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Original article

Views on a new surgical assistance method for implanting the glenoid component during total shoulder arthroplasty. Part 2: From three-dimensional reconstruction to augmented reality: Feasibility study☆

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ABSTRACT

Introduction: The main goal of this study was to propose a new method of surgical assistance for the implantation of a total shoulder prosthesis, with the use of augmented reality (AR). The advantage of this approach is that it supplements information, on the one hand pre-existing or disappeared due to a pathological process, such as the premorbid glenoid, and on the other hand already existing but not accessible to the surgeon during the procedure, such as the so-called “hidden” face of the scapula.
Material and methods: Several information preparation steps were needed. The first consisted in the three-dimensional (3D) rendering of the pathological glenoid, from a point cloud corresponding to the premorbid glenoid based on previously developed regression equations. A library of “healthy” generic glenoids was then created by hierarchical bottom-up analysis. From this database, a so-called adequate normal generic glenoid was fused and matched to the pathological glenoid reconstructed using a morphing technique. An experimental AR application was constructed. Smart glasses were used to display the prepared 3D information.
Results: A pathological 3D glenoid was reconstructed and used for the AR application. A complete display of the scene, reconstructed glenoid and full scapula was obtained. However, an offset from reality was observed. The main limitations were technical, related to the connected tool itself and the operating software.
Discussion/Conclusion: This was a feasibility study of the different steps required to apply AR, from information preparation to its visualization. A new parameter crossing experiment is needed to optimize each step of this process.
Level of evidence: IV, Basic science study.

1. Introduction

Modeling of the premorbid glenoid — as described in the first part of this study — is only truly useful if this information is made available to the surgeon. This novel information could be provided before the surgery during the three-dimensional (3D) planning step using dedicated software. Attempts to correct the pathological glenoid deformity could be guided by data reconstructed from a given patient's native premorbid anatomy.

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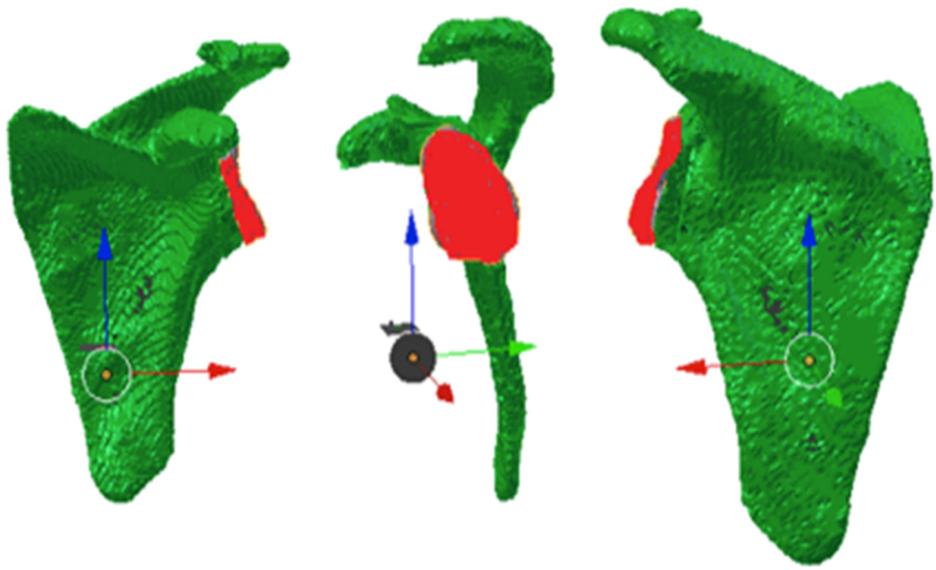

Fig. 1. Image of the 3D reconstruction of the pathological glenoid with the premorbid glenoid in red using Blender® software (Blender Foundation, Netherlands).

This information could also be made available during the surgical procedure itself. However, its transfer from the preoperative plan to the operating room requires that we think about the most appropriate medium, which must be simple, reliable and reproducible. The problem of information loss, and especially of its accuracy, between the planning stage and its implementation, has previously been reported with patient-specific guides (PSG) [1–4]. The added benefit of these newer surgical aids continues to be debated relative to use of conventional instrumentation by an experienced surgeon [5–7].

In this context, a new technological support — augmented reality (AR) — was chosen for this work. AR, in the context of a surgical procedure, designates the information systems that make it possible to superimpose a virtual 2D or 3D model (computer model) to the perception that we have of reality, in real time [8,9]. Consequently, it designates the various methods that make it possible to overlay virtual objects in a realistic manner over a sequence of images [10,11]. When applied to the shoulder project, AR is relevant for superimposing the reconstructed virtual premorbid glenoid over the current pathological glenoid targeted for implantation during the surgery.

