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Feasibility of A-mode Ultrasound-based Registration to Track Scapula Motion: A Simulation Study

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Abstract

We describe an A-mode ultrasound-based scapula tracker for pre-operative diagnosis and planning. One paper investigated this technology but did not assess its rotational accuracy, which is the critical variable. Therefore, we ran simulations and optimizations to investigate whether this technology's rotational accuracy was adequate to make this a viable tool.

Simulations were created by converting a CT-derived scapula into an even density point cloud and positioning it in a neutral pose (our ground truth). This was reposed to a known mid-range motion, and its points were randomly sampled to mimic the data yielded by an array of single-element A-mode ultrasound transducers. This sampled dataset was registered to the ground truth using ICP, and to determine the resultant error, the resulting transformation was compared to the known transformation applied to the ground truth. The Monte Carlo method was applied to this simulation to yield varying samplings; as well, the samples were subjected to varying levels of random noise (replicating ultrasound error) to assess robustness. The effects of the number of sample points and their location were also investigated.

For 10 simulated sensors in an optimized pattern across the scapula, corrupted by random error, registration rotational errors for a sagittal plane 70° shoulder flexion were $0.82° \pm 0.63°$ for posterior tilting, $0.68° \pm 0.6°$ for upward rotation and $0.54° \pm 0.54°$ for internal rotation.

We have successfully demonstrate that, in this simulation study, a clinically viable number of ultrasound sensors (~ 10) could yield adequate accuracy to be diagnostically useful, if they are properly distributed across the scapula.

1 Introduction

Achieving an accurate assessment of scapular kinematics within a clinical setting is critical to the diagnosis of various neuro-muscular conditions and has potential as a novel source of data to guide patient-specific pre-operative surgical planning. To date, measurement of scapular kinematics within the clinic has been limited to goniometry and some attempts to use inertial sensors and markerless depth camera; however, these methods are unable to accurately measure the scapula's 3 DOF rotational motion. A-mode ultrasound based registration is an attractive technique that offers a non-invasive and non-radiologic approach to obtain highly accurate measures of scapula motion.

This technique has been demonstrated for tracking bones with relatively small bone to skin displacements (e.g. the femur [2], skull [5], pelvis etc.). Vicini et al. [7] gauged the performance of this type of technique on the scapula in terms of its root mean square localization error; however, this error metric does not provide the information needed to assess the technique's viability as a diagnosis and planning tool that accurately measures scapular rotational kinematics. The importance of this rotational accuracy is borne out in the scapula kinematics literature [1] where healthy and dysfunctional subjects are compared in terms of rotational differences. Therefore, we undertook a series of numerical simulations, based on the techniques from [2] and [7], to assess the feasibility of this approach with respect to the rotational accuracy achieved with varying numbers of single element A-mode sensors and the configurations of these sensors.

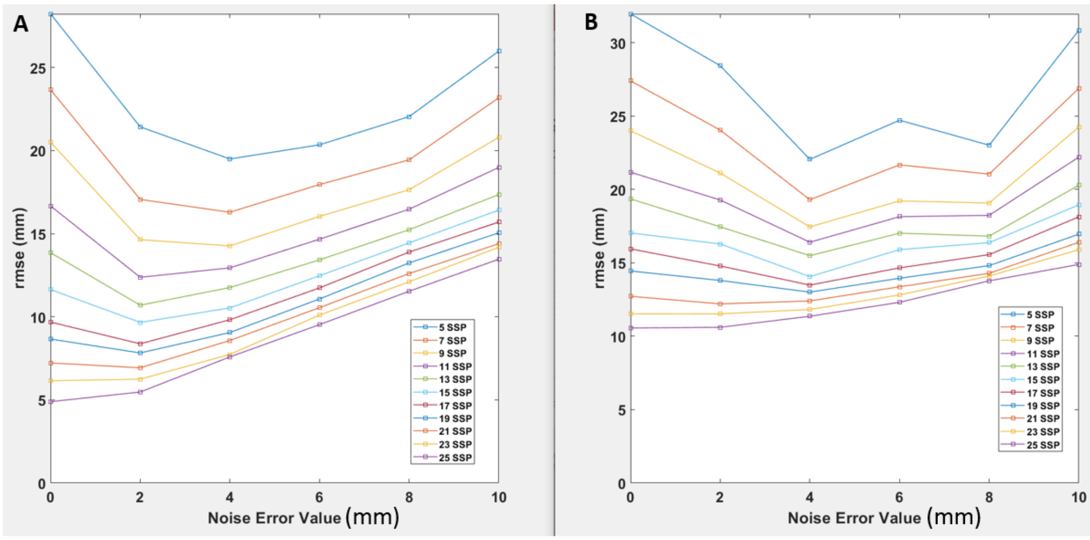
2 Methods: Data Generation, Registration and Simulation Procedure

The simulations in this study rely on data generated through a virtual sampling and registration procedure. First, a 3D point cloud, $\{m_i\}$, modeling the full scapula geometry was retrieved from CT images and pre-processed (details in next paragraph). Second, $\{m_i\}$ was transformed into a 3D pose, $\{n_i\}$, corresponding to a physiologically meaningful scapula motion. Third, a point cloud, $\{d_i\}$, was generated where each point corresponds to the location where the beam of a simulated single element ultrasound sensor intersected the transformed scapula model; these points are called Surface Sample Points (SSPs). The value of each sample point is subjected to random noise to replicate the localization error expected from an ultrasound transducer. Fourth, a registration was conducted to determine the transformation parameters that optimally aligned $\{d_i\}$ to $\{m_i\}$.

