ArthroPlanner: A Surgical Planning Solution for Acromioplasty

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Abstract

Purpose: We present a computer-assisted planning solution “ArthroPlanner” for acromioplasty based on 3D anatomical models, computed tomography (CT) and joint kinematic simulations.

Methods: In addition to a standard static clinical evaluation (anamnesis, radiological examination), the software provides a dynamic assessment of the shoulder joint by computing in real-time the joint kinematics from a database of activities of daily living. During motion, the precise bone resection (location and amount) is computed based on detected subacromial impingements, providing surgeons with precise information about the surgical procedure. Moreover, to improve the subjective reading of medical images, the software provides 3D measurement tools based on anatomical models assisting in the analysis of shoulder morphological features.

Results: We performed an in vivo assessment of the software in a prospective randomized clinical study conducted with 27 patients beneficiating from the planning solution and a control group of 31 patients without planning. Postoperatively, patient’s pain decreased, the shoulder range of motion and the functional outcomes improved significantly and the rotator cuff healing rate was good for both groups without intergroup differences. The amount of bone resected at surgery was comparable between the groups. The percentage of remaining impingement after surgery was in average reduced to 51% without groups difference.

Conclusions: ArthroPlanner software includes all required materials (images data, 3D models, motion, morphological measurements, etc.) to improve orthopedists' performance in the surgical planning of acromioplasty. The solution offers a perfect analysis of the patient’s anatomy and the ability to precisely analyze a dynamic mechanism to fully apprehend the patient's condition and to fulfill his/her expectations. The study however failed to detect any statistically significant difference in clinical outcomes and bone resection between the groups. Short terms clinical and radiological results were excellent in both groups.

Keywords: Shoulder; Subacromial impingement; Acromioplasty; 3D surgical planning; Kinematics; 3D simulations

1. Introduction

The constellation of symptoms attributed to rotator cuff abnormalities is called rotator cuff disease. The pathogenesis of rotator cuff disorders results from a variety of factors, one of them being impingement. Subacromial impingement of the rotator cuff between the anterior [30] or lateral [31] acromion and the superior humeral head is the most common disorder of the shoulder [21, 28]. This condition notably arises when the subacromial space height is too narrow during active elevation or scaption of the arm above shoulder level due to morphology of the acromion, leading to excessive rotator cuff compression.

In severe cases of impingement syndrome, an arthroscopic acromioplasty surgery is usually performed[1]. The exact location and the amount of bone to be resected is generally left to the unique appreciation of the orthopedic surgeon during surgery. Moreover, no evidence-based consensus is available to guide decision-making regarding acromioplasties. The morphology of the scapula and of the humerus is highly variable and bone removal may not be routinely necessary, as acromioplasty may adversely affect the evolution of patient treatment. Avoiding acromioplasty and particularly altering related soft tissue structures, such as the coracoacromial ligament which can be detached or excised during anterior subacromial decompression, may be preferable as it might cause deleterious consequences (e.g., significant anterosuperior translation or even escape of the humeral head [41, 49], weakening of the deltoid origin [20], adhesions between the raw exposed bone on the undersurface of the acromion and the underlying tendon [35], etc.). Nevertheless, it seems that specific acromioplasty, namely lateral acromioplasty, to decrease critical shoulder angle (CSA) [29] – a criteria associated with rotator cuff tears [40] – is a safe procedure that could improve clinical outcome [17]. In a recent study, Gerber et al. [17] did not observe any additional complication of lateral acromioplasty, but reported lower retear rate when CSA was corrected.

To improve the precision of the surgical resection, surgeons could greatly benefit from a surgical planning solution that aims at providing precise information about a personalized procedure. Moreover, since subacromial impingements are the result of a dynamic mechanism, an effective planning solution should analyze both the morphological joint's structures and its dynamic behavior during shoulder movements to fully apprehend the patient joint's condition. To our knowledge, no such planning solution exists for acromioplasty. However, the use of 3D planning software based on patient-specific 3D reconstructions and joint kinematic simulations to improve surgical undertaking is not new, and their utility has been demonstrated in other orthopedic procedures (e.g., total shoulder arthroplasty [22, 45], total hip arthroplasty [36], femoroacetabular impingement arthroscopy [34]).

We thus developed a computer-assisted planning solution called "ArthroPlanner" for acromioplasty. The solution allows to perform standard morphological bony measurements, as well as 3D simulations of the patient's joint during everyday shoulder activities. The software computes the precise bone resection (location and amount) based on detected subacromial impingements during motion. This paper describes the software design, the implementation of shoulder-specific analysis tools, and the results obtained using this

[1] The incidence of acromioplasty has increased dramatically in recent decades. According to the American Board of Orthopaedic Surgery database, the mean number of arthroscopic acromioplasties reported per candidate increased from 2.6 to 6.3 between 1999 and 2008, a 142.3% increase, compared to 13.0% increase in the mean number of all orthopedic procedures [38, 43].

software in a clinical study conducted with patients operated from a rotator cuff repair with or without planning. As individual scapular anatomy and patient's expectations are highly variable, we hypothesized that the ArthroPlanner solution could play a role in understanding the potential zones of impingement according to movements and activities routinely performed by the patient, and in guiding the surgeon intraoperatively for more precise bone resection, if indicated. Another objective of this study was to determine if a planning solution would improve clinical and radiological outcomes, and allow less bone removal.

