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Mixed reality-based support for Total Hip Arthroplasty assessment

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Abstract. The evaluation of hip implantation success remains one of the most relevant problems in orthopaedics. There are several factors that can cause its failure, e.g.: aseptic loosening and dislocations of the prosthetic joint due to implant impingement. Following a total hip arthroplasty, it is fundamental that the orthopaedist can evaluate which may be the possible risk factors that would lead to dislocation, or in the worst cases, to implant failure.

A procedure has been carried out with the aim of evaluating the Range of Movement (ROM) of the implanted prosthesis, to predict whether the inserted implant is correctly positioned or will be prone to dislocation or material wear due to the malposition of its components. Leveraging on a previous patented methodology that consists in the 3D reconstruction and movement simulation of the hip joint, this work aims to provide a more effective visualization of the simulation results through Mixed Reality (MR).

The use of MR for the representation of hip kinematics and implant position can provide the orthopaedic surgeon with a deeper understanding of the orientation and position of implanted components, as well as the consequences of such placements, while looking directly at the patient. To this end, an anchoring system based on a body-tracking recognition library was developed, so that both completely automatic and human-assisted options are available without additional markers or sensors. An Augmented Reality (AR) prototype has been developed in Unity 3D and used on HoloLens 2, integrating the implemented human-assisted anchoring system option.

Keywords: Computer-Aided Surgery, Total Hip Arthroplasty, THA Assessment, Mixed Reality, HoloLens 2.

1 Introduction

Total Hip Arthroplasty (THA) is currently one of the most performed surgical procedures worldwide, intended to replace damaged bone with prosthetic components [1]. Given the great magnitude of the problem and the high prevalence of this surgery, it is fundamental that the orthopaedist can evaluate which may be the possible risk factors that could lead to dislocation, or in the worst cases, to implant failure [2]. Among the most recognized causes of dislocation, intraoperative implant displacement and inadequate patient compliance with postoperative precautions provided by the surgeon play a key role [3].

The occurrence of any complication can represent a risk to the patient's health status and quality of life as well as an increased risk to the patient of implant revision. Moreover, it is related to a greater consumption of economic resources borne by the health care system [4]. From this, it emerges how the sustainability of costs is an important problem for the public administration. It is therefore evident that it is necessary to find tools to reduce complications by preventing them during surgery, and consequently reducing the resulting costs.

A procedure has been carried out with the aim of evaluating the Range of Movement (ROM) of the implanted prosthesis, to predict whether the inserted implant is correctly positioned or will be prone to dislocation or material wear due to the malposition of its components.

The ROM is defined as the maximum angular excursion of the joint before impingement occurs. For a healthy hip, it is defined by the following values [5]: 120° for Flexion, 30° for Extension, 45° for Abduction, 35° for Adduction, 45° for Intra-Rotation, 45° for Extra-Rotation. Among the goals of THA, ensuring the stability of the prosthetic components throughout the ROM necessary for daily activities is of paramount importance [6]. Up-to-now the revision process is supported by an already patented methodology that consists in the 3D reconstruction of pelvis and femoral prosthesis and the movement simulation of the hip joint [7].

This work aims to provide a more effective visualization of the simulation results using Mixed Reality (MR). Many studies have shown how MR visualization has allowed to optimize surgical tools and devices positioning, to avoid multiple X-rays scans, and consequently to reduce radiation exposure, and to decrease surgical time in numerous orthopaedic procedures [8]. MR has found a wide range of applications in orthopaedics, showing great potential to change the current practice of medical training and clinical routine [9]. Different studies have been configured to visualise MR patient anatomy during surgery [10, 11], or to use MR as a guide for insertion of prosthesis [12, 13], pedicle screws [14, 15] and guide wires [16, 17]. In addition to surgery and intraoperative applications, MR is also establishing itself as an important surgical simulation [18, 19] and intraoperative training tool [20, 21], as well as a rehabilitation tool for patients [22].

