Augmented Reality as a Tool to Guide Patient-Specific Templates Placement in Pelvic Resections

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***Abstract*— Patient-specific templates (PST) have become a useful tool for guiding osteotomy in complex surgical scenarios such as pelvic resections. The design of the surgical template results in sharper, less jagged resection margins than freehand cuts. However, their correct placement can become difficult in some anatomical regions and cannot be verified during surgery. Conventionally, pelvic resections are performed using Computer Assisted Surgery (CAS), and in recent years Augmented Reality (AR) has been proposed in the literature as an additional tool to support PST placement. This work presents an AR task to simplify and improve the accuracy of the positioning of the template by displaying virtual content. The focus of the work is the creation of the virtual guides displayed during the AR task. The system was validated on a patient-specific phantom designed to provide a realistic setup. Encouraging results have been achieved. The use of the AR simplifies the surgical task and optimizes the correct positioning of the cutting template: an average error of 2.19 mm has been obtained, lower than obtained with state-of-the-art solutions. In addition, supporting PST placement through AR guidance is less time-consuming than the standard procedure that solely relies on anatomical landmarks as reference.**

I. Introduction

Pelvic resection is a surgical procedure that involves the total or partial resection of the pelvis, induced by the presence of sarcomas, hip replacement revisions, any forms of dysplasia, and severe trauma. Osteosarcoma is caused by a combination of genetic alterations and recurrence rates of the pelvis is about 30%. Therefore, surgical approaches require meticulous preoperative planning. Hip replacement is a surgical procedure in which one or both the femoral and acetabular portions of the hip joint are replaced with new artificial components [1]. Hip dysplasia is defined as insufficient acetabular coverage of the femoral head and the surgical technique to correct dysplasia is the Ganz periacetabular osteotomy (PAO). Conventionally, pelvic resections are performed using computer-assisted surgery (CAS), which uses computer technology for surgical planning, and for guiding or performing the surgical intervention. The surgical instruments can be sensorized to display their position during surgery. The patient-specific templates (PST) provide additional support for the surgeon. They are custom-made surgical instruments, designed to fit a patient's particular bone region and guide osteotomies [2]. This results in sharper, less jagged resection margins than freehand cuts. However, their placement cannot be verified objectively during the intervention, increasing the risk of high osteotomy deviations resulting from incorrect positioning. According to the literature, the minimum accuracy that can be obtained with PST is 0.4 cm [1]. An additional tool to support that has recently been proposed to support PST positioning is Augmented Reality (AR) [4,5,6,7,8]. AR refers to methods whose purpose is to provide the user with an expansion of their sensory capabilities in a virtual way. In AR-based applications, the key challenge is to ensure the highest degree of realism in blending computer-generated elements with the surgical scene [6]. Head-Mounted Displays (HMDs) are emerging as the most efficient AR output medium to support complex manual tasks performed under direct vision (e.g., in surgery). This is owing to their ability to preserve the user's egocentric perception of the augmented workspace and so allow hands-free interaction with it [7]. Recent studies have shown that pelvic resections using the AR, generate an osteotomy margin error of 10.8 mm [8], enough from a clinical point of view. Studies focused on estimating the accuracy provided by these technologies are performed on phantoms, cadavers, or living subjects. Phantoms can be designed to replicate the anatomical structures or the composition of human tissue with more or fewer details. In addition, thanks to 3D printing, patient-specific phantoms can be generated more easily for personalized measurements. The key concept of this work is to merge the benefits of using PST and AR, exploiting the mechanical support of the template and together with the advantages of AR-guided navigation. The AR support aims to simplify the positioning of the template by displaying virtual content. Colored virtual guides are displayed in the correct position, using a tracking mode that is based on the real-time localization of three reference markers, embedded in the surgical template. We evaluated the accuracy provided by the system on a phantom, consisting of the patient-specific pelvic bone replica in acrylonitrile butadiene styrene (ABS) inserted in a thigh replica made of polyurethane foam. Seven colored virtual guides, differing in positioning and shape, were designed, and tested to verify the effectiveness of AR for guiding the positioning of a surgical template in the simulated surgical case. The virtual guides pose is linked to the surgical template pose, and they only appear aligned with their corresponding physical anatomical landmark when the surgical template is correctly positioned

