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Identification of Anatomical Landmarks for Registration of CT and Ultrasound Images in Computer-Assisted Shoulder Arthroscopy

Kathrin Tyryshkin, Parvin Mousavi* *IEEE* Member, David R. Pichora, and Purang Abolmaesumi

Abstract— **This paper presents a phantom study that was conducted for an ultrasound-guided shoulder arthroscopy navigation system. The navigation system uses a surface model generated from pre-operative computed tomography images, which has to be registered to the patient during the procedure. The goal of this study was to determine the optimal regions on the scapula bone of the shoulder to achieve an acceptable registration. Experiments were performed to examine the robustness and suitability of these optimal regions by testing the sensitivity to variations in the initial alignment for two different registration algorithms, namely iterative closest point and sequential least squares estimation technique. The fiducial registration error was analyzed and compared for all experiments. Regions spread over the entire scapula result in significantly smaller registration error (p < 0.001) than regions, concentrated around the shoulder joint and thus accessible during the shoulder arthroscopy. However, the results also showed that the registration is still acceptable for the image-guided navigation system when these accessible landmarks are used.**

I. INTRODUCTION

Shoulder arthroscopic surgery is a minimally invasive procedure commonly used for visualization, diagnosis and treatment of complications and injuries inside the shoulder joint [1]. The main instrument used in this procedure is the arthroscope which is a complex optical system assembled in a (usually) 4mm diameter metal tube. The image from the miniature camera at the tip of the arthroscope is transmitted through a fiber optical cable to the television screen and guides the surgeon during the procedure.

During shoulder arthroscopy the patient is usually in a sitting (beach-chair) position under general anesthesia. The surgery is performed through two (sometimes three or four) small incisions, using the view from the camera of the arthroscope as a guide. Arthroscopic surgery is preferable over open surgery as it is minimally invasive and thus results in significantly shorter recovery and healing times.

* Corresponding author.

K. Tyryshkin is an MSc student at the School of Computing, Queen's University, Kingston, Ontario, K7L3N6, Canada (e-mail: tyryshki@cs.queensu.ca).

P. Mousavi is with the School of Computing, Queen's University, Kingston, Ontario, K7L3N6, Canada (e-mail: pmousavi@cs.queensu.ca).

D. R. Pichora is with the Division of Orthopaedic Surgery, Kingston General Hospital, Ontario, Canada (e-mail: pichorad@kgh.kari.net).

P. Abolmaesumi is with the School of Computing and the Department of Electrical and Computer Engineering, Queen's University, Kingston, Ontario, K7L3N6, Canada (phone: 1 (613) 533-2767, e-mail: purang@cs.queensu.ca).

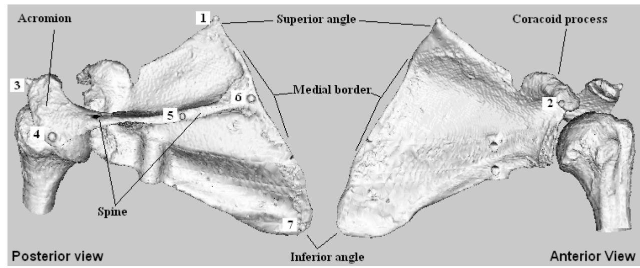

Figure 1 Phantom of a scapula bone of a left human shoulder. Labels 1 to 7 indicate the fiducial markers that were drilled into the phantom to facilitate the validation of registration results. Fiducial markers 2, 3, 4 and 5 are the closest to the shoulder joint, where the shoulder arthroscopy is usually performed.

However, due to the limited arthroscopic view and severe workspace constraints imposed on the surgeon, the procedure requires high skills and experience especially when fat, blood or inflammation blocks the field of view of the arthroscope [1][2][3]. Therefore, a navigation system that displays the arthroscope and surgical tools relative to a three-dimensional (3D) surface model of the shoulder of the patient during surgery was developed [4]. The surface model is constructed pre-operatively from computed tomography (CT) images of the patient.