In this work, through MR, the orthopaedic surgeon can gain a deeper understanding of the patient's status due to the ability to manipulate the 3D virtual model at will, while looking directly at the patient. In this way, the orthopaedic can carefully evaluate every aspect of the prosthesis, from its placement to its orientation, and to understand which are the contact points that may be sources of possible complications. To this end, an anchoring system based on a body-tracking recognition library was developed, so that both completely automatic and human-assisted options are available without additional markers or sensors. Thus, it is possible to automatically recognize the right and left joint centres of the patient's hip and pin the joint hologram to the corresponding location in the real world.

The method will be treated in Section 2, the results will be shown in Section 3 and in Section 4 conclusions will be drawn.

2 Methods

The platform used to develop our MR-based methodology is Unity 3D (https://unity.com/). Implementation builds on an already patented procedure that comprises the 3D reconstruction of pelvis and femoral prosthesis and the movement simulation of the hip joint [7]. The reconstruction of the virtual 3D model of the joint and the implant are performed starting from DICOM images provided by CT scan, hence the algorithm for the measurement of the ROM of the prosthesis highlights the criticalities related to the femoral head and the acetabulum after the implantation of the prosthesis. Results obtained comes visualized using MR and used to simulate the movement of the femur on the pelvis, while looking directly at the patient.

For each kinematic movement simulated, reference values that the model should be able to achieve were set. Reference values have been taken from the work of Röling et al. [23] and have been reported in Table 1.

Table 1. Reference values that the model should be able to achieve.

Movement	Value
Flexion	120°
Abduction	50°
Intra-rotation	50°
IN with 30 FL	60°
IN with 60 FL	40°
IN with 90 FL	30°
IN with 30 FL 20 AD	50°
IN with 60 FL 20 AD	40°
IN with 90 FL 20 AD	30°
EXT with 15 EXL	15°

Each movement is simulated in MR using a local reference system of the femur. During the simulation, the femur moves along predefined directions until it reaches the pelvis in a range of angles from the neutral position (0°) to the previously calculated angle of impingement. Each movement is simulated as a single rotation or as a composition of rotations along predetermined axes using quaternions.

To allow the simulated joint ROM to be compared to the patient's actual ROM, an anchoring system based on a body-tracking recognition library was developed without the use of additional markers or sensors. Anchoring the 3D virtual model to the patient's physiological joint allows the orthopaedist to perform joint ROM simulation while looking directly at the patient, obtaining real-time feedback of the simulation results on the anatomical hip.

To avoid the well-known issues regarding the marker-based motion capture systems [24] and not to introduce additional devices such as depth cameras, the OpenPose library [25] has been chosen.

Two options have been made available for the anchoring system, automatic or human-assisted, to identify the X and Y coordinates of the key points corresponding to human body joints. Then, according to the considered hemi-side of the patient, the joint relative to the hip has been selected, and its coordinates appropriately mapped into real world coordinates.

A prototype has been developed in Unity 3D and then deployed on HoloLens 2 (https://docs.microsoft.com/en-us/hololens/hololens2-hardware). As seen in Fig. 1, interaction with the AR application occurs through three main panels. Users define to which hemi-side of the patient the loaded 3D models belongs (Parameters & Anchoring), choose which movement to simulate (Movements), and sets on which model to visualize the intersection, either pelvis or femoral prosthesis, and their transparency value (Bones Visibility).