Before potential methods for exploiting this information are explored, its quality must be improved first. It depends on use of the information generated on one hand, and its relevance in the surgeon's eyes on the other hand. The premorbid glenoid predictive model proposed at this point is only based on a cloud of points, which is not usable in this format. Transformation and 3D reconstruction of this cloud is a crucial first step for the 3D rendering of a pathological glenoid.

The first aim of this study was to prepare the virtual information desired by, and useful for, the surgeon. The second aim was the concrete application in realistic conditions of the information generated with AR technology. We hypothesized that AR could be a new method of assisted surgery. Challenges with 3D rendering of an object based on a cloud of points, hierarchical ascending classification, morphing, research and handling of connected tools are discussed in sequence. The broad steps of this research process are reported here.

2. Materials and methods

2.1. *Preparation of virtual information — 3D rendering of the pathological glenoid*

The desired virtual information corresponds to the missing portion of the pathological glenoid being treated, hence the native premorbid glenoid before arthritic changes. This is shown in red throughout this study (Fig. 1). The main tool used during the experimental phase was the open-source Blender® software (Blender Foundation, Netherlands) and its PointCloud Skinner and Shrinkwrap plugins.

2.1.1. *Overview of process*

The target is a pathological glenoid being treated that has undergone a preoperative CT scan (Fig. 2b). Using the available predictive equations (Fig. 2a), the position of the missing points is estimated, first by estimating the distance between these points and the points still present on the scapula, and then by calculating the coordinates {x, y, z} of each of these points (Fig. 2, task 1). This uses the static glenoid model described in Part 1 of this study.

Using the generated point cloud (Fig. 2c), the complete premorbid glenoid (before arthritic changes) is reconstructed in 3D as a mesh (Fig. 2, task 2). Given the limited number of points recharacterized ($n = 12$) on this glenoid, it was labeled as "crude" and designated as B (Fig. 2d).

To make the glenoid reconstruction as realistic as possible, an adequate generic glenoid was used as a reference. The aim was to correct or improve the appearance of the pathological glenoid being treated (Fig. 2E). This generic glenoid was designated as A. Morphing of these two glenoids (generic A and pathological reconstructed B) (Fig. 2, task 3) ultimately leads to the availability of a likely reconstructed final glenoid (Fig. 2e).

On the side, we thought about constructing a database of generic glenoids. In fact, we imagined that the adequate generic glenoid A described above (Fig. 2E) could be chosen by the surgeon from a database of generic glenoids (Fig. 2D, task IV). Hierarchical clustering through a bottom-up approach (Fig. 2, task II) was used