Shoulder arthroscopy is performed within proximity of the shoulder joint and where the location of the scapula bone is used as a reference (Figure 1). Therefore, to enable intra-operative navigation, the proposed navigation system requires a registration of the pre-operative surface model of the scapula to the patient in the operating room. To achieve this registration the system uses intra-operative ultrasound images.

This paper presents a study for obtaining an optimal registration of a 3D surface model of the scapula bone, generated from pre-operative computed tomography images, to intra-operative ultrasound images of the scapula. In this study several anatomical landmarks that are accessible with an ultrasound transducer and provide acceptable registration were identified. Registration experiments were then performed with two different algorithms using points selected on ultrasound images captured from the identified landmarks.

The rest of the paper is organized as follows. Section II, describes the image-guided navigation system developed for shoulder arthroscopy. It also presents the setup and design of the experiments performed in this study. Section III

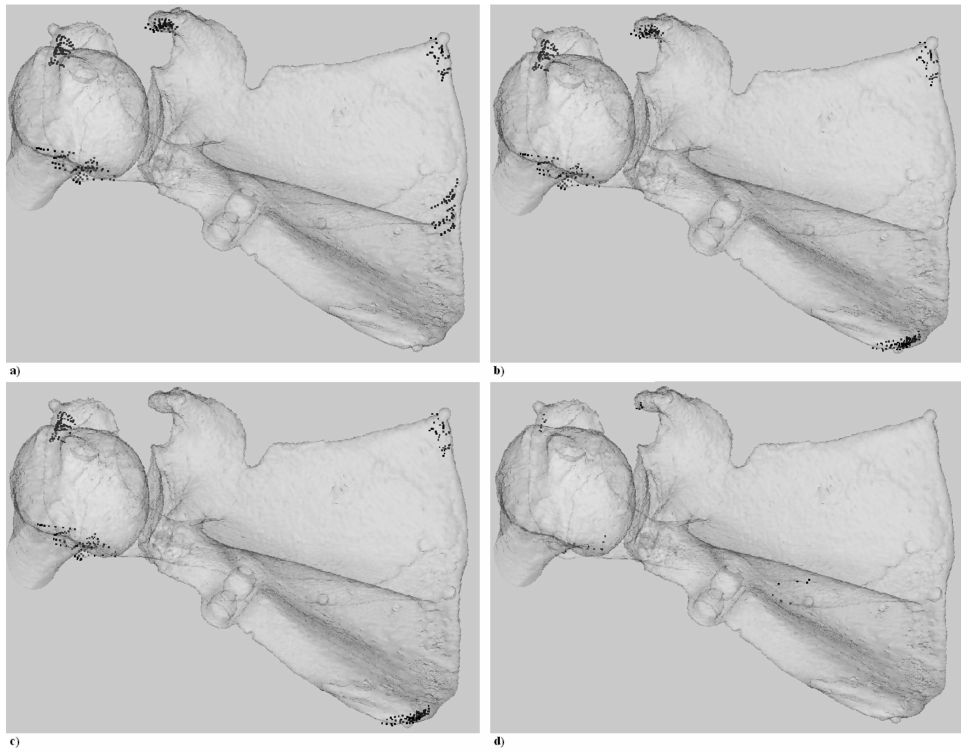

Figure 2. Points segmented from ultrasound images of different anatomical landmarks that were used in four registration experiments. a) to d) correspond to experiments 1 to 4. The 3D model is shown transparent to enhance visibility of the points segmented from the ultrasound images that were used for registration.

reports on the results obtained from four different experiments and presents statistical analysis and discussion of these results. Section IV presents the conclusions drawn from the results of the experiments and additional future work to further improve the applicability of the navigation system.

II. METHODOLOGY

A. *Image-guided Navigation System*

The image-guided system was designed to improve the perception of the surgeon of the 3D space within the human shoulder and to provide guidance during shoulder arthroscopy. The system requires a 3D surface model of the scapula bone generated from CT images of the patient pre-operatively. For a more thorough description of the navigation system the reader is referred to [4]. During the surgery, ultrasound images are used to register the surface model to the patient in the operating room. For the CT to ultrasound registration, the system first requires an initial alignment of the surface model with the ultrasound images. The registration is then improved by applying either an iterative closest point algorithm (ICP) [5] or a sequential least squares estimation technique (Unscented Kalman Filter, UKF) [6]. The algorithms were chosen for their simple implementation, speed and good convergence results.

