3D Reconstruction of the scapula from biplanar radiographs

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ABSTRACT

Access to 3D bone models is critical for applications ranging from pre-operative planning to biomechanics studies. This work presents a method for 3D reconstruction of the scapula from biplanar radiographs, which is based on the combination of a parametric model approach in conjunction with a Moving Least Squares (MLS) deformation technique. A parametric scapula model was created by fitting geometric primitives (with their descriptive parameters) to the CT reconstruction of a dry scapula. These geometric primitives were then used to define a set of handles which allow the user to control the as-rigid-as-possible deformation of the template model in real-time, until optimal correspondence between the actual X-ray images and the retro-projection of the deformed model. When applied to 10 dry scapulae, the presented method allowed obtaining reconstructions which were on average within 1mm of the CT-derived model at scapula regions of interest. Morphological parameters such as the glenoid's dimensions and orientation were determined with errors of 1^{o} and less than 1mm, on average. This is of great interest as the current methods used in clinical practice, which are based on 2D-CT, are subject to uncertainties of the order of 5^{o} for glenoid version. This method is of particular interest as it further reduces our dependence to CT for 3D reconstruction of bones and clinical parameter estimation.

Keywords: Scapula, reconstruction, biplanar radiograph, deformable model, parametric model

1. PURPOSE

Access to personalized 3D bone models is important for many applications, ranging from pre-operative planning to biomechanical studies. Computed tomography (CT) is the modality of choice for 3D imaging of bone because of its high precision. However, its high cost, long reconstruction time and the involved radiation doses are major drawbacks for its use in clinical practice. In order to overcome some of these issues, alternatives to CT have been developed for 3D reconstruction of the lower limb and spine. For example, a few authors have shown that reliable 3D reconstructions could be derived from biplanar radiographs. Methods based on statistical models and/or surface deformation and non-rigid 2D/3D registration techniques have been presented [1–5]. However, adaptation of these methods to bones with complex shapes is not trivial, and no such method has been developed or adapted to reconstruction of shoulder bones such as the scapula. To our knowledge, available methods for 3D reconstruction of the scapula all rely on interactive segmentation of CT slices. Therefore, because of the long and tedious reconstruction process, actual 3D scapula models are not often reconstructed from CT data in clinical practice. Instead, shoulder surgeons rely on 2D estimates (2D-CT slices or planar radiograph) when describing critical 3D scapular parameters such as glenoid version. It is well known that these estimates may induce considerable errors due to projection artifacts or slice selection and orientation. Uncertainties of the order of 5^{o} have been reported in glenoid version estimation from 2D-CT slices [6–8]. It is of common knowledge among orthopedic surgeons that proper positioning of prosthetic components is essential to adequately restore function and for implant durability. Reconstruction of a reliable 3D scapula model from biplanar radiographs would therefore be a major advancement for shoulder surgeons as it would give easy access to a 3D scapula model and scapular parameters. This would in turn help in surgical planning, and could also prove to be useful in kinematics studies and biomechanics simulations. Hence, the purpose of our work is to present a method for 3D reconstruction of the scapula from biplanar X-ray images which would simultaneously allow for precise estimation of various clinically relevant parameters of the scapula.

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2. METHODS

The algorithm presented in this paper uses a combination of a parametric model approach in conjunction with a Moving Least Squares deformation technique [5], [9] to reconstruct a personalized and morphologically realistic model of a subject's scapula. Following digitization of scapula bony landmarks on a set of biplanar radiographs, a set of descriptive parameters is calculated and used to generate a pre-personalized model. This model is then rigidly registered to the radiographs and manually adjusted until optimal correspondence between simulated radiographs of the deformable model and actual biplanar radiographs.

2.1 Parametric generic model

A CT scan with slice thickness of 1mm was obtained of a normal dry scapula of average size and without any sign of degenerative change. Reconstruction of the cortical bone thickness was performed by a shoulder surgeon with the Avizo software (Mercury Computer Systems, Chelmsford, Massachusetts, USA). As it has been presented in a recent publication [10], a set of regions corresponding to various important structures of the scapula was then defined and manually digitized in a dedicated software. Geometric primitives (points, lines, spheres, cylinders) were fitted to each region (figure 1) with least squares algorithms. Descriptive parameters associated to each of the primitives were calculated and used to define a set of descriptive parameters of the scapula. These parameters correspond to dimensions as well as relative orientations and positions of various structures. An orthopedic surgeon specializing in shoulder surgery was involved in the process in order to ensure clinical significance of the calculated parameters. Sensitivity of the parameters to digitization errors was also tested to ensure their robustness.

