Glenoid and humerus bone analysis using CT transverse sections to automate gleno-humeral joint diagnoses and surgery managements

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Abstract

This paper describes an image analysis method that evaluates the glenoid and humerus bone morphology to automate the gleno-humeral (GH) joint diagnoses and surgical managements. This method uses radial B-spline curves to approximate ellipse-like shoulder structures including the humeral stem, tubercle and contact joint as well as the glenoid on every CT transverse section. Radius changes from structure centers to bone boundaries are recognized as convex, concave, separate and hole features that are then identified as pathological spurs, fractures and tumors. The centers and radii of these structures from the transverse sections are integrated to determine the properties of the humeral stem and contact joint with the glenoid, including the stem axis as well as the contact joint and glenoid centers, radii and attitudes. Based on the geometric evaluations of these structures and features, the GH joint surgery including tumor dissect and bone graft, open reduction using screws and plate or nails, and arthroplasty are automatically managed to achieve the normal GH joint functions including dissection of tumors, reduction of fractures or dislocations, and free GH joint motions. This prototype system can be used as a qualitative and quantitative tool for the GH joint diseases diagnoses and surgery managements. A series of examples and case studies illustrate the effectiveness of this automated method.

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1. Introduction

Current modalities for gleno-humeral (GH) joint surgery include preoperative evaluation using X-rays and intra-operative procedure determination that uses guiding tools and template prostheses. Preoperative X-ray evaluation helps determine the abnormalities at the humerus and glenoid, and a modality (conservative, screw-plate or arthroplasty) and also roughly choose the sizes of screws and plate or nails, and prosthetic components [1–6]. These abnormalities include fractures, tumors and spurs on the humerus and glenoid, and humeral head dislocations may limit GH joint motions [7–10]. The guiding tools help determine precise the humeral stem axis, cutting plane for sawing out the humeral head and positions for screws and plates or nails [11–15]. Template prostheses help choose suitable prosthetic components [16,17]. Using the manual X-ray evaluations and trial-and-error methods with the guiding tools and the template prostheses, relatively acceptable surgical procedures and prosthetic components can be obtained and improvement in GH joint motions can be achieved [18,19].

To facilitate the GH joint function, surgeons should use as a large prosthesis as possible to reduce the average loading, let the prosthetic stem axis fit the stem canal and choose a suitable humeral or prosthetic head position to stabilize the GH joint motions. In addition, procedures should be easier to save operation time in selecting the cutting plane for inserting the prosthesis, positions for screws and plates or nails and prosthetic components. However, the X-ray based preoperative evaluation is insufficient in shoulder morphology evaluations, surgeons must use time-consuming intraoperative
trial and errors to avoid uncertainties and compensation impossible procedures [20,21]. Moreover, the surgical result is difficult to be optimal. For example, whether the GH joint is comfortable with a recovered humeral head position or prosthetic components cannot be expected by the trial-and-errors if no evaluations about the glenoid and humerus bone morphology [22–24].

Over the past few years, computer graphics techniques enable real-time visualization and interactive surgical simulation for CT or MRI sections to assist diagnoses and verify surgery management [25]. Meanwhile, feature recognition techniques extract pathological characteristics to help diagnoses and surgery management. Especially, three-dimensional anatomic structures and features provide spatial information to enable accurate and automate diagnoses and surgery management. Current three-dimensional recognition methods use prior (preset) 3D geometric data to search fit structures in 2D sections and then evaluate the 3D structure properties by the fit 2D shapes. For example, an ellipsoid was used as a prior of a femoral head. The structures on sections with ellipse-like shapes are then considered as belonging to the femoral head and are used to estimate the femoral head properties such as the head radius [26]. Similarly, local curvedness of various 3D shapes was used to classify priors of colonic polyps, folds, mucosa or diverticula [27]. Then, analysis of structure curvatures on sections determine the classification of the structures and estimate the structure properties. Such methods are actually difficult to recognize abnormal shapes. For example, the femoral head on sections may not be ellipse-like because of breakage or compression. However, recognizing abnormal cases and estimating the deviations from the abnormalities to the normality are important to diagnose.