ICP is a well known and widely used registration algorithm, which proves to be fast and can converge on complex geometrical 3D shapes. However, since it always monotonically converges to the nearest local minimum, it is known to be sensitive to the initial alignment of the data sets and easily gets trapped in local minimum.

UKF is a sequential least squares optimization technique employed for solving nonlinear systems and is based on the unscented Kalman filter. The algorithm is less sensitive to the initial alignment than ICP because it estimates the transform parameters of the registration for both the state and its covariance matrix and assumes that the state to be estimated is a Gaussian-distributed random variable. The algorithm calculates the registration parameters in the unscented Kalman filter and uses the resulting information for registration [7].

B. *Experimental Setup*

For the laboratory experiments, CT images were collected from a shoulder phantom (Sawbones Inc., Vashon WA) at a resolution of $0.55\times0.55mm^2$ and slice spacing of 1.25mm, using a LightSpeed Plus scanner (GE Medical Systems, Waukesha WI). Mesher software developed at Queen's University, was used to create a 3D surface model of the scapula bone from the CT images.

A Polaris optical tracking system (Northern Digital Inc., Waterloo ON) was used to track the location of two optical markers in real-time. One optical marker was attached to the scapula bone of the phantom and served as the frame of reference. Another optical marker was attached to the ultrasound transducer (Voluson 730 ultrasound machine, GE Medical Systems, Waukesha WI) to capture ultrasound images. To enable the ultrasound scanning, the phantom was submerged in a tub filled with water at room temperature. The registration was done with the ICP and UKF algorithms by matching points segmented from ultrasound images to corresponding areas segmented from the 3D surface model.

To facilitate the validation of the registration results, seven fiducial markers were drilled into the shoulder phantom prior to capturing the CT images (Figure 1). The registration error was defined by measuring the distance between the position of fiducial markers on the surface model after registration and their positions collected with a calibrated stylus probe.

C. *Experimental Design*

To determine landmarks of the scapula bone that can be easily identified and segmented from ultrasound images, one shoulder of a human volunteer was ultrasound scanned and suitable landmarks were determined from the resulting images. The landmarks appeared to be the superior angle, the medial border, the inferior angle, the spine, the coracoid process and the outer rim of the acromion bone (Figure 1).

Ultrasound images of these areas were captured from the shoulder phantom and the bone contour was manually segmented from the images on a graphical screen. Four registration experiments were conducted using the segmented points (Figure 2).

"Experiment 1" employed ultrasound images of superior angle, intersection of medial border and the spine, the acromion and the coracoid process (Figure 2a). These regions capture the translational and rotational degrees of the upper scapula. For "Experiment 2" ultrasound images were collected from superior and inferior angles, acromion and coracoid process (Figure 2b). "Experiment 3" involved images collected from superior and inferior angles and the acromion (Figure 2c). Regions in these two experiments capture the translational and rotational degrees of entire scapula.

During shoulder arthroscopy the patient is usually placed in a beach chair position such that only the coracoid process, the acromion and the lateral part of the spine of the scapula are easily accessible with an ultrasound transducer. Therefore, in "Experiment 4" we analyzed registration results where ultrasound images were collected from these accessible regions (Figure 2d). The goal was to investigate to what extend these regions capture the translational and rotational degrees of the scapula.

Since for the CT to ultrasound registration, an initial alignment of the surface model with the ultrasound images is required, the sensitivity to the initial alignment was investigated in each experiment. One hundred random transformations with uniform distribution in the range of ±10mm and ±10º were applied to a nearly optimal registration. This nearly optimal registration was achieved by aligning fiducial markers segmented from the 3D model with the markers positions collected with a calibrated stylus probe and then improving the alignment with the ICP algorithm. After each experiment the histograms of the registration results for each algorithm were analyzed.