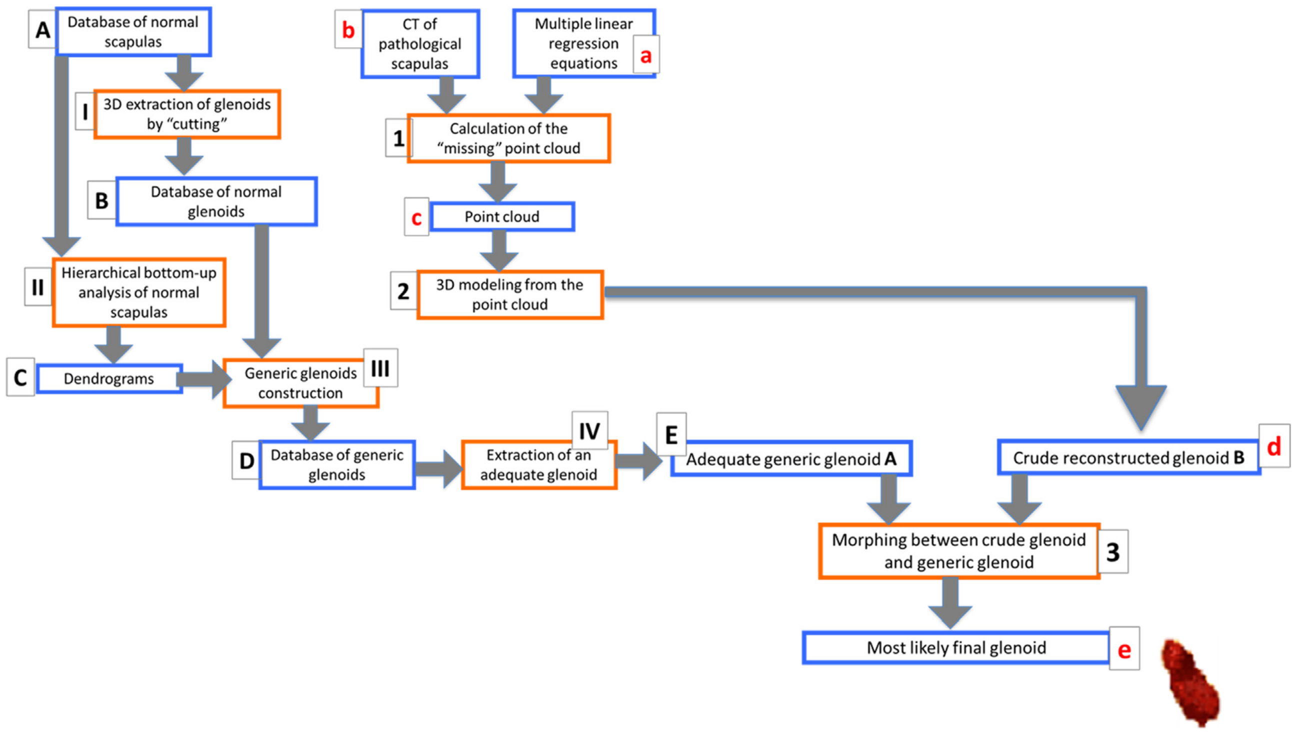

Fig. 2. Overview of the process for the 3D virtual reconstruction of a pathological glenoid (in the blue frame: available or created data; in the orange frame: tasks performed).

to analyze the data and form families of healthy glenoids. For each family, morphing operations provided 3D "average" glenoids, which we called generic glenoids (Fig. 2, task III). Given the extensive nature of each of these steps, only the main ones are listed here.

2.1.2. Crude reconstructed glenoid B rendered from point cloud

To create a 3D file of the likely reconstructed premorbid glenoid, the first step was to import the file containing the patient's pathological scapula into Blender® (Fig. 2, task 2). Next, the adequate glenoid file was imported, which contained the coordinates of the first points modeled on the glenoid surface and the additional points from the body of the glenoid obtained by merging the files. The PointCloud Skinner plug-in was used for this 3D polygonal rendering of the premorbid glenoid.

Since this method was based on a limited number of glenoid points, we labeled the reconstructed glenoid "B" as crude. Refinement of this model was then performed using Subdivision Surface Modifier for Blender®. The refined glenoid was designated as B'.

2.1.3. Morphing between crude glenoid B and generic glenoid A

It was assumed at this step that a database of generic glenoids already existed, and that the surgeon had chosen the adequate generic glenoid A (Fig. 2, task 3). The aim was to refine the crude B model (or B') at the correct scale, based on the intricately modeled information contained in A, but using any scale.

A morphing technique was applied during this step. The generic glenoid A — after being scaled-up — and the reconstructed pathological glenoid B (or B') were the target and source image, respectively. The transformation process of one to the other (interpolation algorithm; Shrinkwrap Modifier in Blender) generated intermediate images, among which the most likely reconstructed final glenoid was chosen (Fig. 2e).

2.1.4. Construction of generic glenoid database

The first step involved obtaining 3D files of healthy glenoids (Fig. 2D). This was done using the Bisecter function of Blender® to "cut out" the glenoid from the 43 available healthy scapulas.

The second step consisted of hierarchical clustering analysis of the healthy scapulas. We used an agglomerative "bottom-up" approach based on calculating the resemblance (distance or dissimilarity) between two scapulas (Euclidean distance, Euclidean squared distance, Manhattan distance) and a metric governing the fusion strategy of scapulas (minimum jump, maximum jump, Ward's method). A dendrogram was generated that allowed us to evaluate the proximity between the analyzed scapulas and to create families.

The third and final step consisted of iterative pairwise fusion of the glenoids. In each family of "similar" scapulas, each pair was fused progressively into a single glenoid (see Section 2.1.4). At each iteration, a new virtual glenoid was generated and added to the temporary database of glenoids to cluster, at which point the original two glenoids were removed.

2.2. Application of AR for transferring information

2.2.1. Terminology and operating principles of an AR application

The following must be defined upfront to ensure our work is understood fully, as described in this section. Thus:

- reality corresponds to everything that exists, the physical world;
- scene is all the virtual objects that are superimposed to reality, via and on the connected tool applying the AR (i.e. on the lens of the smart glasses for this study);
- target corresponds to the real object that will be recognized to initiate and apply the AR;
- mask corresponds to the 3D virtual reference object to the target; this is a 3D image of the target, derived from a preoperative CT scan of the patient's shoulder.