We have developed three-dimensional feature recognition techniques for the musculoskeletal system including intervertebral discs, spinal bones and hip structures for 2D transverse CT or MRI sections [28–30]. Instead of using a prior geometry to match, we search some initial properties on every 2D section (such as centers of separate bone structures). These properties were then used to decide structures and structure properties on 2D sections (such as ellipse-like structure and its radius) or to integrate into 3D properties (such as axes of the bone structures). Spatial information of structures and structure property deviations about the normal values were then estimated to determine pathological characteristics and thus to automate diagnoses and surgery management. The managed surgical modalities can be simulated by our reported surgery simulator that recognizes new bones generated from the cut swept surfaces on bones to enable various orthopedic surgical procedures [31]. The simulation results can demonstrate surgeons how bones are opened, corrected or repositioned, closed and fused, a prosthesis is inserted, and screws and plate are positioned [32,33].

In this study, we extend our method to automatic GH joint diagnoses and surgery management that uses successive transverse CT sections to evaluate the humerus and glenoid morphology. This method identifies the humeral stem, tubercle and contact joint as well as the glenoid to recognize concave, convex and hole features on these structures. These features on the successive sections are integrated to indicate abnormalities of spurs, fractures and tumors and their positions and volumes. The structure properties on the sections such as radius of the contact joint, the glenoid or the humeral stem are then used to calculate the structural spatial properties such as the contact joint center and radius, the glenoid attitude, the boundary plane between the contact joint and tubercle, and the stem axis. These properties can be used to evaluate whether a structure is dislocated or compressed or the humeral stem axis is sheared. Based on these structure and feature evaluations, the surgical procedures are then automatically managed to dissect tumors and bone grafts, reduce the dislocated humerus and compressed structures and position a prosthesis or screws and plate. These surgical procedures are then simulated for verification and rehearsal using our orthopedic surgical simulator.

We describe sample cases with various shoulder diseases in the GH joint. The results of image-analyses by our method were compared with data obtained by traditional clinical investigations, diagnosis and operative findings. These results suggest effectiveness of this method in promoting the diagnostic rate and managing accurate surgical procedures.

2. Methods

2.1. Theory study

Fig. 1(A) shows an idealized GH joint, at which the contact joint of the humeral head rotates inside the glenoid cavity to transfer the load on the humeral stem to the glenoid. The ratios, distances and angles among the contact joint, the stem and the glenoid must be in normal ranges to maintain the GH joint stability. Some diseases change the ratios, angles or distances to result in abnormalities in the rotations or the stability. For example, a dislocated humerus results in an instability because it has large deviation from the contact joint center to the ideal position (on the glenoid attitude vector) thus it cannot rotate stably inside the glenoid cavity as shown in Fig. 1(B), and a fractured segment obstruct the humerus rotation as shown in Fig. 1(C). A set of CT or MRI transverse sections may be used to resolve the humerus and glenoid. The most inferior sections (Section A in Fig. 1(A)) resolve only the humeral stem. More superior sections resolve the tubercle or the contact joint or the glenoid depending on the section position and the arm attitude. For example, Section B in Fig. 1(A) resolves only the tubercle, Section C resolves the contact joint and the tubercle and Section E resolves the contact joint and the glenoid; while Section D resolve all the tubercle, the contact joint and the glenoid.

In the followings, Section 2.2 introduces our method that analyzes the humerus and glenoid morphology on transverse sections to recognize anatomic structures and associated features. Section 2.3 introduces the method that integrates these 2D structures and features to obtain three-dimensional structure and feature properties useful for diagnoses and surgery management. Section 2.4 introduces surgery management method based on these properties.
2.2. Two-dimensional structure and feature recognition on respective transverse section

The recognition of ellipse-like structures and associated features employ our previous work [29]. We determine the (initial) center of each stem canal on a transverse section by averaging the positions of the pixels of the stem bone, and then use a vector starting from the center along every (totally 360) integral angular position to intersect the first bone (canal) boundary (Fig. 2(A)). Because the canal boundary is ellipse-like, the distance (radius) from the center to the boundary changes smoothly except concave and convex features. The radius inside a feature is interpolated by the two radii of the two feature ends. Then, 360 radii are used to re-determine the stem center using the B-spline approximation. The concave or convex features on the bone boundaries and hole (bone osteolytic lesion) features inside the bone or separate fractures outside the bone boundaries are then determined by the change of the radius from the stem center to the bone boundaries as illustrated in Fig. 2(B).