In experiment 4, the registration error for each individual fiducial marker was also recorded. Since shoulder arthroscopy is performed near the shoulder joint, it is important to investigate the local registration error. Therefore, registrations using only fiducial markers that were close to the surgery area in shoulder arthroscopy (Figure 1) were also analyzed for both algorithms.

Table 1. Registration results for all four experiments (in mm) showing the mean, standard deviation (std) and median of the registration error for 100 tests. In experiments 1 and 2 the outliers were filtered from the results of the UKF algorithm.

Experiment 1 (in mm)			
Algorithm	Mean	STD	Median
ICP	2.67	0.72	2.38
UKF	3.36	0.67	3.13
Experiment 2 (in mm)			
Algorithm	Mean	STD	Median
ICP	2.70	0.72	2.54
UKF	2.46	0.27	2.47
Experiment 3 (in mm)			
Algorithm	Mean	STD	Median
ICP	2.61	0.48	2.36
UKF	2.26	0.20	2.18
Experiment 4 (in mm)			
Algorithm	Mean	STD	Median
ICP	4.05	1.70	3.73
UKF	4.13	1.67	3.98

Table 2. Registration results of experiment 4 (in mm), considering the registration error only for the fiducial markers 2, 3, 4 and 5. The table shows the mean, standard deviation (std) and median for 100 tests.

Algorithm	Mean	STD	Median
ICP	3.70	1.29	3.61
UKF	3.84	1.53	3.70

III. RESULTS

The UKF registration algorithm has a tendency to have outliers in the error distribution. For experiment 1, 15% of the outliers were filtered leaving 85% of data with a maximum fiducial registration error of less than 4.16mm. For experiment 2, 22% of the outliers were filtered leaving 78%

of data with a maximum error of less than 3.36mm. In the results of experiment 3 there were no outliers and the maximum error of all registration results were less than 3.07mm. For experiment 4, 18% of the outliers were filtered leaving 82% of data with a maximum error of less than 9.93mm. The data were filtered to show more realistic results, since the outliers can be easily detected and solved for by changing the initial alignment and rerunning the algorithm.

The registration results of the ICP algorithm were more uniformly distributed than the results of the UKF algorithm. For the ICP algorithm all registration errors were less than 4.01mm in experiment 1; and for experiments 2 and 3 all errors were less than 4.10mm and 3.73mm, respectively. For experiment 4, 9% of the outliers were filtered leaving 91% of data with a maximum error of less than 9.32mm.

Table 1 shows the registration results for all four experiments. By comparing the means of the error, it can be seen that for both ICP and UKF algorithms the registration results are similar in experiments 1-3. However they are significantly worse ($p < 0.001$) for the fourth experiment where points were collected from only the acromion, coracoid process and the spine. This indicates that when ultrasound images are collected from areas of the scapula bone that are further apart and spread over the entire scapula bone, the registration error is reduced.

Table 2 shows the registration error of experiment 4 when only fiducial markers close to the shoulder joint were considered in the error calculations (Figure 1). The results indicate that if only the acromion, the coracoid process and spine are accessible during surgery, a fiducial registration error of less than 4mm can be achieved. If a smaller registration error is required, a method to access the superior and inferior angles on the scapula bone needs to be developed.

IV. CONCLUSION

This paper presents a methodology to obtain CT to ultrasound registration of the scapula bone of the human shoulder. On the scapula bone of the shoulder different regions suitable for ultrasound imaging were investigated. Laboratory experiments on a shoulder phantom show that by employing regions that are spread over the entire scapula bone an accurate registration can be achieved. However, during shoulder arthroscopy not the entire scapula is accessible with an ultrasound probe due to the beach-chair position of the patient. Our results demonstrate that if registration error is only considered for the areas close to the shoulder joint, an acceptable fiducial registration error of less than 4mm can still be achieved. Further laboratory and clinical studies are under way to validate the performance and to test the usability of the navigation system registration technique.

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