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on the patient's anatomy. All the virtual guides were designed to be overlaid at areas of the pelvic bone that are visible during the conventional surgery (such as the iliac and the periacetabular area). Twelve subjects (technicians and surgeons) positioned the surgical template on the phantom following two methodologies: freehand and with AR. In particular, as AR interface, we used the VOSTARS [9] system: an AR HMD capable of providing both video see-through (VST) and optical see-through (OST) visualization modalities. The system was developed in the framework of the European project VOSTARS Our results show that AR simplifies the surgical task and optimizes and speeds up the correct placement of the template with respect to conventional freehand technique, where the subject has no virtual reference available, if not previous knowledge of anatomical landmarks is present. In addition, we also prove that the obtained accuracy is closely influenced by virtual guides design.

II. MATERIALS AND METHODS

1. *Design of Virtual and Real Content*

The selected surgical case is the osteotomy performed with a surgical template for the revision of a hip prosthesis with the conventional implantation of a pelvic prosthesis (Fig. 1). The choice was focused on this case for two main factors: the anatomy of the patient is more generalizable with respect to other types of pelvic resections and osteotomy divides the hip into two distinct fragments with margins dependent on the correct placement of the surgical template. The 3D models of the template used in this surgery were provided to us free by the company Waldemar Link GmbH & Co KG. The bone replica was made starting from the patient's CT images. The virtual bone model was extracted via segmentation with 3DSlicer software [10] and it was split with a sagittal plane to keep only the right hemipelvis. CreoParametric software was used to insert 3 spheres with a diameter of 2 mm on the bone surface at a known position. These landmarks were used to estimate the positioning accuracy in terms of AR overlay as explained in section 2 of the template (Fig.2). The bone model was printed in ABS using the Stratasys Dimensions Elite P09446 3D printer. Subsequently, the 3 spheres printed on the bone model were colored in red to improve their visual recognition. To better reproduce the real scenario, the bone model was incorporated inside a female thigh replica made of polyurethane foam covered with a layer of silicone to simulate the skin layer (Fig.2). As mentioned above, the accurate AR superposition of the virtual guides on the 3D printed physical models is achieved using a tracking modality which relies on the real-time localization of three reference markers; for this reason, three spherical markers (11.25 mm in diameter) were incorporated into the CAD model of the surgical template (Fig.2). The markers were colored in fluorescent green, to increase the camera sensor response and improve the robustness of their detection in uncontrolled lighting conditions. The focus of the work was the creation of the virtual guides displayed during the AR task, which have the role of simplifying the positioning of the template. They have been defined with information from surgeons on the visual field of action that is available during conventional operation and represent dotted or superficial guides of exposed bone. Creo Parametric software was used to design seven virtual guides with different shapes to fit the contour or a portion of the surface of the pelvic bone (Fig.3). These were saved as. wrl models to be imported by the software framework and displayed as the virtual content of the AR scene. The virtual content is bound to the reference system of the template reference markers; therefore, an incorrect placement of the surgical template leads to an incorrect overlay between of the virtual guide and the reference bone.

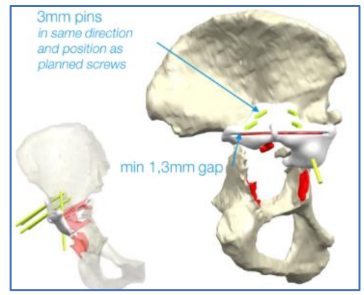

Figure 1. Surgical procedure selected for study.