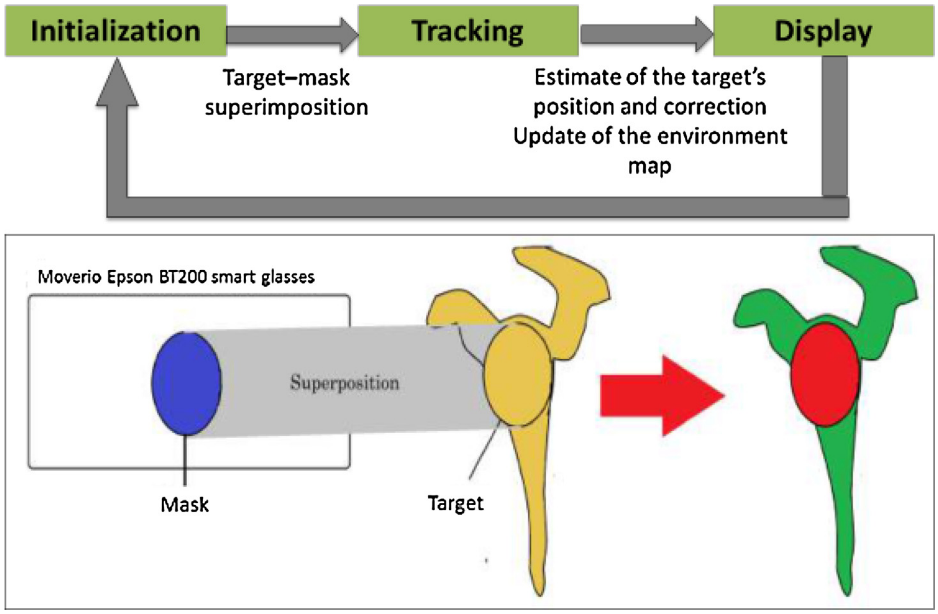

Fig. 3. The three fundamental steps of an augmented reality application. Representation of the shoulder project application.

The general operating principles of an AR application encompass three main steps: The first is initialization, which consists of identifying the real physical target in the images captured by the camera. A transparent mask is displayed in the center of the glasses' screen. The aim is to superimpose the target and mask perfectly. This step requires 3D environment recognition algorithms, which are based on the correspondence of a certain number of edges on the mask with those of the target. Once this synchronization has occurred, the next two steps can start. The second step corresponds to tracking of the object. It is based on the fact that the camera on the connected tool is not fixed, in the same way as the environment. This requires software tools to follow the target. The third step consists in redisplaying the scene each time the target is detected (i.e. 3D virtual model of the scapula, superimposed to the view of reality) (Fig. 3).

2.2.2. Materials

Epson Moverio BT-200 smart glasses (Seiko Epson Corporation, Nagano, Suwa, Japan) were chosen for this study after in-depth analysis of the rapidly changing commercially available options at the time the project started (2014). The main features of these glasses were the Android® version 4.0.4 operating system (Google, Mountain View, CA, USA), presence of multiple sensors (gyroscope, accelerometer, GPS, camera), WiFi connectivity, dual-core 1.2 GHz processor, 1GB RAM and 8 GB internal memory. Metaio Creator® software (Metaio, Munich, Germany) was used to develop the desired AR scenario.

2.2.3. Technical aspects of the experiments with an augmented reality application

To apply the operating principles of an AR application described above to the shoulder project, several preliminary experimental steps were needed. The first was the configuration of a test environment, using the Blender® software, with the preparation of a mask based on the defined target, in this case, the glenoid portion of the scapula. This resulted in a 3D model of a healthy scapula, which was colored green. To simulate arthritic wear, a random fragment of the glenoid was removed. This removed fragment was colored red, to be considered as the missing portion. The scapula, representing the patient's existing bone, colored in green, was again cut out from the remainder of the glenoid to prepare the mask, which was colored in blue (Fig. 4). The resulting blue mask was then used to construct a tangible target (portion of the scapula visible to the surgeon during the procedure) by 3D printing that was used in the tests.

Next, we compared the various tracking algorithms to determine which was the most appropriate. This experimental phase also allowed us, in parallel, to analyze the important features of the AR application, such as the quality of the mask used and the importance of the environment's lighting and the application's scene.

At the end of the various experimental steps, the AR application underwent final testing on a mock-up model.

3. Results

3.1. Preparation of virtual information–3D model of pathological glenoid

The 3D pathological glenoid reconstructed from the point cloud of the premorbid glenoid with the morphing step is shown in Fig. 5. The steps for creating a database of generic glenoids are shown in Fig. 6.