At the humeral head, the stem canal becomes obscure due to filling with cancellous bone; therefore, an initial 2D humeral head center at each superior section resolving the humeral head is extrapolated by the stem canal centers at the inferior sections. Then, a vector starting from this humeral head center along every integral angular position is used to intersect bone boundaries using the similar may as described above. The concave and separate features are recognized as fractures, the hole features are tumors, the small convex features are spurs, and the arc (at the first intersected bone boundary) with a smooth radius change is recognized the contact joint as illustrated in Fig. 2(C). The tubercle area is obtained by excluding the contact joint area and the line connecting the boundary pixels of the two areas is defined as the boundary line. The pixels on the contact joint are then used to B-spline approximate the 2D contact joint center on the section. This center is then used to re-determine the features at the contact joint area and the radii from this center to the pixels on the contact joint arc. The average of the radii of all the contact joint pixels is defined as the 2D contact joint radius on the transverse section. The intersections (at the second intersected bone boundary) with smooth radius changes at the lateral side are the pixels on the glenoid. These pixels are used to determine the 2D glenoid center and the 2D glenoid radius. These center and radius are then used to determine the concave fracture or convex spur on the glenoid.

2.3. Three-dimensional structure and feature property calculations

Three-dimensional features of the humeral stem are calculated by the 2D canal centers obtained at the inferior sections.

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Fig. 1. A simplified graphical representation of the right humerus and glenoid. Ocher areas: surfaces of bones. Blue planes: transverse sections. Green axis: glenoid attitude vector. (A) Spatial relation of the humerus and glenoid. (B) Dislocated humerus that cannot rotate stably inside the glenoid cavity. (C) Fractured humeral head fragment that obstructs GH joint rotations.

Fig. 2. Structure and feature recognitions on transverse sections. (A) Stem canal recognition: averaging bone pixels to obtain the initial canal center, then B-spline approximating the canal. Blue curves: concave and convex features on the canal boundary. (B) Stem feature recognitions: using B-spline approximated canal center to detect concave and separate fractures, concave spurs or crest, and hole tumors. (C) Center of humeral head: extrapolated by the stem axis, used to determine smooth contact joint, small convex spurs, concave and separate fractures and hole tumors. Green line: boundary line.
Meanwhile, the 3D features of the contact joint and glenoid are determined by the centers of the 2D contact joint areas obtained from the superior sections. The boundary lines of the contact joint areas on these superior sections also determine the 3D boundary between the tubercle and the contact joint.

### 2.3.1. Humeral stem recognition

The recognition of the humeral stem and associated features bases on our previous work that processed similar geometric shape of the femur [30]. First, the canal centers on the inferior sections are used to regress to the humeral stem axis. If the distance between the centers of two neighboring sections is too large, a shear dislocation is considered existing inside the stem. Thus, two respective centerlines are used to regress to the separate humeral stem axes at the two sheared parts of the stem as illustrated in Fig. 3(A). The 2D concave, convex, hole and separate features at these sections are then integrated to calculate the 3D position and volume for each 3D pathological feature (fracture, spur, tumor or cyst, and avulsion).

### 2.3.2. Contact joint and glenoid recognition

To calculate the 3D contact joint center, the centers of the 2D contact joint areas obtained from the superior sections are used to regress to an axis passing this center as the regression for the stem axis. Then, the following equation based on the Pythagoras theorem is used to determine the position of the contact joint center (Fig. 3(B)).

\[
d_i^2 + r_i^2 = d_j^2 + r_j^2 = R^2;
\]

\[
r_i^2 - r_j^2 = d_j^2 - d_i^2 = c(2d_i + c) \quad (1)
\]

\(R\) is the 3D contact joint radius and assumed uniform from the contact joint center to any point on the joint surface. \(r_i\) and \(r_j\) are the 2D average radius at the \(i\)th section and the \(j\)th section, respectively. \(d_i\) and \(d_j\) are the distances from the 3D contact joint center to the calculated 2D centers of the contact joint areas at the \(i\)th section and the \(j\)th section, respectively. \(c\) is the interval between these two sections. The unknown \(d_i\) can be solved by \(c\), \(r_i\) and \(r_j\) to determine the position of the contact joint center. One solution for the position can be obtained from the most superior section with each of the other sections resolving the contact joint. We use the average of all the solutions to determine the position. Then, \(R\) is determined as the average of the radii from this contact joint center to all pixels on the contact joint. The 2D concave, convex, hole and separate features at the sections resolving the contact joint are then integrated to calculate the 3D position and volume for fracture, spur, tumor or cyst, and avulsion features.