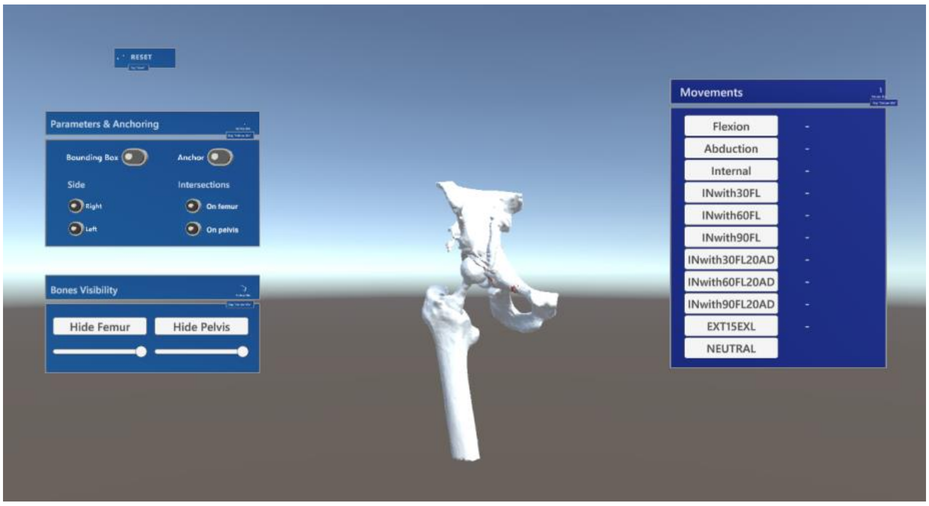

Fig. 1. Unity scene view of panels and holograms at Start.

In this Augmented Reality (AR) application the orthopaedist can position and manually manipulate the patient's 3D femur and pelvis models obtained from CT images after THA surgery, and interact with holograms through hand gestures, gaze, and head movement. By observing the joint model and interacting with it, the surgeon can verify the kinematics through the implemented simulation and check the impingement limits for each movement while looking directly at the patient **(**Fig. 2 and Fig. 3**).**

Besides, to improve the visualization of the zone of impingement without the hindrance of the model, there is the possibility to modify the transparency of femoral prosthesis and pelvis, or to remove the models completely. This will make it easier for the orthopaedist to visualize bones intersections and related prosthetic components, and carefully evaluate the bone points affected by impingement.

A user interface provides the orthopaedist with the results obtained from the simulator, allowing to study the situation without ambiguity. For each simulated movement the maximum angular excursion reached before the articular impingement is reported. The impingement zone at the limit of the movement comes coloured red by the simulator and displayed alternatively on the pelvis on the femur model (**Error! Reference source not found.**).

Fig. 2. 3D model anchored to the patient hip joint while lying on his back.

Fig. 3. 3D model anchored to the patient hip joint while performing Flexion movement simulation.