3.2. Application of AR

The surgical environment was reproduced (Figs. 3 and 7, and Video 1). The surgeon was presented with a glenoid from a complete scapula, which was covered in a red tissue to represent the shoulder's musculature. This scenario resembles the one a surgeon would encounter during a shoulder arthroplasty procedure, with the glenoid exposed and accessible, and the remainder of the scapula being hidden and deeply buried. While wearing the smart glasses, the surgeon launched the application. A directional light was set up behind him (to simulate operating room lights) to provide good lighting on the surface of the glenoid being identified (target). During the initialization, the surgeon superimposed the target and the previously constructed 3D virtual image displayed on these glasses, i.e. the blue mask. The various AR steps were completed through the smart glasses, with the aim of displaying virtually the entire scapula (first component in the scene, in green), tracking it by following his gaze, displaying the reconstruction of the premorbid glenoid (second component in the scene, in red)

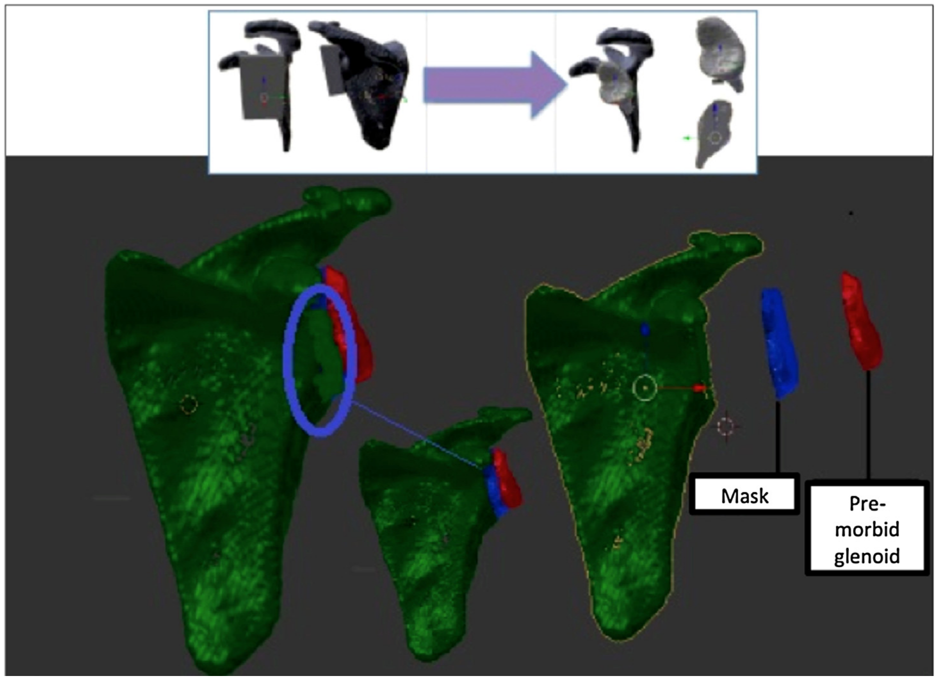

Fig. 4. Image of the cutting and coloring operations of a normal scapula with its glenoid for the tests (Blender®, Blender Foundation, Netherlands).