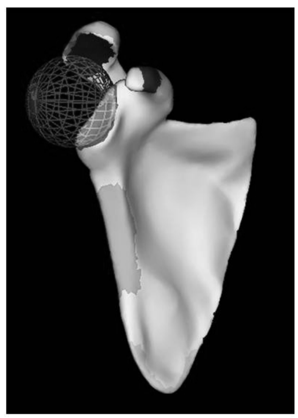

Figure 1. Subset of scapula regions and example of a least-squares sphere fitted to the glenoid cavity.

2.2 Deformable model

The geometric primitives were used to define a set of handles which are in turn used to adjust the position and shape of the parametric generic model on the patient-specific structure. The 3D deformation method is based on the moving least-squares (MLS) algorithm [5], [9]. This technique allows a fast as-rigid-as-possible 3D deformation by approximating a similarity transformation of each point of the surface model by a moving least-squares optimization with a linear closed-form solution. The user can manually control the deformation of the template model in real-time by manipulating the set of handles previously defined on the surface. Handles in the shape of points, lines and ellipses are used to control the dimension and orientation of various structures of the template model, yielding morphologically realistic deformations.

2.3 Reconstruction

Radiographs were acquired with the EOS™ system (EOS Imaging, Paris, France). This system allows for the simultaneous acquisition of 2 calibrated, low-dose, orthogonal radiographs with the subject in standing position. The radiographs can then be exported to a calibrated virtual 3D environment, in which the reconstruction process is performed.

Following radiograph acquisition, the user digitizes a set of scapular landmarks, corresponding to the predefined set of deformation handles, on each of the orthogonal images. On any set of radiographs, only landmarks which are clearly visible are digitized, therefore, either stereo-correspondent or non-stereo-correspondent landmarks can be digitized. These then yield 3D points or projection lines which are used to calculate a subset of descriptive parameters of the patient specific structure. A first approximation of the shape of the imaged scapula is generated by automatically deforming the generic model, based on the previously calculated subset of descriptive parameters. The resulting pre-personalized model is then rigidly registered on the digitized landmarks. Registration is realized with an algorithm based on the SVD algorithm [11] by finding the best fit, in a least squares sense, between the set of 3D handles digitized into the pre-personalized model and the corresponding set of 3D points and projection lines digitized on the biplanar radiographs.

Shape of the scapula model is further refined by manually adjusting the deformation handles. During this process, two digitally rendered radiographs are obtained by ray-casting the generic scapula model in both image planes in order to simulate in real-time a set of biplanar radiographs. Optimization of the model is performed by finding the best fit between the simulated X-ray images and both radiographs of the subject. Position and shape of the pre-personalized model are adjusted on the subject-specific structure by controlling deformations of the model through displacement of its handles. Model deformation is performed iteratively until correspondence between the simulated and true images is reached (figure 2).

Regions and geometric primitives which have been deformed during the reconstruction process then allow automatically calculating various morphological and clinical parameters of the scapula. Depending on the desired application various axes, planes, and coordinate systems can be embedded into the model and automatically calculated during the reconstruction process, allowing for fast access to the desired information.