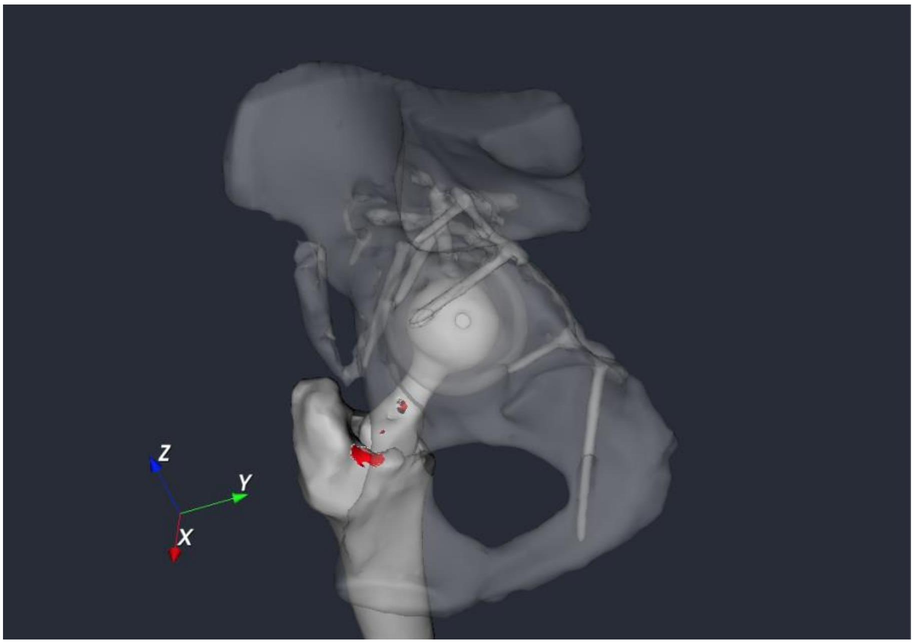

Fig. 4. Intersection for intra-rotation with 30° of flexion movement visualized on femur. To improve visualization of the impingement volume, the close-up image of the intersection condition has been obtained removing the background and modifying transparency of pelvis exploiting the feature of our application.

3 Results and Discussion

The developed methodology has been designed to simulate the hip joint movement after the THA in order to assess the correct positioning of the prosthetic implant. Indeed, a bad positioning could result in excessive wear or even potential dislocations. At present, surgeon provides indications to the patient after some tests consisting of carefully making him move the hip joint along predefined directions. If the patient feels pain after performing specific movements or cannot reach the expected ROM, countermeasures must be taken, possibly a new intervention in the worst case. These tests are susceptible to errors. The presented system can predict critical movements and allow the surgeon to provide more specific indications to the patient about the correct prosthesis use. By doing so, a simpler and more specific communication can also lead to improve the doctor-patient relationship.

Some parameters to describe the performance of the developed methodology were evaluated. Spatial anchoring system ensure the orthopaedist to visualize dynamic updates of the position and orientation of the 3D model of the joint related to the position of the anatomical joint in the real world [26]. Currently, several strategies of spatial anchoring exist, that leverage on sensor-based, marker-based or markerless tracking system. OpenPose library has been used as a markerless pose-detection tracking system for human re-identification, retargeting, and human-computer interaction [25]. Nakano et al. [27] calculated the accuracy of the used body tracking library by comparing its performance with that of an optical marker-based tracking system.

Simulation accuracy is of paramount importance to correctly perform tests on the patient after THA and can be considered ± 1 degree along the predefined position [7]. Anchoring should be as robust as possible to provide the surgeon a tool for the simulation visualisation directly on the patient. Nonetheless, anchoring does not influence the simulation results, hence the accuracy obtained by Nakano et al. [27], below 30 mm in 80% of cases, has been evaluated enough for this work, also considering that the system in not intended to substitute the surgeon during the assessment, but to support him/her. That being said, a future work could focus on anchoring accuracy to improve visualization and better support the test operator.

To assess performance of our automatic anchoring system, 9 sample videos were analysed. The mean frequency of automatic update of the 3D model position was calculated to be about 9.30 times per second. This is a software limitation, considering that HoloLens 2 would be able to reach update frequencies even 10 times higher. As regards reliability of the anchoring system, target was recognized in 97.22% of cases, with a standard deviation of 2.10%. Target detection failure can occur in cases of overlapping parts, missing or false parts detection and blurred images.

Tests have been performed to evaluate the methodology and the usability of HoloLens 2 for the intended purpose, considering the interaction with the virtual content and its visual perception. Seven subjects among biomedical and computer engineer students were recruited for the study and subjected first to a training phase to learn gestural interaction, and then to a test phase in which they had to complete certain tasks in sequence. The questionnaire submitted to the participants was formulated in order to assess visual perception, interaction, and ergonomics.

The questionnaire, which is reported in Table 2, comprises 20 items, each rated using a Likert 5-point scale (from 1 "strongly disagree", to 5 "strongly agree"). The items express positive and negative attitudes towards a specific feature of the application. Participants were asked to indicate, for each item, their degree of agreement or disagreement with what the statement expresses. The items were drafted in such a way that favourable (affirmative sentences), and unfavourable (negative sentences) items could be compared. In particular, all statements were formulated in such a way that a high score (5) corresponded to a positive aspect for our study. The aim of these judgements was to delineate the subject’s attitude towards the object of the test.