2. Materials and Methods

2.1. Software design

We developed a computer-assisted planning solution known as "ArthroPlanner" for acromioplasty. The solution includes two different software: a planning software to be used by the engineer to prepare the patient's data and perform the actual 3D planning, and a simple 3D viewer dedicated to the surgeon to allow him/her to replay all simulations, observe impingements dynamically and review the resection plan according to patient's expectations.

The planning software is designed for Microsoft Windows systems. The 3D viewer is however compatible for Mac and PC. The software was written in conventional C++ using Microsoft Visual Studio. Development was based on the VTK open source toolkit [48], which enabled us to quickly include medical images compatibility, a set of 3D interaction widgets, as well as visualization and image processing components. Graphical user interfaces were implemented using the cross-platform toolkit Qt [47].

2.2. 3D planning

The framework is based on computed tomography (CT). Despite the invasiveness of this modality, CT provides a better visualization of bones compared to Magnetic Resonance Imaging (MRI). However, MRI or arthro-MRI (i.e., using contrast agent) are more appropriate and routinely used for diagnosing rotator cuff tears. In this study, CT was hence performed for planning purpose only and in addition to the standard radiological examination. In particular, CT was used to reconstruct patient-specific 3D models of the shoulder joint (scapula and humerus from the humeral head to the mid-shaft) using Mimics software (Materialise NV, Leuven, Belgium). The reconstructed bones are then imported into the planning software and the following steps are performed:

First, generic bone models are produced using a template fitting approach (WrapX, R3DS, Russia) that deforms a bone template with an optimized topology (one for the scapula and one for the humerus) to the reconstructed bone. The average accuracy of this template fitting approach is typically around 0.5 mm. This allows us in the next steps to exploit anatomical correspondences and to automatize landmarks and points selection on the mesh.

Second, biomechanical parameters are computed to permit motion description of the glenohumeral joint. The glenohumeral joint center is automatically calculated by a sphere fitting technique [37] that fits a sphere to the humeral head using the points of the proximal humerus model (Figure 1A). Bone coordinate systems are established for the scapula and humerus (Figure 1B) based on the definitions suggested by the International Society of Biomechanics (ISB) [50] using anatomical landmarks defined on the bone models. Landmarks that cannot be automatically selected on the 3D meshes, such as the lateral and medial epicondyles, are identified on the CT image. To do so, the operator can interactively place missing landmarks on the image using point widgets.

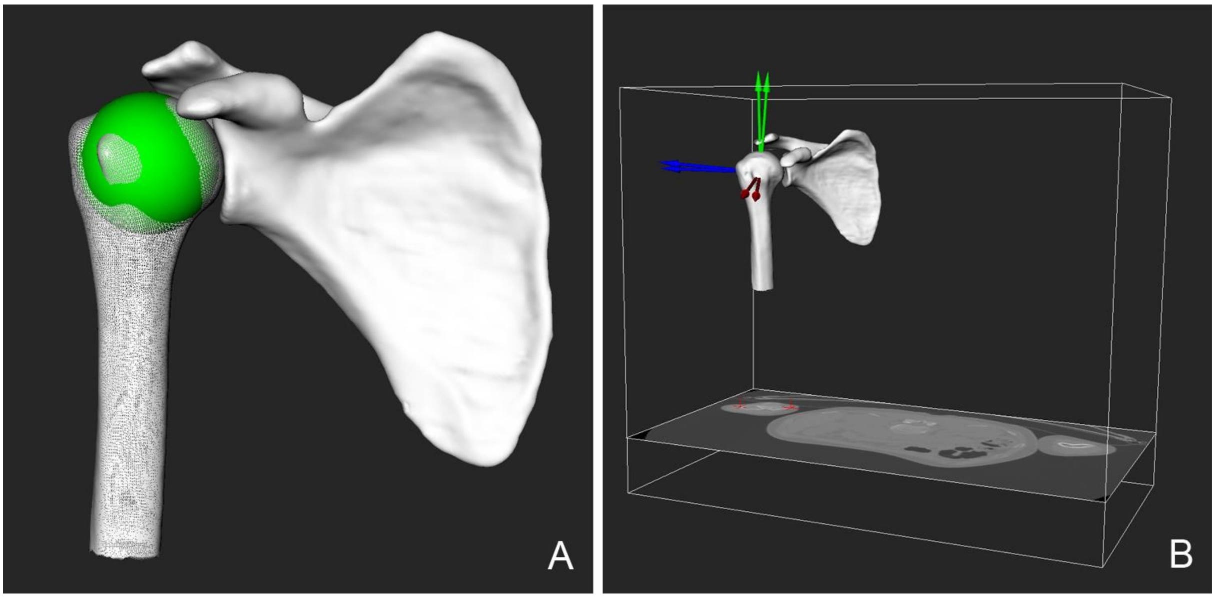

Figure 1: A) Glenohumeral center computation by fitting a sphere (in green) on the humeral head, B) bone coordinates systems for the scapula and humerus with landmarks (red crosses) defined on the CT image.