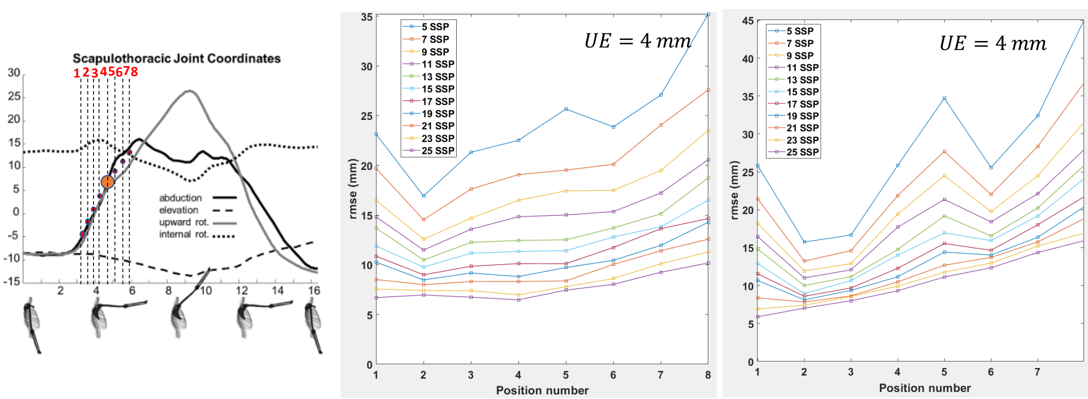
The model dataset, $\{m_i\}$, was obtained, from a CT derived STL model, by conditioning its faces into a 3D point cloud by leveling out the point distribution density and conducting a PCA-based curvature analysis that enabled clinically unsamplable high curvature areas to be removed [3] (i.e. areas where an incident ultrasound wave wouldn't return a signal). This enabled the use of Monte Carlo simulations that respect the need for a truly random sampling of the scapula geometry and mimicked a clinical situation where certain bone surfaces are not accessible by ultrasound. ICP was utilized to register the data and coupled with a Perturbation Search (PS) to avoid local minima[2]. Noise modeling ultrasound transducer data was added to the sample points with magnitudes in the range of 0mm to 10mm. The robustness of the algorithm to the motion range of the scapula was also tested by displacing the point cloud, $\{n_i\}$, to physiological poses based on a scapulothoracic joint model in the literature [6]. For each number of sample points (e.g. simulated ultrasound transducers) (from 5 to 25 sensors) and for each noise magnitude (6 levels across the above range) we ran the 300 simulations. Hence, $20 \times 6 \times 300 = 36000$ simulations were conducted. Additionally, we applied a Simulated Annealing (SA) algorithm to determine the optimal sensor distribution across the scapula by quantifying the variability in registration error across the configurations. This consisted of selecting one point in a N points set, initially randomly selected, and moving it to a constrained zone at a distance proportional to a temperature metric. The registration error of the new set is computed, the temperate metric is accordingly modified, and then the cycle was repeated for another point. The algorithm ran 18,000 iterations on average for 150 simulations.

3 Results

The registration accuracy (average RMSE) as a function of the noise magnitude is shown in Figure 1a while Figure 1b shows the accuracy during arm flexion in the sagittal plane. When the noise or range of motion is increased, the registration accuracy remains sufficiently constant to indicate the system is adequately robust. Unsurprisingly the registration accuracy increased as the number of SSPs increased (Figure 1). Furthermore, use of the Perturbation Search decreased registration error by 54.4% on average. More interestingly, the rotational error associated was investigated with varying the number of randomly positioned sample points with the scapula posed in 70° of shoulder flexion in the sagittal (Figure 2a) and scapular (Figure 2c) planes (see Figures 2b and 2d). When considering an array of 10 sample points (chosen as clinically feasible number of sensors) that are optimally distributed using the SA algorithm, the procedure yielded rotational errors of $0.82° \pm 0.63°$ for posterior tilting, $0.68° \pm 0.6°$ for upward rotation and $0.54° \pm 0.54°$ for internal rotation. During scapula plane flexion (Figure 2c), rotational errors reached $0.17° \pm 0.14°$ for upward rotation.