Table 2. User testing questions. Items 1 to 8 refer to visual perception, items 9 to 13 refer to interaction and ergonomics, items 14 to 20 refer to workload and engagement. The table contains the occurrences of the answers given (1, 2, 3, 4, or 5) among the participants.

Item	Questionnaire items	*1*	*2*	*3*	*4*	*5*
1	The virtual content is correctly aligned to real objects.	0	0	0	3	4
2	It is easy to perceive the spatial relationships between real and virtual objects	0	0	1	5	1
3	I did not notice motion of virtual content.	0	0	0	1	6

4	I did not notice latency (lag, delay) between virtual content and real objects.	0	0	1	4	2
5	I did not notice jitter (high frequency shaking of the virtual content).	0	0	1	3	3
6	I did not experience double vision.	0	0	0	1	6
7	I did not notice colour separation.	0	0	1	4	2
8	The field of view (FOV) is adequate for the application.	0	1	3	1	2
9	I did not experience postural discomfort during the application.	0	0	1	2	4
10	I did not experience visual fatigue.	1	1	1	2	2
11	Gesture interaction is easy and intuitive.	0	1	1	4	1
12	It is easy to follow the movement simulation.	0	0	1	2	4
13	It is easy to visualize the intersection volumes obtained from the simulation.	0	0	1	3	3
14	The task was not mentally demanding (mental demands).	0	0	2	4	1
15	The task was not physically demanding (physical demands).	0	0	0	0	7
16	The pace of the task was not hurried or rushed (temporal demands).	0	0	1	3	3
17	I was successful in performing the task (own performance).	0	0	1	2	4
18	I have worked hard to achieve my level of performance (effort).	2	0	2	1	2
19	Performing the task is engaging (engagement).	0	0	0	1	6
20	I was not insecure/discouraged/irritated/stressed/ annoyed while performing the task (frustration).	1	0	1	2	3

Users expressed overall satisfaction with their own performances (Table 2**)**. Positive feedback was obtained on the visual perception of the simulation results (items 1 to 8), showing that AR visualisation could improve the understanding of the implant situation and facilitate its evaluation. Gesture interaction was also found to be effective regardless of previous level of experience with AR and HoloLens. In terms of ergonomics (items 9 to 13), users rated the use of the HoloLens positively and had no difficulties following the simulation and viewing the results.

Lowest score regards HoloLens field of view, that was judged insufficient by some of the users, and level of effort involved. This could be explained considering that, especially up close, it is not possible to view all the user interface panels and the 3D model at the same time. A solution would be to optimise the size of the panels for the user's field of view, so that the user never looks away from the simulation. Another important aspect concerns the user interfaces, designed in attempt to give the user maximum freedom of visualisation. Their correct use therefore requires learning the gestures for interacting with different types of buttons (simple buttons, radio-buttons, toggle buttons, sliders, etc.), suggesting that a high training should be required.

4 Conclusion

Total hip arthroplasty is a surgical procedure that could greatly benefit from 3D simulation. In this context, the possibility of assessing the surgery success immediately after prosthesis insertion could play a key role.

In this work, we present an innovative post-operative THA assessment tool, which uses patient-specific 3D modelling to carefully evaluate the outcome of the surgical case under investigation. Using MR, the quality of the simulation is improved thanks to a more effective visualisation of results, and realistic real-time feedback is obtained by directly observing the simulation results on the patient. Moreover, an interactive and immersive experience for the orthopaedist is built, enriching the field of view with information that facilitates the evaluation of the surgery compared to the normal follow-up medical examination.

Future works will be focused on setting up a prototype equipped with a completely automatic anchoring system. This task will be faced both from the software and the hardware side identifying the most suitable solutions to link the body tracking library and the smart glasses. Then, the whole procedure will be tested on a more extended set of case studies for the validation.

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