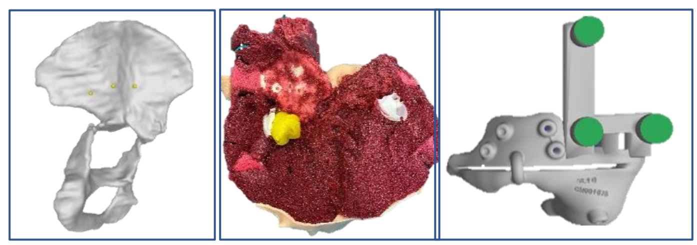

Figure 2. On the left: the bone model extracted from CT images with the 3 landmarks. In the center: the phantom of polyurethane foam. On the right: the markers-template system for the optical tracking.

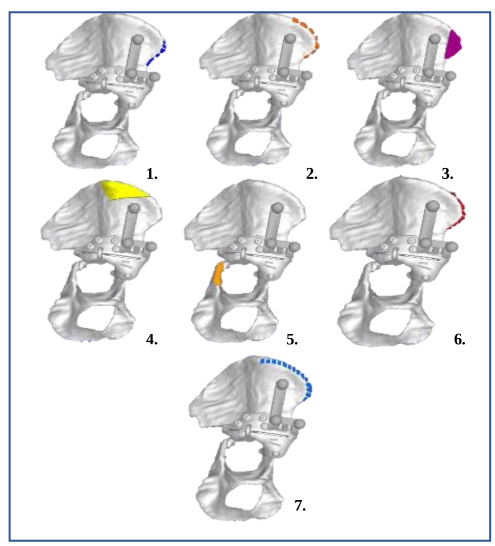

Figure 3. The virtual content: seven colored guides.

2. *Protocol of the Study*

Twelve subjects, with normal visual acuity or corrected-to-normal acuity, were recruited from technical employees, University students, and surgeons to perform the AR task (Fig.4). During the AR trials the subjects were asked to place the surgical template on the bone replica using the colored virtual guidance as reference. During freehand trials the user had the opportunity to visualize the planned position of the template. Subjects were randomized to start with the freehand or with AR trials. Moreover, during the AR trials, the virtual guides were administered in random order. The steps followed in the AR task are:

1) Visualization of a random virtual guide.
2) Manual placement of the physical template on the bone replica by successive movements (i.e., rotations and translations) guided by the AR guide so that the real bone and the virtual guide are overlapped.
3) Conclusion of the task when the user is satisfied with the alignment achieved.
4) AR visualization of the 3 virtual validation landmarks to estimate the accuracy of the template placement (this step is for experimenters only).

The task was also performed without AR to see what the differences were in the qualitative and quantitative results obtained compared to the task performed with AR. To define the accuracy of the positioning of the surgical guide with the AR task, the image distance was calculated between the centroids of the 3 fixed landmarks on the bone model and the centroids of the 3 virtual landmarks displayed at the end of the task (Fig.5). A CreoParametric software tool was used to identify the centroids on the extrapolated images at the end of the AR task. A mathematical proportion was used to convert pixels into millimeters using known data such as the diameter of the spherical markers [6]. We also timed the task without AR, to verify if the new implemented task speeded up the placement of the template. At the end of the experimental session, subjects were administered a 5-points Likert questionnaire to qualitatively evaluate how much the virtual guides simplified the positioning and how intuitive the task was with AR.

Figure 4. Subjects during the task.

Figure 5. Calculation of the distance between the centroids.

III. RESULTS

Qualitative Evaluation

Table 1 reports the qualitative results and the respective medians. Guide 5 (Fig.3) obtained a median evaluation of 5 and is the only one located on the periacetabular zone. With this result, it is possible to say that the positioning has been simplified and that the task has been very intuitive. While guide 4 got the median score lower than 3.5. One cause could be its design.

Quantitative Evaluation

Table 2 summarizes the mean and standard deviation values of the placement accuracy. The qualitative and quantitative results are consistent since the average error is lower than 2.19 mm as calculated with guide 5, whereas with guide 4 the average error was higher than 4.72 mm. These results appear rather promising if compared with the state of the art, since conventional and AR techniques for pelvic resections achieve errors of 4 and 10.8 mm [1,8], which were greater than the results calculated in our experiment.