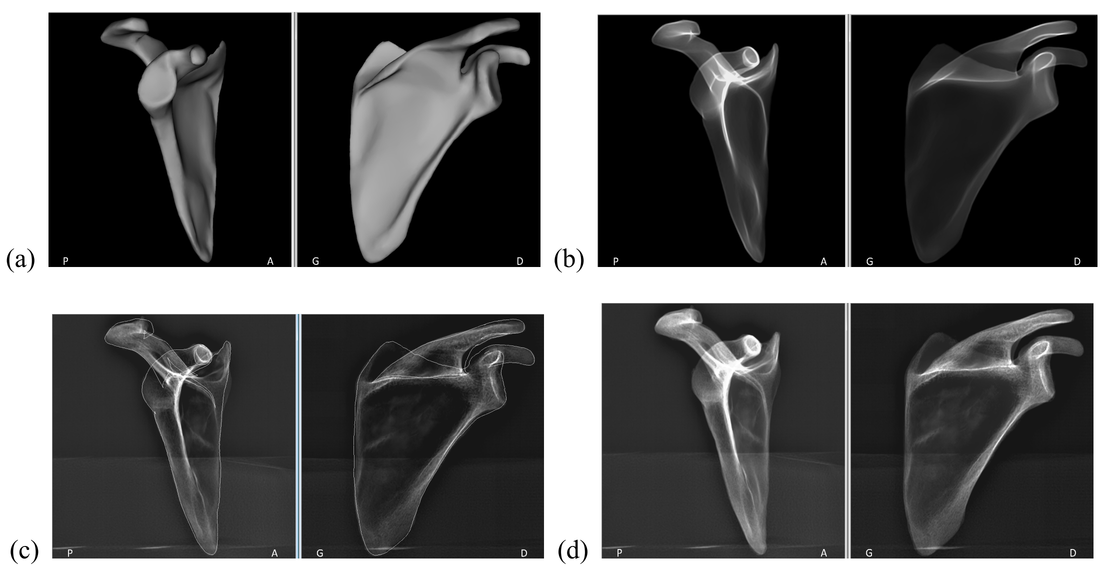

Figure 2. Visualization of the personalized model of the scapula: (a) surface model, (b) simulated radiographs, (c) projected contours superimposed to the actual radiographs, and (d) simulated radiographs superimposed to the actual radiographs.

2.4 Validation

Shape accuracy results were obtained on 10 dry scapulae in order to validate the present approach, as illustrated in figure 3. Scapulae covering a broad range of anatomic shapes and dimensions were selected. Axial CT scans with a slice thickness of 1mm were acquired of each scapula and reconstructions were performed by a shoulder surgeon with the Avizo software (Mercury Computer Systems, Chelmsford, Massachusetts, USA). Biplanar radiographs were then acquired of the same 10 scapulae. During acquisition, the scapulae were held in a radio-transparent foam block and oriented at approximately 10^{o} to 20^{o} of one of the orthogonal acquisition planes, with the scapular spine close to horizontal. This positioning was meant to reproduce the orientation of the scapula during in-vivo acquisitions. The reconstructions obtained from the CT and radiographs were then rigidly registered using an algorithm based on the Iterative Closest Point method [12]. Shape accuracy was verified by calculating the point-to-surface distance between the fitted models for the whole scapula and for each of the previously defined regions. Descriptive and clinical parameters of the scapula were also compared. Average errors as well as 2*RMS values were calculated and used to describe the accuracy of the reconstruction obtained from the biplanar X-rays.

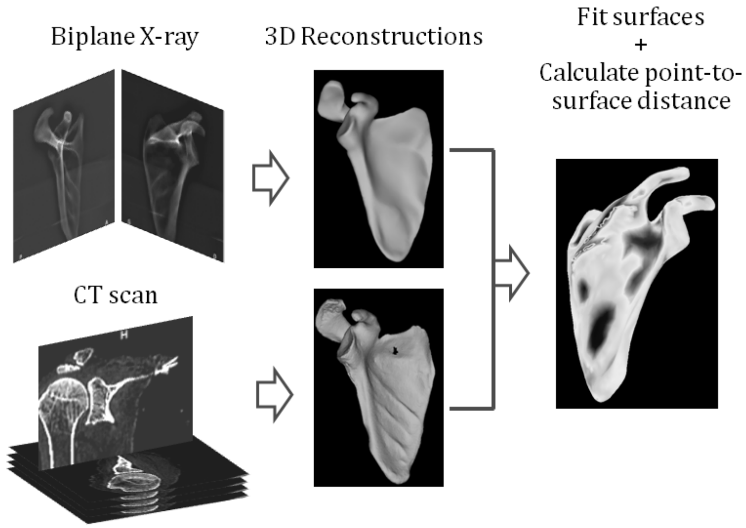

Figure 3. Validation process for shape accuracy. Reconstructions of the same scapulae obtained from CT and biplanar radiographs were rigidly registered, and point-to-surface distances were calculated.

3. RESULTS

Reconstruction of the scapula from biplanar X-ray images was performed in approximately 20 minutes for each of the 10 dry scapulae. The reconstruction process allowed obtaining a personalized model for which surface points were on average within approximately 1mm of the CT reconstruction, while 95% of points were within 3.4mm (2*RMS). When considering specific regions such as the glenoid cavity, results improved with 95% of values smaller than approximately 2mm (2*RMS) (table 1).

Estimation of morphological parameters with the embedded parametric model was also very good. For example, mean errors for the orientation and dimensions of the glenoid cavity were of about 1^{o} and 0.5mm respectively (table 1).