Third, morphological measurements are performed to analyze individual shoulder anatomy. A set of measurement tools was implemented in 3D, improving the subjective reading of medical images. Indeed, measuring in 3D space, that is independently from the patient positioning in the scanner, has the advantage to provide more accurate, reproducible and repeatable results. Two important criteria related to the glenoid orientation and associated with rotator cuff tears are considered: one important parameter is the CSA [29] (Figure 2A). It is based on the angle formed by the line AB connecting the superior (A) and inferior (B) bony margins of the glenoid, and the line BC connecting B and the most lateral border of the acromion (C). Deviation from the normal geometry is usually associated with greater CSA (>35°). Another parameter is the β angle [27] (Figure 2B) between the floor of the supraspinatus fossa (a) and the glenoid fossa line (AB). The angles are automatically computed in 3D by the software based on bony landmarks and can be, if necessary, interactively adjusted by the operator by manipulating the 3D handles of the line widgets in the viewer.

Fourth, shoulder ROM (3 rotations and 3 translations) is applied at each time step to the humerus model in its anatomical frame with real-time evaluation of impingement. The main idea of the proposed software is that 3D functional models can provide valuable insight into the understanding of shoulder pathology. To this end, the software integrates a dynamic module that computes shoulder joint kinematics from standard kinematic sequences (e.g., elevation, scaption, internal/external rotation). This is achieved by increasing the relevant rotational angle of 1° at each time step. To test a wide variability of realistic movements, a motion database of daily activities (e.g., cross arm, comb hair, hand behind back) is also available. These movements were acquired in previous works by optical motion capture in a group of 20 healthy volunteers. Shoulder kinematics were computed from the markers trajectories based on the definitions suggested by the ISB and using a validated biomechanical model [5, 6] which accounted for skin motion artifacts and joint translations (i.e., 6 DOF joint model, accuracy: translational error <3 mm, rotational error <4°). More details about the model and its validation can be found in Charbonnier et al. [6]. Finally, the shoulder ROM of the 20 volunteers' trials were averaged for each activity and the final values were stored in the database.

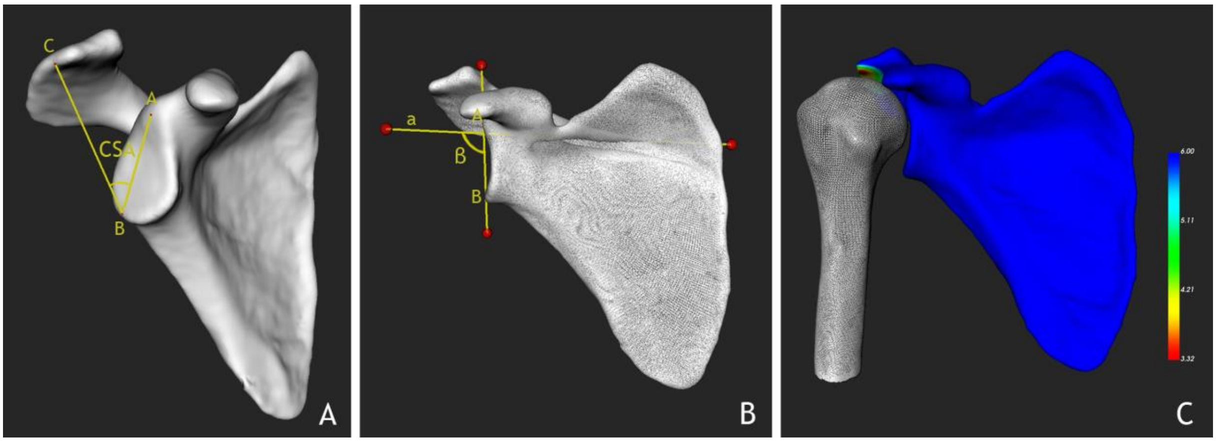

Figure 2: A) Definition of the CSA, B) definition of the β angle, C) visualization of the humero-acromial distance during motion. The colors represent the variations of distance between the acromion and humeral head with the red color denoting the zone of minimum distance.