Table 3 reports the time taken in the task with and without AR and the respective averages: an average time of 24 s for the AR task and an average time of 28 s for the task without AR. It follows that the AR task is faster. With these data, it is possible to affirm that the user without visual references tends to spend more time looking for anatomical reference points on the exposed bone and performs the task with less confidence, which is a parameter that impacts the full length of the test.

Statistical comparison

The Wilcoxon signed ranks test with Bonferroni correction was performed to estimate whether there is a statistically significant difference in the use of the different virtual guides. The test found a statistically significant difference (using a P_value = 0.05) between the use of guide 5 and guide 4, guide 5 and guide 2, guide 5 and guide 7.

Table 1. Qualitative Evaluation. Guide (G).

	G1	**G2**	**G3**	**G4**	**G5**	**G6**	**G7**
Median	4	4	4	3.5	5	4	4

Table 2. Quantitative Evaluation. Guide (G).

	G1	**G2**	**G3**	**G4**	**G5**	**G6**	**G7**
Mean [mm]	3.15	2.94	2.82	4.72	2.19	2.8	3.7
Std Dev [mm]	1.48	1.65	1.46	2.62	1.23	1.21	1.7

Table 3. Subjects (U). In the column "Error", the results are reported in the task without AR. In the column "Time AR", the temporal results are reported in the task with AR. In the column "Time No AR", the temporal results are reported in the task without AR.

Subjects	***Error [mm]***	***Time AR [s]***	***Time No AR [s]***
U1	5.32	29	28
U2	4.69	27	24
U3	4	26	25
U4	4.09	20	41
U5	5.19	25	24
U6	6.98	23	35
U7	5.76	25	23
U8	4.66	20	26
U9	6.73	35	28
U10	3.80	19	31
U11	5.31	17	50
U12	4.69	29	30
Mean	5.12	24	28

IV. Discussion

The correct placement of PST in pelvic resections is a critical step that conditions the surgical outcome. However, there is no current solution capable of efficiently guiding their installation, with the surgeon that can only rely on his/her intuition/experience and verify the placement by visual inspection. External devices providing guidance and allowing an objective verification can therefore represent a significant improvement in using PST, minimizing errors, and improving precision. In this paper, we propose the use of AR to guide and verify template placement. AR has proven to be a new technology that can rapidly reduce the learning curve for users and improve the performance of this task. The steps for creating an effective AR task were the segmentation of the patient's bone using the 3DSlicer software and then 3D printing of this in ABS. The surgical template used in the analyzed case was 3D printed, and it embodies a small "L" support containing 3 markers (3 spheres) for tracking purpose. By moving the sensorized template, the user overlays the seven virtual guides designed and located in areas visible during conventional surgery, with the real underlying bone, so that there is a correct correspondence between real and virtual. The results obtained are qualitative and quantitative. The qualitative results, based on a Likert questionnaire, highlight the preference of virtual guide 5, which obtained a median evaluation of 5. The quantitative results, representing the average error committed in model placement, show that guide 5 also obtained the smallest average error committed of 2.19 mm. This is a positive result, since the surgical execution of pelvic resections, at the state of the art, has an average error committed of 4 mm and 10 mm, while our work has obtained an error of less than 3 mm. Furthermore, the temporal results, calculated by comparing the time spent in a task with and without AR show that the user without visual references (without AR), tends to spend more time looking for anatomical landmarks on the bone and performs the task with less confidence, thus affecting the full length of the test.

V. Conclusion

In this study, we present a guidance tool for a surgical guide placement with AR. The system was validated on a phantom designed to provide a more realistic setup. Analyzing the collected results, we prove that: the use of AR simplifies the surgical task, optimizes the accurate positioning of the cutting template, speeds up the task, and the accuracy in the placement is affected by the design of the virtual guide. These promising results must be confirmed by a more structured user study involving more surgeons prior to clinical validation.

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