(a) **Simulation registration results (average RMSE) as a function of noise magnitude A** Registration average RMSE with perturbation search till convergence. **B** Registration average RMSE without perturbation search



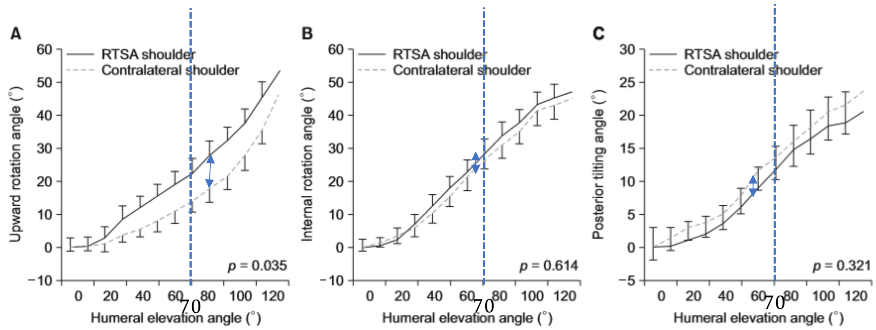
Scapula joint kinematics during flexion

Relationship between range of movement and accuracy with ICP and PS till convergence

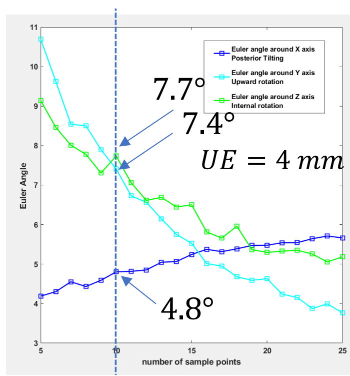
Relationship between range of movement and accuracy with ICP without PS

(b) **Robustness to movement :** average RMSE as a function of the position of the scapula during flexion

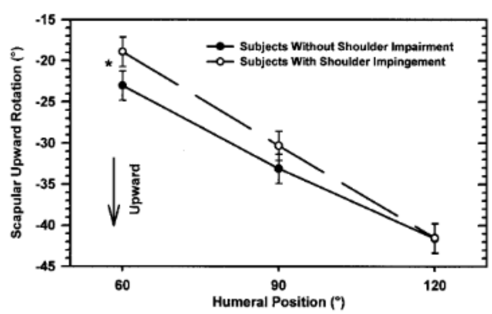
Figure 1: Numerical simulation results. In Figure 1a, each curve accounts for a given number of sample points. The robustness to noise is evaluated by increasing the noise error value and observe the subsequently modified RMSE. In Figure1b, on the very left the 8 "sampled" situations during scapula flexion are displayed. The corresponding RMSE can be seen on the two figures on the left, respectively from left to right with and without PS, for varying number of sample points.



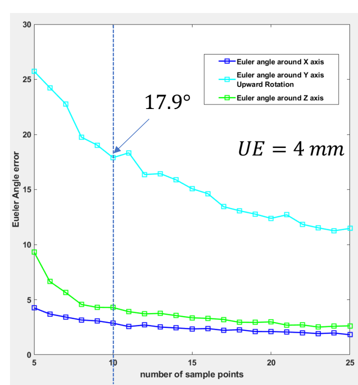
(a) **Graph showing the measured angles during sagittal plane flexion , adapted from** [1]



(b) **Graph showing rotational registration error for sagittal plane flexion at** 70° **elevation**



(c) **Graph showing the measured upward rotation angle during scapular plane flexion, adapted from** [4]



(d) **Graph showing rotational registration error for scapular plane flexion at** 70° **elevation**

Figure 2: Registration angular error of the numerical simulation using standard ICP registration. Figure 2a and 2c respectively show the rotational discrepancies between patients with Reverse Total Shoulder Arthroplasty (RTSA) and healthy patients and between patients with shoulder impingement and healthy patients. In Figures 2b and 2d, the proposed method results rotational registration errors for the corresponding situations in Figure 2a and 2c can be seen.

4 Discussion

The registration rotational errors in Figure 2b and 2d exceeded the clinically meaningful differences in the literature [1] and [4] when using standard ICP and thus would not be able to assist in diagnosing conditions like scapular dyskinesis. Alternatively, the SA optimization of the distribution of 10 SSPs provided registration accuracy for arm flexion in the sagittal and scapular planes that are sufficient to be clinically useful in identifying people with and without shoulder impingement syndrome. These data also showed that differing regions of the scapula have varying significance with respect to the overall level of registration accuracy achieved. Some simplifications/assumptions were made in this study including discretizing the scapula surface mesh, assuming that our would-be sensors had direct line of sight to the scapula, and only investigating one scapula geometry.

5 Conclusion

This study yielded three important findings. First, a randomly distributed array of single element ultrasound transducers is unlikely to provide sufficient accuracy when using a feasibly small array. Second, an optimized array pattern using a clinically viable number of sensors does exist that minimizes error in a simulated lab setting. Third, within the context of these simulations, this optimized array pattern provides sufficient accuracy to be clinically useful.

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