During motion simulation, the minimum humero-acromial distance that is typically used for the evaluation of subacromial impingement [8, 19, 42] is measured at each time step. This distance is calculated in millimeters based on the simulated bone models' positions [6]. A color scale is also used to map the variations of distance on the scapula surface (red color = minimum distance, other colors = areas of increased distance), as shown in Figure 2C. Given the thickness of the potential impinged tissues, subacromial impingement is considered when the computed humero-acromial distance is < 6 mm, as suggested in the literature [6, 8, 26].

Fifth, the software computes the acromial resection plan based on the 3D simulation results. This is obtained by calculating for each point of the acromion the smallest humero-acromial distance computed over the different motion simulations. To visualize the resection plan, the same color scale is used to map the variations of distance on the scapula surface (Figure 3). As a result, the software provides both the exact location of the impingement zone and the amount of bone to be resected on each area of the acromion as indicated by the color scale.

The results at each step of the planning procedure are carefully validated by the engineer before continuing to the next. One planning including the 3D reconstruction takes in average 40 minutes, which is clinically applicable in routine practice. At the end of the planning, a PDF report containing patient's information and the results of the measurements performed is automatically generated using the PDF3D SDK [46]. The bones and the simulation data (i.e., the minimum humero-acromial distances for each simulated motion and the resection depths for the resection plan) are also exported to be used in the simple 3D viewer dedicated to the surgeon (Figure 3). With this viewer, the surgeon can reload the patient's data and get prepared for surgery. The viewer integrates the following features:

- User-friendly interface for easy manipulation of CT volumes
- User-friendly interface for controlling the display and orientation of 3D models
- Motion selection from a database
- Simulation replay with impingement visualization, including time controls (play, stop, step forward/backward)

- Resection plan review
- Patient information review
- Screenshot (JPG or PNG)

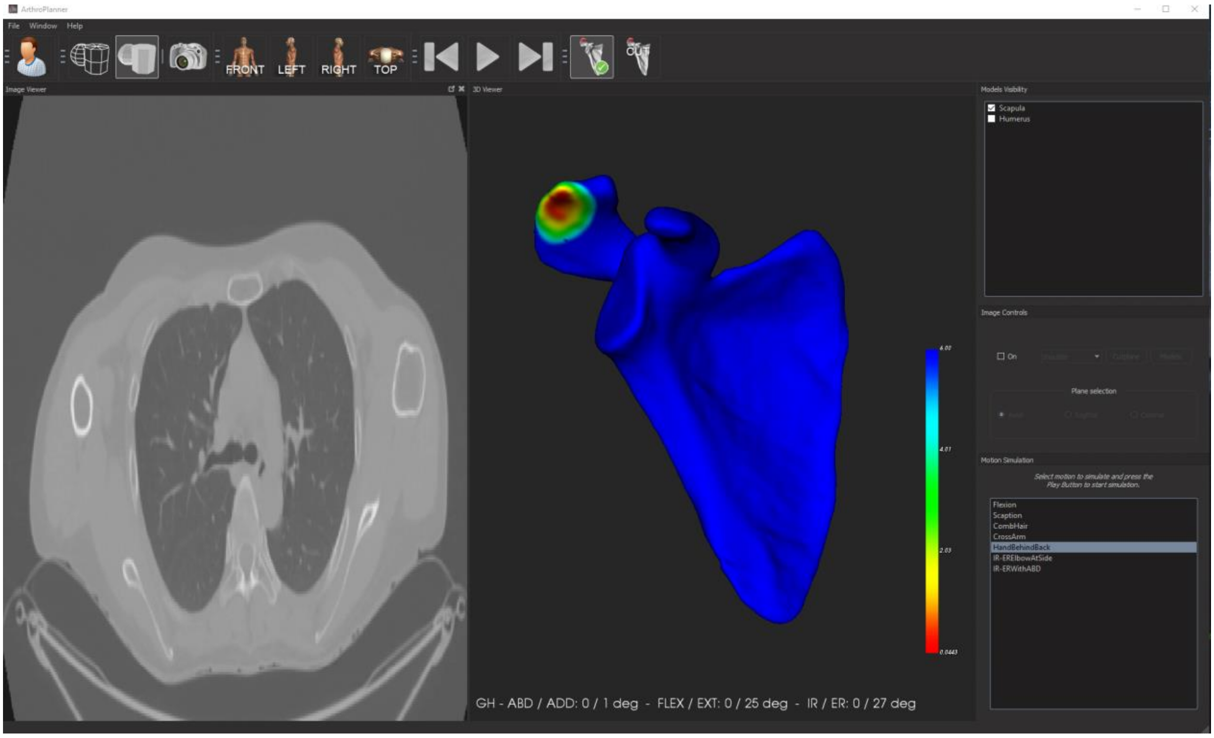

Figure 3: Screenshot of the 3D viewer dedicated to the surgeon with the visualization and simulation tools. The window on the right shows the acromial resection plan.