The 3D glenoid center is determined by the method as described above. Then, the glenoid attitude vector is determined by averaging the vectors from the glenoid center to all the pixels on the glenoid. The normal position of the contact joint center is then set as the addition of \(R\), the contact joint radius with the normal gap between the contact joint and the glenoid along the glenoid attitude vector. The 2D concave, and convex features at the sections resolving the glenoid are then integrated to calculate the 3D position and volume for fracture and spur features.

### 2.3.3. Recognition of tubercle and contact joint boundary

The following equation is used to regress the boundary lines between the tubercle and the contact joint areas on the superior transverse sections to the boundary plane (assumed as \(ax + by + cz = d\)) between the tubercle and the contact joint.

\[
A^TAW = 0(2), \quad \text{in which} \quad A = \begin{bmatrix} X_1 & Y_1 & Z_1 \\ X_2 & Y_2 & Z_2 \\ X_3 & Y_3 & Z_3 \\ X_4 & Y_4 & Z_4 \\ \vdots & \vdots & \vdots \end{bmatrix},
\]

\[
W = \begin{bmatrix} a \\ b \\ c \end{bmatrix}
\]

\((X_1, Y_1, Z_1), (X_2, Y_2, Z_2), (X_3, Y_3, Z_3), (X_4, Y_4, Z_4), \text{etc.},\) are the boundary lines on the sections (Fig. 3(C)). \((a, b, c)\) in the boundary equation is determined by the above equation. Then, one boundary line can determine a solution of \(d\) in the boundary equation by the \((a, b, c)\). We use the average of all the solutions from the superior sections resolving the glenoid to determine \(d\).
2.4. Treatment, surgical planning and verification

Treatments for GH joint diseases are categorized as: (1) conservative treatments; (2) open reduction; (3) dissection and bone grafting; (4) hemi-arthroplasty and (5) total arthroplasty [34,35]. Conservative treatments are applied if there have only small spurs (convex features) or fractures (concave or separate features) and benign tumors (hole features) and humeral head dislocation.

Open reduction uses screws and plate or nails to fix a humerus or a glenoid with fractures. These fractures may also result in a humeral dislocation to bring contact insufficiency of the humeral head with the glenoid [36,37]. Morphological changes are corrected during the open reduction including bone fractures, humeral head or glenoid compression, humeral head dislocation and contact insufficiency. Dissection and bone grafting is used to remove large benign tumors. Screws and plate or nails may be accompanied to the open reductions and the bone grafting to fix the reduced fractured bone segments or the grafted bone.

Hemi-arthroplasty is applied in patients with a large fracture or four (or more) fractures or malignant tumor at the humeral head. Total arthroplasty is used when severe fractures or arthritis changes, or Avascular Neurosis (AVN) occurs which let the contact joint radius changes irregularly or become much small [38]. Whether a commercial or custom-made prosthesis is required depends on where malignant tumor is present. If there has any malignant tumor inside the stem, a custom-made prosthesis must be used. The prothetic contact joint and the glenoid are set as the size of the one at the normal shoulder. The radius of the prothetic stem refers the smallest radius of the stem canal from all the transverse sections to meet the requirement of the proximal cortical fit. The boundary plane between the tubercle area and the contact joint is set as the cutting plane to insert the prosthesis.

Surgical procedures of the above dissection and graft, open reduction and arthroplasty can be simulated on our reported simulator to confirm suitability of the planned surgical procedures [33,34]. We have transferred all sizes of template prostheses provided by several manufacturers into 3DS MAX representations [39]. Each prosthesis for simulation is then converted into the volume representation to simulate the managed modality and procedures.

3. Results

The final diagnoses were confirmed by operative findings and were consistent with the diagnoses obtained by the study method to automatically diagnose and manage GH joint diseases. From January 2003 to December 2004, CT transverse sections in Orthopedic Department of Taipei Medical University Hospital had performed 21 GH joint diseases. Among which, 3 were conservative and 18 surgeries have been operated including 3 humeral head fractures with dislocations, 3 begin tumors, 7 four part fractures at the humeral heads, and 5 avulsion fractures. All 18 operated patients had clinically satisfactory outcomes after a mean follow-up period of 1.25 year (range, 2 year–1 month, and 1 year). Fourteen (78%) patients had excellent results and four (22%) patients had good results. There were no cases of fair and poor (no improvement) outcomes. The results of the individual steps of diagnosis and evaluation are listed in Table 1.

