system	1	1	5

Positive perceptions of usability are reflected both in the high median values (4 – 5) of responses to positive items and in low median scores (1 – 2) for negative ones, as this asymmetry is expected in systems perceived as usable. As evidence of this, the median score obtained for SUS is 82.5, with an interquartile range of 72.5 to 88.125 and scores ranging from 60 to 95, suggesting a high degree of perceived usability. The absence of outliers and the narrow distribution of scores indicate that the user experience is positive across the participant group. However, items 1, 2, and 10 show greater variability, indicating that although most users found the system easy to use, some felt it was complex or required some initial learning effort.

4. Discussion

The present study introduces an MR-based framework designed for the objective assessment of joint replacement and demonstrates its applicability through a THA case-study. Both the system's clinical relevance and its usability, as perceived by orthopedic surgeons, were evaluated to assess its potential integration into current workflows.

The findings in Section 3.1 confirm that simulated ROM is consistent with retrospective clinical postoperative CT examination. The observed ROM thresholds are coherent with minimum functional ranges reported in the literature [42,43], and the identified impingement patterns qualitatively align with established biomechanical principles of THA impingement, supporting the clinical relevance and internal consistency of the proposed framework.

The ROM analysis presented in this study has been designed for ten specific movements, considering the literature and the experience of an orthopedic team; nonetheless, these movements can be easily adapted to the patient-specific issues, allowing for tailored clinical assessment. In particular, the ROM assessed in this context is specific to the interaction between the acetabular and femoral components of the implant, deliberately excluding contributions from the distal limb, thus separating prosthetic behavior from compensatory mechanisms or unrelated musculoskeletal factors. By focusing directly on the implant interface, clinicians gain a more targeted and useful understanding of joint function, enabling early identification of prosthesis-related limitations. ROM simulation is computed taking the supine posture with stretched legs as a reference, that is, the position in which the patient must lie when undergoing a CT scan, hence the resulting position in the 3D model. Furthermore, this posture is adopted at the beginning of the revision process and is also considered the standard reference to ensure accurate registration between the virtual representation and the physical joint, which is critical not only for the accuracy of the simulations but also for maintaining a reliable anatomical reference throughout the revision process.

An additional advantage is that, by combining 3D visualizations with movement simulations, clinicians can better explain complex biomechanical concepts to patients, such as the movements that are most likely to cause implant dislocation. As patients are more likely to understand their condition and the functional implications of prosthesis performance, the system improves patient adherence to therapeutic plans, leading to shorter convalescence times, improved clinical outcomes, and a more efficient use of healthcare resources. However, particular cases documented in Table 3 underscore the need for the orthopedist's expertise in the clinical assessment procedure. Thus, by offering a repeatable and measurable support system that can improve surgical planning and diagnostic accuracy, the tool is meant to supplement the orthopedist's judgment.

Although the overall SUS results indicate a high level of usability, confirmed by a median SUS score of 82.5, items 1, 2, and 10, which showed wider response distributions, were further examined. While most users found the system to be easy to use and intuitive, the dispersion of responses to these items suggests that some users encountered initial barriers to adoption, which may influence both short-term performance and long-term engagement. MR environments, in comparison to traditional interfaces, require the use of spatial interactions and different input methods (such as gestures, gaze, and voice commands), which may not be obvious to all user groups. Even though MR training was performed, additional tutorial sessions or in-app contextual guidance can help to speed up the adaptation process and drastically lower perceived complexity. Such precautions are particularly crucial in critical settings like healthcare, where user error or inefficiency caused by unfamiliarity can compromise the system's overall usefulness or safety. Therefore, user training should not be considered as an auxiliary support activity but directly integrated into the system design and implementation strategy, given the importance of user confidence and perceived ease-of-use in determining sustained system usage.

Although the present validation focuses on THA, the proposed framework was designed with a modular architecture that enables application to other joints. The core computational components, including 3D model reconstruction, mesh-based collision detection, adaptive angular refinement, and MR visualization, are joint-independent and can be directly reused. However, joint-specific adaptations are required at the anatomical and biomechanical levels. In particular, pivot identification must reflect the physiological center of rotation or functional axis of the joint under investigation. For example, while hip motion can be approximated as rotation around a fixed center, the knee requires modeling of coupled rolling-sliding kinematics, and the shoulder involves multi-planar motion with greater degrees of freedom and potential scapulothoracic contributions. Similarly, the set of simulated movements and minimum acceptable ROM thresholds must be defined according to joint-specific clinical standards. Despite these adaptations, the collision detection logic and impingement analysis remain conceptually identical, as they rely on detecting geometric intersection between articulated components.