2.3. Clinical study

We recruited 64 patients with a posterosuperior rotator cuff tear. They were randomized in two groups of equal size: the first group underwent arthroscopic rotator cuff repair with acromioplasty planning (ArthroPlanner group) and the second without planning (control group). Institutional ethical approval (CCER n°15-151) was obtained prior to data collection and the study was registered at ClinicalTrials.gov (NCT02725346). All procedures performed in the study were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was obtained from all participants included in the study. We excluded patients with incomplete documentation, follow-up of less than six months, if they had a history of shoulder surgery, had acute trauma, had a chronic dislocation or preoperative infection, had rotator cuff arthropathy with glenohumeral osteoarthritis and superior migration of the humeral head, had a partial repair, had a fatty infiltration > grade 2 [18], had psychiatric problems that precluded informed consent or inability to read or write, and had other serious issues that precluded participation in the study.

Clinical evaluation was performed preoperatively and postoperatively at six months by an independent observer (O.R.) blinded to study design and purpose. The shoulder range of motion (ROM) was measured using a digital goniometer Dartfish express (Dartfish© Alpharetta, GA, USA) on a video recorded physical examination and included forward elevation, internal/external rotation with elbow at side, and internal/external rotation with arm at 90° of abduction. Active internal rotation was estimated to the nearest spinal level according to the following documentation: level 1, hip; level 2, bottom; level 3, sacrum; level 4, L5; level 5, L4, level 6, L3; level 7, L2; level 8, L1; level 9, T12; level 10, T11; level 11, T10; level 12, T9; level 13, T8; level 14, T7; level 15, T6; level 16, T5. In addition, pain was evaluated using the visual analog scale (VAS) graded from 0 (no pain) to 10 points (maximal pain). Functional outcome scores were also gathered, including a Constant score [11], the Subjective Shoulder Value (SSV) [12], the American Shoulder and Elbow Surgeons (ASES) [33], and the simple shoulder test (SST) [25].

Patients were operated by a single, experienced shoulder specialist (A.L.) and a consistent operative technique was used during the study period. Preoperatively, 3D CT reconstruction and acromioplasty planning were performed for all patients by two biomechanical engineers (C.C., S.C.). However, the surgeon could review the results of the planning for the ArthroPlanner group only. At surgery, the size and type of rotator cuff tears were assessed after subacromial bursectomy but before rotator cuff debridement. Massive rotator cuff tears as defined by Lädermann et al. [23] (>2 tendons with a minimal grade 2 retractions according to Patte [32]) were subclassified into 5 types based on the Collin's classification [9]: type A, supraspinatus and superior subscapularis tears; type B, supraspinatus and entire subscapularis tears; type C, supraspinatus, superior subscapularis, and infraspinatus tears; type D, supraspinatus and infraspinatus tears; and type E, supraspinatus, infraspinatus, and teres minor tears. Anterior and lateral acromioplasty limited to the impingement site with preservation of the coracoacromial ligament were performed if necessary in the control group to flatten a hooked or curved acromion, and reduce CSA. An acromioplasty was realized according to preoperative planning in the ArthroPlanner group.

Postoperatively, all patients followed the same standardized rehabilitation protocol [13]. When the use of sling was discontinued after four weeks, patients were asked to continue to perform passive overhead stretches until range of motion were obtained. Active overhead motion was then allowed, and patients were asked to perform adequate activities according to previous recommendations [7]. At the six-months follow-up visit, ultrasound of the operated shoulder was obtained by a musculoskeletal radiologist (F.K.) to evaluate the integrity and quality of the repaired tendons based on a previously validated protocol [10]. A postoperative CT scan was also acquired at six months and a 3D model of the scapula was reconstructed to quantify bone removal on the acromion. The same imaging protocol and reconstruction parameters were used as preoperatively. For comparison, the preoperative scapula model and the postoperative scapula model were first registered together using the Iterative Closest Point algorithm [2]. Then, the two models were compared to provide quantitative measures of the actual bone resection performed at surgery (*volume of bone resected at surgery*) versus the bone resection recommended by the planning software (*volume of bone to be resected according to planning*). In addition, we quantified the difference between the actual bone resection executed at surgery and the bone resection recommended by the planning (*error with respect to planning*). To provide a more detailed indication on the performed surgical gesture, we also evaluated the amount of bone that was not resected enough (*missing volume to be resected*) or too much resected (*unnecessary volume resected*) at surgery compared to planning.