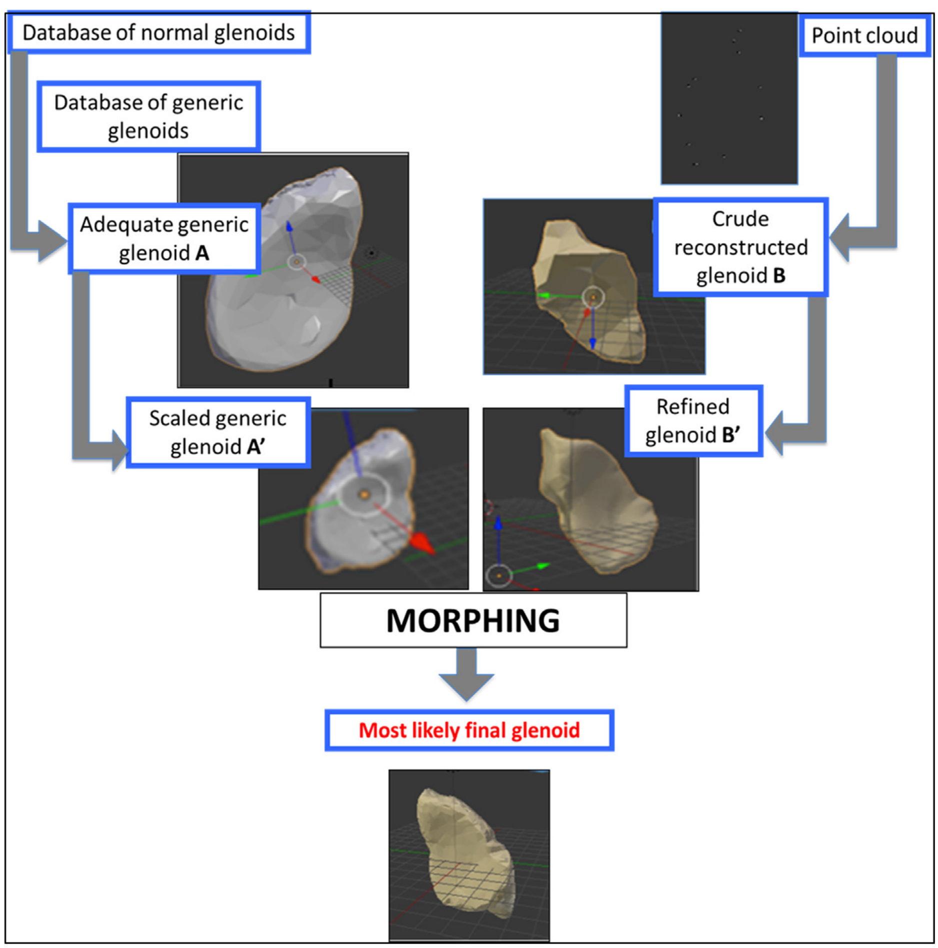

Fig. 5. 3D reconstruction of the pathological glenoid.

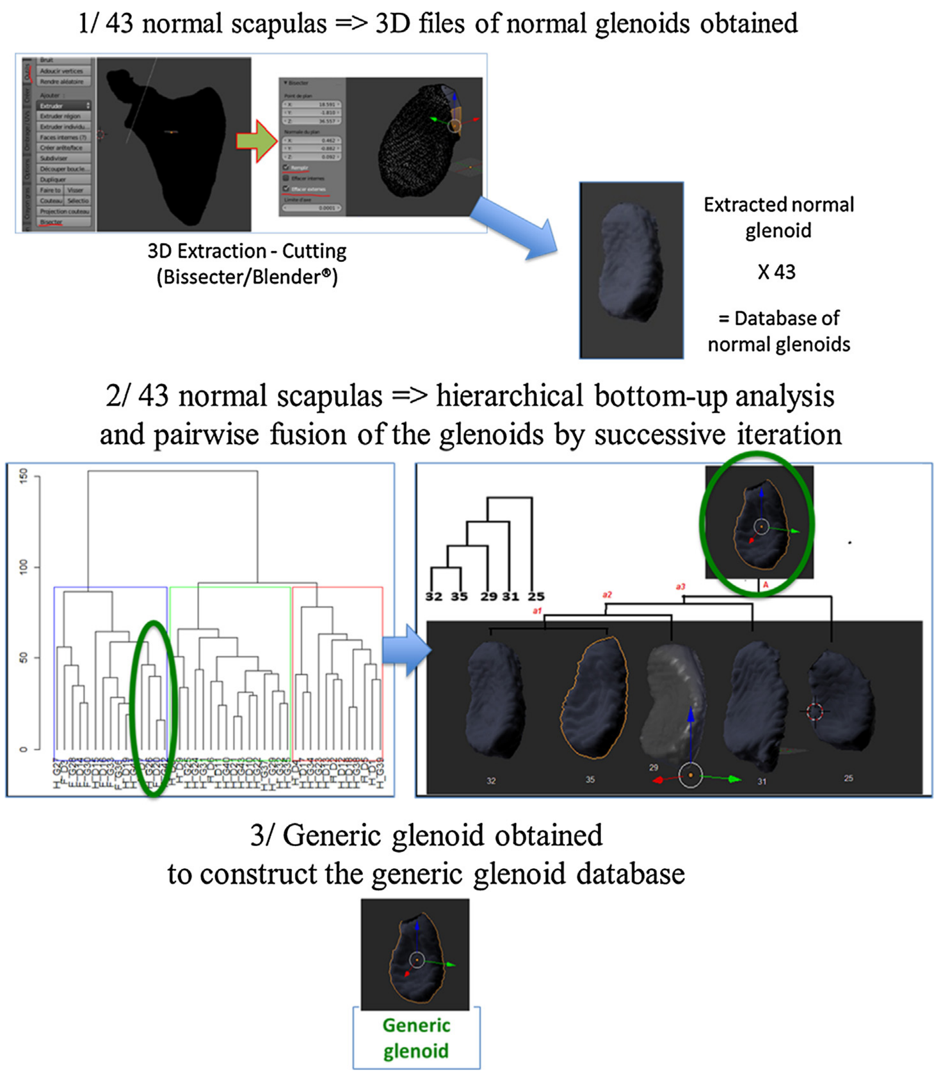

Fig. 6. Main steps of the glenoid database creation process.

and its tracking also, if we were to consider that one fragment was missing (like in osteoarthritis).