Table 1. Reconstruction shape accuracy and error on the estimation of scapula parameters.

Regions (point-to-surface distance)	**Mean error**	**2*RMS**
Whole scapula (mm)	1.3	3.4
Glenoid surface (mm)	0.9	2.3
Glenoid border (mm)	0.8	2.1
Parameters	**Mean error**	**2*RMS**
Glenoid version (^{o})	1.0	3.5
Glenoid inclination (^{o})	1.1	3.8
Glenoid width (mm)	0.5	1.6

4. DISCUSSION

The work presented here represents a first attempt at reconstructing the scapula and calculating its 3D morphological parameters from biplanar X-ray images. The method presented in this paper adapts some of the existing methods used for lower limb and spine reconstruction [1], [4], [5] to scapula. The MLS deformation technique [5], [9] has proven to allow applying morphologically realistic deformations to a generic scapula model through manipulation a predefined set of deformation handles. Based on two orthogonal radiographs, the shape of an actual scapula can be adequately replicated with this method. The method which was presented in this paper also includes the use of a parametric model approach, which allowed precise positioning of the deformation hands in the generic model, as well as automatic calculation of various morphological and clinical parameters associated to the resulting personalized scapula model.

The results presented in this paper were obtained by comparing reconstructions obtained of the radiograph of dry scapulae to their exact CT reconstruction. Even though these results are promising, it is important to note that analysis of in-vivo shoulder radiographs can be more complex than that of dry scapulae. The complex shape of the scapula, as well as inter-individual shape and orientation variability, can make subject positioning in the X-ray acquisition system difficult, leading to superimposition of various bony structures (spine, ribs) and soft tissue to the scapula. This can cause visibility issues for some bony structures of the scapula. In order to minimize these issues, some authors have used different X-ray incidences (0^o and 42^o for example) when studying shoulder kinematics from biplanar X-ray images or fluoroscopy [13], [14]. However, the EOS™ system, while having the advantage of very low radiation doses and high image quality, is limited to orthogonal acquisition planes. The method presented in this paper was designed with this limitation in mind. Also, in order to evaluate the method in conditions as close to actual in-vivo conditions as possible, the acquisition and analysis of radiographs of the dry scapulae were performed in a manner meant to replicate these in-vivo conditions: the dry scapulae were oriented realistically in the acquisition system, and only bony structures which are usually visible on in-vivo radiographs were used in the reconstruction process. Preliminary tests have also been realized in-vivo and are very promising.

It is also to note that in its current form, the presented method requires manual intervention from the user and requires approximately 20 minutes to perform a full reconstruction. Even though it is faster than obtaining a full reconstruction from CT slices, it may still be too long to be effectively used in clinical practice. Integration of automatic segmentation and registration techniques to the method would allow making it faster, and therefore increase its appeal for clinicians. Application of the method to scapulae presenting deformities would also be of great interest in clinical practice. Even though normal anatomical variations and small deformities could be reconstructed with our method, important deformities due to fractures or various pathologies may not be adequately represented. Adaptation and validation of our method in this context would therefore be required.

Reconstruction of the complex shape of the scapula from radiographs will be a major advancement in bone 3D imaging by further reducing our dependence to the high radiation doses and cost of CT. This work will be of particular interest for shoulder pre-operative planning as well as shoulder biomechanics studies. For example, while reducing cost and radiation doses, this method could yield glenoid version estimation with an uncertainty similar or smaller to that of 5^o reported for current CT estimation methods [6–8].

5. CONCLUSION

This work presented an interactive method for reconstruction of the scapula and morphological parameter calculation from biplanar radiographs. By combining a parametric model approach and an MLS deformation technique, the presented method allows a user to obtain a reliable reconstruction of the scapula in approximately 20 minutes. Other advantages of this method over CT, which is the current reference, are its low cost, low radiation dose and direct access to 3D clinical and morphological parameters. Even though this work is very promising, automatization of the deformation process could reduce the reconstruction time and further improve the accuracy of the method. Future work will include the study of a database of over 40 in-vitro scapulae in order to determine normal relations between descriptive parameters and build a parametric model partially controlled by statistical inferences. This would allow generation of a more reliable pre-personalized model while reducing the need for user interaction. This could therefore set the path for fast and efficient image processing techniques. Combination of these approaches will allow for fast and accurate reconstruction of the scapula with limited user interaction.

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