All volumes were reported in cubic centimeters and were computed as follows:

$$Volume\ of\ bone\ resected\ at\ surgery = \sum_{t\,\in\,A} ARV_t$$

$$Volume\ of\ bone\ to\ be\ resected\ according\ to\ planning = \sum_{t\,\in\,A} PRV_t$$

$$Error\ with\ respect\ to\ planning = \sum_{t\,\in\,A} abs(PRV_t - ARV_t)$$

$$Missing\ volume\ to\ be\ resected = \sum_{\substack{t\,\in\,A \\ where\ PRV_t>0 \\ and\ PRV_t>ARV_t}} PRV_t - ARV_t$$

$$Unnecessary\ volume\ resected = \sum_{\substack{t\,\in\,A \\ where\ PRV_t<ARV_t}} ARV_t - PRV_t$$

Where:

- A is the list of indexes of all the triangles of the preoperative model that are located on the acromion;
- ARV_t is the Actual Resection Volume for triangle t which is the product of the area of triangle t with the distance between the triangle t and the postoperative model;
- PRV_t is the Planned Resection Volume for triangle t which is the product of the area of triangle t and the resection depth provided by the planning software.

Finally, to evaluate the prevalence of persistent postoperative impingement (or *remaining impingement after surgery*), the ratio between the *missing volume to be resected* and the *volume to be resected according to planning* was calculated in %. Indeed, if the surgeon is able to cut at 100% the volume of bone of acromial areas dictated by the planning software, this would result in an impingement-free shoulder after surgery.

2.4. Statistical analysis

Descriptive statistics are presented in terms of mean and standard deviation (SD). Statistical analysis was performed using SPSS software, v21.0 (IBM SPSS Statistics). One-way ANOVAs (with groups as factor), Mann-Whitney and chi-squared tests were used to evaluate difference between the groups. Two-way repeated measures ANOVAs were used to assess effect of the surgery on the clinical outcomes (preoperative and postoperative values as repeated measures and groups as factor). Level of significance was set at $P < 0.05$.

3. Results

3.1. Patients and groups

Out of the 64 patients recruited in the study, 2 patients refused the controlled CT, 3 had incomplete data and 1 was lost at follow-up. The ArthroPlanner group consisted of 27 patients and the control group consisted of 31 patients.

Baseline demographics (age, gender, side of shoulder pathology, limb dominance, etc.), preoperative clinical data (ROM, pain and functional scores), and intraoperative rotator cuff tear size and type were comparable between the groups. The intraoperative findings are summarized in Table 1. In average, the surgeon spent less time at surgery to treat the patients of the ArthroPlanner group (58.1 ± 16.4 minutes) than the controls (65.2 ± 17.9 minutes), but this was not statistically significant ($F(1, 56) = 2.39$; $P = 0.127$) as shown by a one-way ANOVA (with groups as factor).

Glenoid orientation measured using the 3D morphological tools revealed a mean ± SD CSA of 41.5° ± 6.5 for the ArthroPlanner group and of 39.8° ± 4.2 for controls, and a mean ± SD β angle of 79.7° ± 9.7 and of 85.0° ± 6.4 for the ArthroPlanner and control groups, respectively. Moreover, the β angle was statistically bigger in controls ($F(1, 56) = 6.048$; $P = 0.017$) as shown by a one-way ANOVA (with groups as factor).

3.2. Clinical findings

Table 2 reports the shoulder ROM, pain score and functional outcome scores before surgery and at six months postoperatively. Pain significantly decreased for all patients after surgery. All functional outcome scores significantly increased after rotator cuff repair for both groups. Moreover, all patients had a significant ROM improvement after surgery compared to baseline values. According to these results, the surgical intervention had a positive effect on the patients. There was however no significative difference in the clinical findings between the groups as shown by a one-way ANOVA (with groups as factor). In further analyses, we performed additional statistical tests by first applying non-parametric tests (Mann-Whitney) to compare the median in each group. We also categorized the measures (e.g., unsatisfactory, fair, good, very good, excellent) for each shoulder ROM, pain score and functional outcome scores and then computed the frequencies per category to test possible differences in the frequency of distribution of each category between the groups. Table 3 summarizes the results of the different statistical tests performed with the definition of the categories used in the tests.

3.3. Postoperative imaging findings

At 6 months' follow-up, the overall healing rate for the rotator cuff in the ArthroPlanner and control groups was respectively 100% and 97%, with no groups difference ($F(1,56) = 0.49$; $P = 0.484$), as revealed by a one-way ANOVA (with groups as factor).

Table 4 reports the results of the comparative assessment performed with the preoperative and postoperative 3D scapula models. The estimated volume resected at surgery was comparable between the groups (mean ± SD: 3.1 ± 2.6 cm^3 vs. 3.1 ± 2.2 cm^3 for the ArthroPlanner and control groups, respectively), thus the surgeon did not spare more bone when having access to planning. According to planning, the amount of bone to be resected at surgery was also comparable between the groups. Moreover, having access to planning did not improve the surgeon's ability in achieving an ideal bone resection, as the errors with respect to planning were similar for both groups. However, postoperative impingement was overall lower. The percentage of remaining impingement in the ArthroPlanner and control groups was respectively in average reduced to 57% and 46%, without groups difference ($F(1,56) = 2.05$; $P = 0.157$) as shown by a one-way ANOVA (with groups as factor).