4. Discussion

The aim of this study was to implement a complete process to assess the feasibility of a new surgical assistance method, from the creation of information useful to a surgeon to its practical use.

The first element was making a 3D virtual model of the likely pathological glenoid. The various steps of this process were described. They consisted of preparing a set of multiple linear regression equations, geographic determination of the points of interest missing from the glenoid and constructing a crude 3D model of the glenoid from this cloud of points. A morphing step with the 3D model of an adequate generic glenoid was also carried out to acquire the final 3D model of the reconstructed glenoid. In parallel, we created a database of generic glenoids that can eventually be made available to the surgeon.

AR technology was chosen as a potential tool for using the information generated before and during the surgical procedure. The first advantage of AR is that it provides information directly, through its display on smart glasses, without additional transfer tools. The second advantage is that other information can be added, as long as it is created and imported beforehand into the connected tool being used. In the application that we developed, the "hidden" face of the scapula could be visualized, along with the 3D model of the pathological glenoid. The scapula information in itself could help a surgeon understand the orientation of the scapula and to position the glenoid instrumentation based on this information.

The main functions required for this work, especially the preparation of the 3D virtual information, were identified and tested in several free software programs. The development of comprehensive software could be considered, based on the idea of interapplication communication (navigation between software applications). However, we will need to group or even automate certain burdensome steps in one or several software programs beforehand, with appropriate scripts. Several time-consuming operations had to be performed manually in this study. This methodological and technical limitation has previously been discussed for the point-capturing step required during the first phase of statistical modeling of the premorbid glenoid.

In practice, the availability of the premorbid glenoid to use a reference when reconstructing the pathological glenoid is relevant information for the surgeon who may need to add a graft or determine which type of implant to use — standard or specific, augmented or compensated [12]. The implant choice could itself be guided through a search of the database of generic glenoids that we constructed. After the morphing step between the adequate generic glenoid and the reconstructed pathological glenoid, an