The proposed framework can be contextualized within the broader domain of medical informatics as a patient-specific clinical decision-support tool that implements a form of musculoskeletal digital twin, enabling simulation-based interpretation of postoperative outcomes by transforming imaging data into an interactive biomechanical model [48,49]. Unlike black-box predictive models, the framework emphasizes interpretability and explainability through explicit geometric modeling and collision-based computation, allowing clinicians to visually and quantitatively understand the origin of movement limitations. In this sense, it aligns with emerging trends in explainable computational medicine, where transparent simulation-based approaches complement data-driven analytics [50,51].

From a digital health perspective, 3D reconstruction from DICOM data is already routinely employed in clinical practice for static visualization of anatomical structures, both during diagnostic assessment and in pre- or postoperative evaluation. The proposed framework builds upon this established workflow by extending static 3D visualization toward dynamic, simulation-based analysis. By enabling the simulation of relative motion between the anatomical and the prosthetic components, the framework provides a quantitative evaluation of critical ROM conditions that are not directly observable through static imaging alone. This capability may support clinical decision-making both in the diagnostic phase, by quantifying potentially limiting implant positions, and in the postoperative setting, where simulated ROM assessment can complement manual physical examination and assist in interpreting persistent functional limitations. While integration with Picture Archiving and Communication Systems (PACSs) is inherently supported through DICOM-based reconstruction, the framework is primarily intended for use in contexts where advanced imaging is already available as part of standard clinical assessment. In such cases, particularly in the presence of suspected impingement, unexplained pain, or functional limitation, the quantitative ROM outputs may enrich objective evaluation and support clinical interpretation without modifying established imaging workflows. When appropriately structured, these outputs could also facilitate documentation within Electronic Health Records (EHRs) or orthopedic registries, contributing to more consistent and comparable postoperative assessments.

5. Conclusions

In this work, a patient-specific MR framework for evaluation of joint replacement is presented, enabling objective quantification and MR visualization of prosthesis ROM thanks to the integration of motion simulation with three-dimensional modeling. The case study on THA focuses on the femoral-acetabular interface to provide precise insights into implant behavior, thus enabling early detection of mechanical limitations and facilitating data-driven surgical decision-making. Moreover, its flexibility allows for tailoring the movement set to individual patient conditions, enhancing its clinical relevance.

Preliminary findings confirm the system's clinical relevance and usability. Participants reported high satisfaction, and the simulated ROM values showed strong agreement with physical examinations and literature benchmarks, supporting the validity of the approach. The framework thus represents a promising tool for integration into existing clinical workflows, both as a diagnostic aid and a means of improving doctor-patient communication.

CRediT authorship contribution statement

Luca Ulrich: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Chiara Innocente:** Writing – original draft, Visualization, Validation, Software, Investigation, Formal analysis, Data curation. **Giorgia Marullo:** Writing – original draft, Visualization, Validation, Software, Investigation, Formal analysis. **Andrea Audisio:** Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation. **Alessandro Aprato:** Writing – review & editing, Supervision, Resources, Investigation, Formal analysis, Data curation, Conceptualization. **Alessandro Massè:** Writing – review & editing, Supervision, Resources, Investigation, Formal analysis, Data curation, Conceptualization. **Sandro Moos:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. **Enrico Vezzetti:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Ethical committee approval

The study was approved by the Ethics Committee of the A.O.U. Città della Salute e della Scienza di Torino under protocol DB-2021, approved on 3 September 2021, and informed consent was waived.

Summary table

Problem or issue	Joint replacement is a common yet complex procedure in which implant stability through the functional ROM is critical to avoid complications. Current post-operative assessments are largely subjective, lacking quantitative and interpretable tools for objective joint evaluation.
What is already known	MR is an increasingly adopted technology in orthopedics, enabling immersive visualization and interaction with patient-specific anatomical data. Previous studies show its effectiveness in surgical planning, navigation, and implant positioning.
What this paper adds	This study introduces a MR-based approach that enhances the objectivity and interpretability of postoperative joint evaluation, advancing precision assessment in orthopedic surgery. The presented tool combines immersive 3D visualization with ROM simulation and real-time tracking to enable clinicians to explore joint anatomy, quantitative measurements, and assessment results directly in MR, improving understanding, interpretability, and confidence in evaluation processes.
Who would benefit	Clinicians involved in joint diagnosis and assessment, researchers developing interpretable medical tools, and developers of Mixed Reality systems for clinical decision support and musculoskeletal applications.

Ethics in Publishing Statement

This research presents an accurate account of the work performed, all data presented are accurate and methodologies detailed enough to permit others to replicate the work.

This manuscript represents entirely original works and or if work and/or words of others have been used, that this has been appropriately cited or quoted and permission has been obtained where necessary.

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All authors have been personally and actively involved in substantive work leading to the manuscript and will hold themselves jointly and individually responsible for its content.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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