4. Discussion

Our main goal in designing the computer-assisted ArthroPlanner solution was to support orthopedists with the analysis of shoulder motion in order to detect accurately the subacromial impingement zone and to provide precise information about the bone resection to be performed at surgery. We aim at providing clinicians with new dynamic information (which is not available yet in classic clinical approaches) to better apprehend the patient's condition according to his/her specific expectations (i.e., sports, activities). Moreover, the software improves the accuracy of the morphological measurements.

To test the validity of the software, we performed an in vivo study with 58 patients undergoing rotator cuff repair. The surgeon reported that the 3D planning changed completely his way to handle the surgery. He decreased the prevalence of acromioplasties, and if the planning software advised to perform a bone resection, it was rather laterally or even posteriorly. Interestingly, the planning did not recommend resection of anterior spurs or acromial bone that would have inevitably lead to at least some coracoacromial ligament thinning and disruption with subsequent risk of anterosuperior instability in the presence of a failed rotator cuff or irreparable tear [14, 24]. Coracoacromial ligament respect has always been possible in the ArthroPlanner group and may be preferable in the long term regarding alteration of the coracoacromial arch [44]. Another important aspect is that there is nowadays still a debate regarding the efficiency of acromioplasties. Whereas it has been theorized that anterior and lateral acromion may have a significant impact on subacromial impingement [3, 31], several recent studies have called into question the role of acromioplasty [4, 15, 16, 39]. In the present study, the software showed that impingement was constant in patients with complete rotator cuff tears but at different locations (posterior, lateral, medial) and that routine bone removal was unfounded. Consequently, the advantages of planning are to have a perfect analysis of patient’s anatomy including proximal humerus, glenoid orientation, and the ability to precisely analyze a dynamic mechanism in order to guide the surgeon on the appropriate surgical undertaking.

A second objective of this study was to assess if acromioplasty planning would allow to spare bone and improve clinical results. Postoperatively, patient’s pain decreased, the shoulder ROM and the functional outcomes improved significantly and the rotator cuff healing rate was good for both groups, but without intergroup differences. The amount of bone resected at surgery was also comparable between the groups. Postoperative impingement was however significantly reduced. Acromioplasty planning did hence not improve final clinical results that were excellent in both groups.

This absence of differences between the groups may result from an insufficient number of patients tested. However, some trends seem to be emerging which could have a desirable and favorable impact (e.g., shorter surgery time for the ArthroPlanner group). We believe that the most plausible reason that could have hindered the benefit of 3D planning on the clinical outcomes and bone resection is the fact that only one surgeon was involved in the analysis. Indeed, the unblinded surgeon, already aware of potential deleterious effect of important anterior acromioplasty, might have treated the control group less aggressively than in his previous experience, meaning that differences between groups may have been consequently decreased. Future work should hence consider testing additional patients treated by surgeons with less experience or knowledge of acromioplasty adverse effects.

This study has several limitations. First, clinical and radiological outcomes were limited to six months’ follow-up. It is therefore impossible to conclude whether differences between the tested groups changed in the mid- to long term. Nevertheless, it has previously been demonstrated that tendon healing can be adequately determined 6 months after surgery [1, 13]. Second, as aforementioned, only one surgeon participated to the study. We were thus unable to determine the effects of the planning solution with surgeons of different surgical expertise. Third, the acromial resections being of small magnitude (a few millimeters), the measurements of bone volume performed in the comparative assessment of 3D scapula models could have been affected by small segmentation and registration errors, which could also explain the absence of intergroup differences. Eventually, as frequently done for surgery planning, patient's irradiation is required during CT scan acquisition. Although less appropriate for bone reconstruction, MRI could be used instead of CT imaging, avoiding thus the latter problem. However, the planning would have been less accurate and the comparative assessment of 3D scapula models would have been even more affected by segmentation errors due to less visibility of bones on MRI.

In conclusion, the ArthroPlanner solution includes all the required materials (images data, 3D models, motion, morphological measurements, etc.) to improve orthopedists' performance in the surgical planning of acromioplasty. The software could play a role in understanding the potential zones of impingement according to movements and activities routinely performed by the patient, and in guiding the surgeon intraoperatively for more precise bone resection. The study however failed to detect any significant difference in clinical outcomes and bone resection between the groups. Short terms clinical and radiological results were excellent in both groups.

Conflict of Interest: The authors declare that they have no conflict of interest.

Research involving humans: Institutional ethical approval (CCER n°15-151) was obtained prior to data collection and the study was registered at ClinicalTrials.gov (NCT02725346). All procedures performed in the study were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was obtained from all participants included in the study.

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Table 1 Type and frequency (in %) of rotator cuff tears.