4. Case studies

Herein, we describe here the results of five cases (Cases 1, 4, 14, 19 and 21 in Table 1): one was screw and T-plate, one was screw and washer, one was hemi-arthroplasty and two were conservative. The intervals for transverse sections are actually tradeoffs of X-ray exposure to patients and adequate resolution for our humerus and glenoid bone morphology analyses. The intervals here were set as all in 3 mm for comparisons.

4.1. Open reduction with screw and T-plate for fractured humeral head

This 43-year-old man (Case 1 in Table 1) suffered from severe pain with deformity over the left shoulder and immediately after automobile accident. Chief compliments and X-ray showed-fracture dislocation of the left shoulder. Close reduction of the left humeral head was performed under general anesthesia. Residual fracture of the left humeral head fracture and dislocation was noted and physical examination revealed a deformity limiting the left shoulder motions. These clinical findings were indicative fractures at the left head fracture with a dislocation.

CT was performed in 54 transverse sections. Fig. 4(A) shows a 3D image rendered from the isosurface reconstructed from the MC isosurface reconstruction algorithm [40]. At the left humeral head, two brought outward head fractures and the head dislocation can be clearly observed. Fig. 4(B) shows a transverse section resolving the right humeral stem and the left humeral head and the image analysis result for this section. The result at the right humeral stem demonstrates a B-spine approximated canal without pathological convex, concave and hole features. The result at the left humeral head shows the two head fractures, the contact joint center and the glenoid attitude vector that reveals a large deviation (dislocation) from the contact joint center to the glenoid attitude vector. Fig. 4(C) shows a transverse section resolving the normal right humeral head and glenoid at which only little deviation from the contact joint center to the glenoid attitude vector can be observed.

The calculated deviations of the humeral heads to the ideal positions were (−1.3, −1.0, 1.5) and (9.1, −7.8, 16.5) for the right and left shoulder, respectively. These indicate a left humeral dislocation (about 20 mm). Table 2 shows the image analysis results of the transverse sections resolving the humeral head fractures and dislocation. In each section, two concave fractures exist on the left head boundary and the distance between the left 2D contact joint center and the ideal position is large that reveals the dislocation and fracture at the left humeral head. The angular positions of each fracture in the consecutive sections were close to each other, indicating these 2D fractures indicate the same 3D fracture. These 2D fractures were then integrated to obtain the 3D fracture position and volume.

Fig. 5 shows parts of simulated images for the open-reduction surgery. Fig. 5(A) shows a tool swept surface was cutting the first tuned out bone fragment. Fig. 5(B) shows the tuned out frag-
<table>
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<th>Subject No.</th>
<th>Age (year)</th>
<th>Sex</th>
<th>Automated diagnosis ( \text{a} )</th>
<th>Automated surgical management ( \text{b} )</th>
<th>Confirmation of diagnosis by operative findings</th>
<th>Satisfaction condition under our method</th>
<th>Follow up post-operation</th>
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- **ORIF**: open reduction with internal fixation; Min, minute; ++++, strong valuable; **+, moderate valuable; +, loss valuable; −, no valuable; M, male; F, female; H, humerus; fr, fracture; tu, tumor; E, excellent; G, good; R, right; L, left.

- **a**: Automated diagnoses based on image analysis of transverse sections.
- **b**: Automated surgery management based on image analysis of transverse sections including three types of surgeries: A, ORIF; B, arthroplasty; C, conservative treatment.
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<th>Section no.</th>
<th>Fracture 1 (°)</th>
<th>Fracture 2 (°)</th>
<th>Right contact joint center (x, y, z)</th>
<th>Left contact joint center (x, y, z)</th>
<th>Right contact joint radius</th>
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<th>Right glenoid center (x, y, z)</th>
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Fig. 4. Images of isosurface reconstruction and analysis for a humeral head fracture and dislocation. (A) 3D reconstruction of bone surface. Oblique view: solid arrows, turned out fractured segment. Green, blue and red lines: primary axes of volume. (B) A transverse section with (left) head dislocation and fractures, and (right) normal stem. Yellow curve: approximated B-spline canal boundary. Yellow point: regressed contact joint center. Solid arrows: fractures. Red centerline: glenoid attitude vector projecting onto this section. (C) A transverse section with normal humeral head. Yellow point: contact joint center. Blue line: boundary line between tubercle and contact joint. Red centerline: glenoid attitude vector.