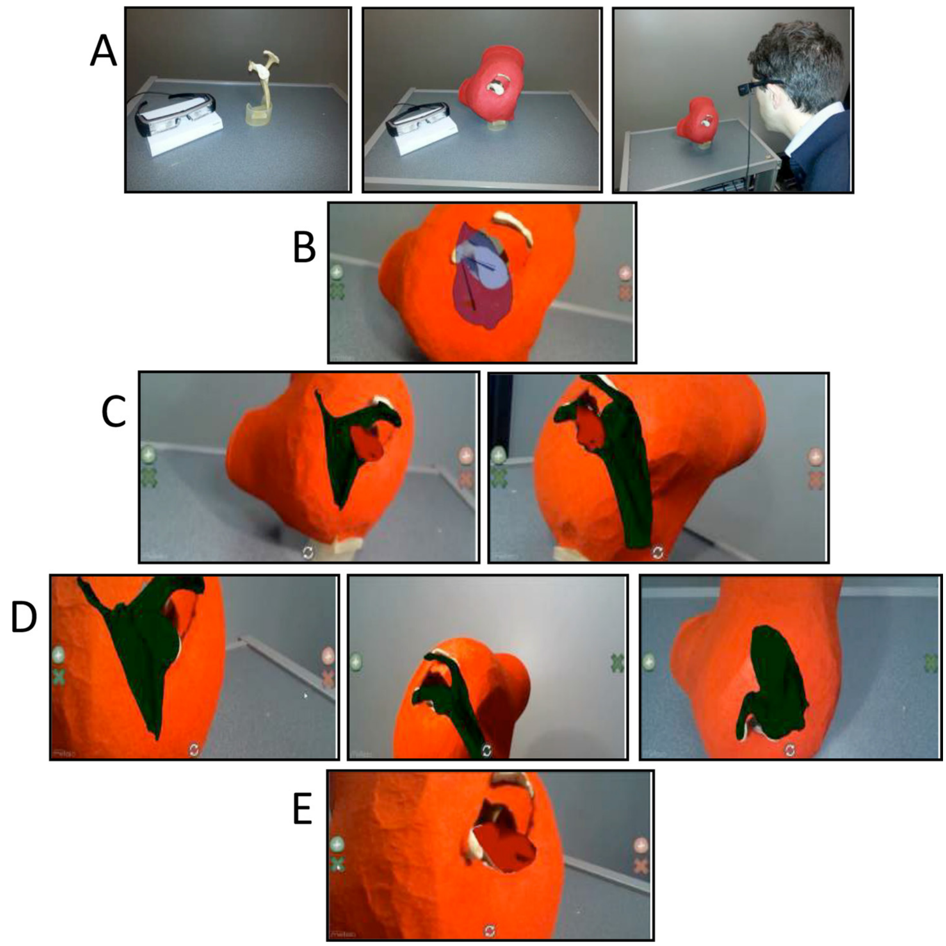

Fig. 7. Demonstration of the augmented reality application for the shoulder project. A. Artificial surgical environment created for augmented reality experiments. B. Initialization: the blue mask appears on the glasses; the surgeon tries to match it to the target glenoid. C. Full display of the scene: 1st element — the scapula (green) and 2nd element — the virtual 3D reconstructed pathological glenoid (red) are shown simultaneously. The recognition between target and mask was made, which automatically displays the entire scene and it is followed regardless of the orientation of the surgeon's gaze. D. Partial display of the scene: 1st element — the scapula (green). The surgeon can subtract the 2nd element from the scene. Tracking of this single element of the scene can be done in the same way. E. Partial display of the scene: 2nd element — the reconstructed pathological glenoid (red). The surgeon can subtract the 1st element from the scene. Tracking of this single element of the scene can be done in the same way.

equivalent library of available glenoid implants could be created and used to select the implant best suited to the patient's condition. In an extreme case, if the design of the available glenoid is not compatible with the patient's condition, 3D printing could be used to immediately make a customized implant.

The principles of AR design and operation allow us to contemplate adding as much information as desired to reality. This is currently limited by the tools used (smart glasses and operating systems) and the fact that this technology is still at its infancy [13,14]. One of the major problems that we encountered, which we have not yet solved, is the accuracy of the superimposition of the scene to the physical world (reality). This was particularly obvious during the experiment performed on the mock-up (Video 1), where this distance offset between the scene and reality was even greater when the surgeon's gaze was moving. The superimposition flaws were larger at the acromion and coracoid process, which are the anatomical area further away from the glenoid where the initialization between the mask and target occurred. New experiments, specifically focused on the first two steps of the AR process (initialization and tracking), must still be performed to optimize the final step of the display on the smart glasses. The accuracy level need for AR use must be at least as good as that currently reported for PSGs. This latter tool, which integrates only positional information and has few functional outcomes [15], allows the preoperative planning to be reproduced with an accuracy around 3 mm [5,16]. An evaluation of the accuracy of the superimposition of the scene to reality was initiated for the experimental model described here, but the tested method could not be validated. This analysis is essential for retaining AR as a surgical assistance tool. AR's advantage of being able to deliver several pieces of virtual information for a given surgical scenario is only useful if this information is very accurate, and thus reliable, when it is displayed.

Use of AR in orthopedic surgery is an innovative field of research. Its application to glenoid implantation is just the start. The same thought process could be used for other joints, while incorporating the technical challenges specific to their treatment. Thus information about the "hidden" side of the acetabulum could be relevant during revision hip arthroplasty or tumor removal in the lesser pelvis. Other applications could be spine surgery and trauma surgery. However, all of these potential applications are faced with a common challenge: defining and generating the 3D virtual information to be used in the connected tool. The nature of this information should obviously not compete with information provided by other surgical aids, such as PSG. The complementary nature of information and thus use of surgical aids should be considered. For example, AR could be used to verify and validate the implant position achieved using the PSGs [17].

5. Conclusion

This study assessed the feasibility of using AR in orthopedic surgery. This article was written in an unusual format because of the original nature of this application. The initial hypothesis that AR could be a new surgical assistance method was verified. We were able to prepare a 3D reconstruction of a pathological glenoid based on statistical prediction from a premorbid glenoid. We were also able to identify and view the location and the orientation of the scapula corresponding to this reconstructed glenoid in its environment.

Beyond the nature of the information created for the proposed model, the steps of the process itself must be retained. Various concepts of virtual 3D information preparation and AR implement were explored. Their limitations (material, software) were identified. New research projects have been started based on our findings in this initial study.

Disclosure of interest

The authors declare that they have no competing interest.

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Author contributions

Julien Berhouet: study design, investigator and primary author.
Mohamed Slimane: supervision.
Maxime Facomprez: data acquisition.
Min Jiang: data acquisition.
Luc Favard: supervision.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.otsr.2018.08.021.

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