Type of lesions	ArthroPlanner (n = 27)	Control group (n = 31)	P value Diff. between groups†
Isolated supraspinatus	10 (37%)	9 (29%)	0.517
D type	17 (63%)	21 (68%)	0.517
E-type	0 (0%)	1 (3%)	0.346

† P values obtained with use of chi-squared test

Table 2 Shoulder ROM, pain score and functional scores before surgery and at six months' follow-up.

Measure	ArthroPlanner group (n = 27)		Control group (n = 31)		P value Pre vs. post††
	Preoperative†	6 months†	Preoperative†	6 months†	
Forward flexion	92.0 ± 35.9	141.5 ± 23.8	106.5 ± 47.0	145.4 ± 26.1	< 0.001*
External rotation (elbow at side)	26.2 ± 13.7	42.6 ± 18.8	25.7 ± 16.1	37.7 ± 14.0	< 0.001*
External rotation (with arm at 90° abduction)	33.7 ± 16.7	54.4 ± 23.5	42.9 ± 25.0	54.7 ± 21.9	< 0.001*
Internal rotation (with arm at 90° abduction)	18.4 ± 20.8	27.8 ± 21.6	17.1 ± 16.0	33.9 ± 20.3	< 0.001*
Internal rotation (spinal level)‡	7 ± 4	10 ± 4	7 ± 5	10 ± 4	< 0.001*
VAS pain score	6.4 ± 2.3	2.2 ± 2.4	6.8 ± 1.5	2.3 ± 2.0	< 0.001*
Constant score	42.1 ± 18.3	67.6 ± 21.2	37.8 ± 18.7	66.0 ± 19.8	< 0.001*
ASES score	43.6 ± 18.9	79.8 ± 19.2	38.9 ± 16.1	73.5 ± 18.3	< 0.001*
SSV score	50.9 ± 20.7	80.1 ± 16.7	45.6 ± 21.9	75.3 ± 15.4	< 0.001*
SST score	5.0 ± 2.3	8.9 ± 2.6	4.3 ± 2.1	8.7 ± 2.2	< 0.001*

† Mean ± SD

†† P values obtained with use of two-way repeated measures ANOVAs (preoperative and postoperative values as repeated measures and groups as factor)

‡ Spinal levels according to our documentation

Table 3 Differences in shoulder ROM, pain score and functional scores between the groups at six months' follow-up.

Measure	P value Interaction with groups (test on the mean)†	P value Interaction with groups (test on the median)††	P value Difference in frequency distribution of each category†††	Definition of categories
Forward flexion	0.41	0.035*	0.62	<110 bad; 110-130 medium; 131-150 good; >150 excellent
External rotation (elbow at side)	0.408	0.072	NA	No category here, depends on the constitution of the patient (hyperlax or not)
External rotation (with arm at 90° abduction)	0.47	0.885	0.093	<30 bad; 30-40 medium; 41-50 good; > 50 excellent
Internal rotation (with arm at 90° abduction)	0.2	0.227	0.44	<10 bad; 10-30 medium; 31-50 good; > 50 excellent
Internal rotation (spinal level)‡	0.478	0.806	NA	No category here
VAS pain score	0.8	0.684	0.28	0-1 excellent, 2-3 good, 3-4 medium, ≥ 5 bad
Constant score	0.66	0.778	NA	Categories too sensitive to multiple factors (age, sex, etc.)
ASES score	0.77	0.599	0.155	< 30 unsatisfactory; 30-39 fair; 40-59 good; 60-69 very good; ≥ 70 excellent
SSV score	0.93	0.67	0.847	< 30 unsatisfactory; 30-39 fair; 40-59 good; 60-69 very good; ≥ 70 excellent
SST score	0.527	0.861	0.885	<3 unsatisfactory; 4-5 fair; 6-7 good; 8-9 very good; ≥ 10 excellent

† P values obtained with use of one-way ANOVA (with groups as factor)
†† P values obtained with use of Mann-Whitney test
††† P values obtained with use of chi-squared test
‡ Spinal levels according to our documentation

Table 4 Bone volumes† (in cm^3) computed in the comparative assessment performed with the preoperative and postoperative 3D scapula models, and percentage of remaining impingement after surgery.

Measure	ArthroPlanner group (n = 27)	Control group (n = 31)	P value Interaction with groups††
Estimated volume resected at surgery	3.1 ± 2.6	3.1 ± 2.2	0.94
Volume to be resected according to planning	3.3 ± 2.3	3.8 ± 2.2	0.44
Error with respect to planning	4.6 ± 1.9	4.6 ± 1.5	0.844
Missing volume to be resected	1.9 ± 1.6	2.1 ± 1.8	0.72
Unnecessary volume resected	2.2 ± 1.9	2.0 ± 1.4	0.67
Remaining impingement after surgery	57% ± 27%	46% ± 28%	0.157

† Data are mean ± SD
†† P values obtained with use of one-way ANOVA (with groups as factor)