Fig. 5. Surgical simulations for reduction of head fracture and dislocation. Near frontal view. (A) Cut swept surface (red) on a turned out fractured segment (blue). (B) Reduction of the fractured bone segment (light gray). (C) Reduction of dislocated humerus (pink) and screw (blue) and T-plate (yellow) on reduced fractured bone fragment.

ment was repositioned onto the head in a translation following a $90^\circ$ rotation. Fig. 5(C) shows the left humeral head has been recognized and repositioned near to the glenoid to reduce the dislocation and finally the calculated screw and T-plate (sizes and positions) has been used to fix the repositioned fractured fragment onto the humeral head. Because the repositions of the two fractured fragments and the humeral head were in accordance to the calculations of the system, the reductions were suitable.

4.2. Hemi-arthroplasty for humeral head with tumor and communicate fractures

This 58-year-old female (Case 4) suffered from right shoulder pain with motion limitation following a falling down to the ground. Abnormalities were noted during physical examination: limited external rotation and local tenderness of the right shoulder. A comminuted fracture over the right humeral head was observed on the X-ray. These findings were indicative of the right humeral head: a benign tumor with comminuted fracture.

CT was performed in 67 transverse sections. Fig. 6(A) shows a 3D reconstructed image for a tumor on the right humeral head. Fig. 6(B and C) shows a respective transverse section resolving a respective hole that is considered generated by the same tumor hole. Because the outside cortical bone was only little fractured in the lateral side, we can only observe this pathology from a specific perspective (Fig. 6(A)). However, this pathology hole can be clearly analyzed at the superior transverse sections to indicate the tumor position and volume.

The image analysis result indicates one large hole tumor (with large radius change) in each section resolving the superior right humeral head. Because of this tumor, the hemi-arthroplasty is required. The calculated boundary plane is also calculated to determine the base plane for inserting the prosthetic head. Fig. 7 shows parts of the simulations of the hemi-arthroplasty based on the feature recognitions, evaluations and surgical manage-
ments by the system. **Fig. 7(A)** shows a saw cutting the humerus along the boundary plane between the tubercle and the contact joint. The calculated prosthetic stem and head also appeared. **Fig. 7(B)** also shows the recognition (highlighted as another color) and insertion of the prosthetic stem. Before this insertion, the humerus was recognized and translated to easy the surgical simulation. **Fig. 7(C)** shows the insertion (following the recognition) of the prosthetic head and the movement of the humerus into the normal place. The position and size of the prosthesis resulted in good morphology matching with the normal left shoulder. These hemi-arthroplasty simulations indicate the planned hemi-arthroplasty surgery can achieve good shoulder functions postoperatively.

### 4.3. Open reduction with screw and washer for avulsion fracture

This 39-year-old man (Case 14) suffered from right shoulder pain with motion limitation following a falling down to the ground. Abnormalities were noted during physical examination: limited range of right shoulder motions, lifting disability and local tenderness over right shoulder area. An avulsion fracture fragment beside the right humeral head was observed on X-ray. These findings were indicative of avulsion fracture at the humeral head.

CT was performed in 49 transverse sections. **Fig. 8(A)** shows a 3D reconstructed image demonstrating the separated fracture outside the right humeral head. **Fig. 8(B)** shows a transverse section resolving the right humeral head with the separated fracture. **Fig. 8(C)** shows the surgery simulation result that the separate fragment has been recognized and repositioned back onto the humeral head and a screw and washer has been positioned the separate fragment.

### 4.4. Conservative cases

This 55-year-old woman (Case 19) suffered from right shoulder pain with shoulder trauma 2 days ago. The following abnormalities were noted during physical examination: limited range of motions, and elevation disability over the right shoulder. These clinical findings and X-ray were indicative of glenoid fracture at the right humeral head. CT was performed in 36 transverse sections. **Fig. 9(A)** shows a 3D image revealing the glenoid fracture. **Fig. 9(B)** shows the image analysis of a transverse section resolving the fractured glenoid. The image analysis result indicates a small fracture at the glenoid revealing a (conservative) fixation with sling for 3 months.

This 16-year-old woman (Case 21) suffered from right shoulder pain with lifting disability for ten months. She had 2-year history of shoulder pain. The following abnormalities were noted.
during physical examination: local tenderness with limited range of motion. These clinical findings and X-ray were indicative of a small benign tumor over the humeral head. Fig. 9(C) shows the image analysis of a transverse section resolve a small benign tumor revealing only closed observation is required.

5. Discussion

Three-dimensional geometric estimation for fractures and tumors as well as the humeral head dislocations are important factors in deciding the appropriate diagnostic modality and surgical procedures for GH joint diseases. Current techniques are mainly based on clinical experiences, analyses of X-rays [1–6], observation on MRI or CT sections without the benefits of qualitative and quantitative analyses of 3D humerus and glenoid bone morphology. In this study, we proposed a method that analyzes the 3D geometry of humerus and glenoid bones to estimate the humeral head dislocation, and fractures and tumors in the humerus and glenoid. As the result, precise diagnoses and surgical procedures for tumor dissection and bone graft, open reduction and arthroplasty can be automatically determined.

Our method uses radial B-spline curves to approximate the stem canal, the humerus head and the glenoid as ellipse-like structures at every transverse section. Concave, convex or hole features on these structures are then recognized as pathological features such as fractures, spurs or tumors. The centers and radii of these ellipse-like structures obtained from the transverse sections are used to determine 3D structure axes, attitudes and centers to evaluate structural deformities such as humeral head dislocation or compression. Three-dimensional pathological feature position and volume are integrated from feature properties on the transverse sections. These 3D structure and feature properties are used to determine the parameters in GH joint surgery including reduced distances of the humeral dislocation and fractured fragments, dissecting and bone grafting volumes and positions for tumors, and sizes and positions of prosthetic components or screws and plate.

Three-dimensional reconstructed isosurfaces by volume visualization techniques let surgeons choose a suitable perspective to visualize pathological characteristic on bones; however, it is not easily used to observe interior tumor and cannot provide precise geometry when the section number is not enough. For example, the humeral heads in the reconstructed images of all the studied cases seem shorter (about 0.8–0.9 times) than normal because the head height is about 10 times to the section interval to bring maximum 20% of resolution miss. Different from the 3D reconstruction approach, our method analyzes anatomic structures and associated features in 2D sections and then integrates these 2D structures and features to obtain 3D structure and feature properties. Although simple 3D geometric entities such as lines and planes are used to evaluate the structure properties, the estimations using these entities (e.g. the distance between the contact joint and glenoid attitude vector to estimate the humeral dislocation) are near to the general values. That means the evaluations based on these simplified 3D entities are acceptable.

Three successful simulation cases of open reduction and arthroplasty based on the 3D morphology analysis of humerus and glenoid bones shows that GH joint diseases can be accurately diagnosed and managed to operate and achieve the GH joint morphological stability. These successful simulations also indicate that this diagnostic and managing tool can be combined with the surgical simulation tool for use in automated diagnosis, surgical planning and verification, prognosis assessment and management. Thus, our method provides not only accurate diagnosis but can also provide detailed surgical parameters including distances for reduction, sizes of prosthetic components, and position and volume for opening and dissecting and grafting bones. Uses of our method can save surgical time because the need for trial and errors of fitting template prostheses and uses of various guiding tools can be avoided. Meanwhile, the use of the simulator can be used to train the interns and students because of the seldom occurrence in non-conservative GH joint surgery.

Twenty-one patients with GH joint diseases participated in this study were compared with the intraoperative findings and were consistent at more than 1-year postoperative follow-up. The diagnoses and managed surgical modalities, dislocated distance as well as the positions and volumes of fractures and tumors were also confirmed intraoperatively. The operation time was also reduced in the trial and errors of using template prostheses and guiding tools. However, these examples do not include all
possible GH joint surgery (lack of total arthroplasty and tumor dissecting and bone grafting) because these two modalities were not required during the studied two years. Such examples should be also studied to demonstrate the effectiveness of our method. The low occurrence of the GH joint diseases also brings a problem of deciding constants in our models. For example, the constants to decide whether conservative treatment or open reduction or dissecting and bone grafting should be applied depend on the volume of spur or fracture or benign tumor or humeral head dislocation but now accord the experiences of the author. These constants should be studied to vary according to given specification (including age, sex, race and so forth) under statistically meaningful number of cases.

Acknowledgment

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References

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