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D. M. Magnusson
Antonie J. van den Bogert, *Cleveland State University*
J. L. Ronsky, *University of Calgary*

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IN-VIVO 3D MOTION ESTIMATION OF THE SHOULDER JOINT UTILIZING MAGNETIC RESONANCE IMAGING DURING A SIMULATED PUSH TASK

D.M. Magnusson[1], A.J. van den Bogert[1], & J.L. Ronsky[2]

[1]Department of Biomedical Engineering, Cleveland Clinic Foundation, Cleveland, Ohio, USA, [2]Department of Mechanical Engineering, University of Calgary, Canada

Introduction

Shoulder stability requires coordination between several passive and active stabilizing mechanisms [12]. Pathologies of the shoulder can be associated with uncharacteristic translation of the humeral head relative to the glenohumeral cavity. Impingement may be defined as the superior translation of the humeral head causing the supraspinatus tendon to become compressed against the acromioclavicular shelf [3]. This is a common injury in wheelchair users, as well as affecting able-bodied individuals [9,10].

Among the methods utilized for the quantification of shoulder function have been clinical measures of shoulder joint laxity, medical imaging, and motion analysis. While each of these techniques provides insight into shoulder joint function, there are several problems. Clinical tests have been shown to have poor inter- and intra-observer reproducibility [8]. Radiographical assessment of shoulder dysfunction becomes limited as a result of its restriction to two planes of imaging, as well as the projectional artifacts that are present [1,4,6]. As noted by several researchers, standard high field (closed) MR and CT are restrictive in that the arm cannot be imaged in clinically relevant positions, or during functional tasks. Recently, however, open MR systems are being used [5].

In-vivo movement analysis is a non-intrusive way of measuring the translation and rotation of body segments. In the shoulder joint, the scapula “floats” on the musculature of the upper torso, as well as moving over a large surface area. The result is that the skin markers will only reflect the movement of the skin/muscle surface as the scapula passes underneath it. The use of bone pin markers, such as was utilized by Koh et al. [7] is not suitable for clinical applications.

Therefore, the purpose of this experiment was threefold:

- to design a methodology for the measurement of in-vivo translation of the shoulder joint during a push task,
- to define measures of joint space change and,
- to test the repeatability and variability of the proposed method.

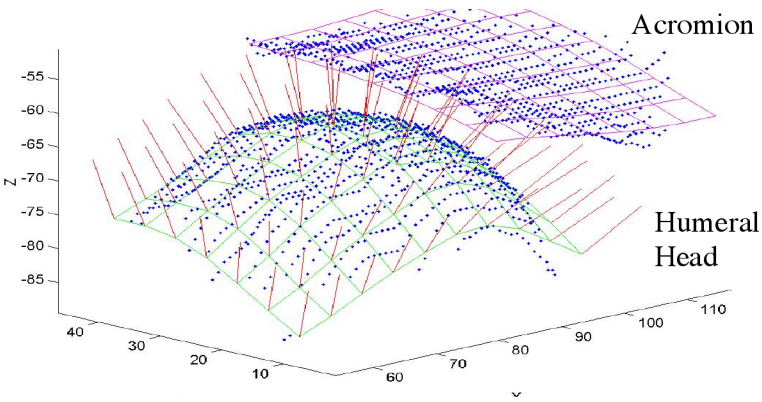

Figure 1. Application of TPS to two clouds of points

Materials and Methods

Two subjects were scanned in a 0.2 T open MRI scanner (Magnetom Open, Siemens, Erlagen, Germany) and a T1-weighted, Flash 3D Volume Gradient Echo sequence (TR=34ms, TE=12ms, FA=40°) at a spatial resolution of 1.04 x 0.78 x 1.56 mm^3

Table 1. Variability due to digitization. Decrease in joint space during push task is indicated by a negative value.

	Change in median proximity (mm)	Change in mean proximity (mm)	Change in minimum proximity (mm)
HH-AC (n=4)	-0.21 ± 0.21	-0.19 ± 0.21	-0.24 ± 0.20
HH-GH (n=4)	-0.10 ± 0.11	-0.17 ± 0.18	-0.73 ± 0.45

Table 2. Reproducibility between trials. Decrease in joint space during push task is indicated by a negative value.

	Change in median proximity (mm)	Change in mean proximity (mm)	Change in minimum proximity (mm)
HH-AC (n=4)	-0.25 ± 0.25	-0.20 ± 0.25	-0.32 ± 0.22
HH-GH (n=4)	-0.01 ± 0.34	-0.03 ± 0.26	-0.16 ± 0.48

(FOV=200mm^2, acquisition time of 3 minutes and 58 seconds) was applied. A gantry for measuring applied load and providing force feedback information was built. The gantry design kept the subject stationary while the scan was completed. A handle, similar in dimensions to a wheelchair handrim, was placed at the hip level, approximating where the actual handrim would be. This handrim object was attached to a three-dimensional force/torque transducer. Force feedback to the subjects was given via a 10x10 LED grid display so that they could maintain a constant sub-maximal force level during the imaging process. All electronics were appropriately shielded for operation within a high magnetic field. A target force level of 45 N inferiorly and 15 N anteriorly, reflecting the point of peak force application [11] during a wheelchair push movement, was provided for the subject. With the arms stationary, an active force production MR image was taken, followed immediately by a passive MR image of the shoulder. The MR image was completed 4 times to assess the variability and reliability of the technique between trials. The subject was given adequate time to rest between trials (5-10 minutes) to prevent fatigue.
The 3D images were transferred to a computer (SGI Octane, Silicon Graphics Inc., Mountain View, CA), where the bones of interest were segmented using a manual tracing program (Image Processing Group, Dept. of Biomedical Engineering, Cleveland Clinic Foundation, Cleveland, OH). The bone surfaces of interest were the superior and medial surface of the humeral head, the inferior surface of the acromial process, and the lateral aspect of the glenohumeral face of the scapula. The output of this program provided coordinate information for each voxel that had been traced, per slice (32 slices total). This produced three output files with a total of approximately 7000-9000 voxel coordinates. Utilizing a C++ program, the voxel coordinates were transformed into Cartesian coordinates and sent to several output text files. These output files were then utilized by a Matlab

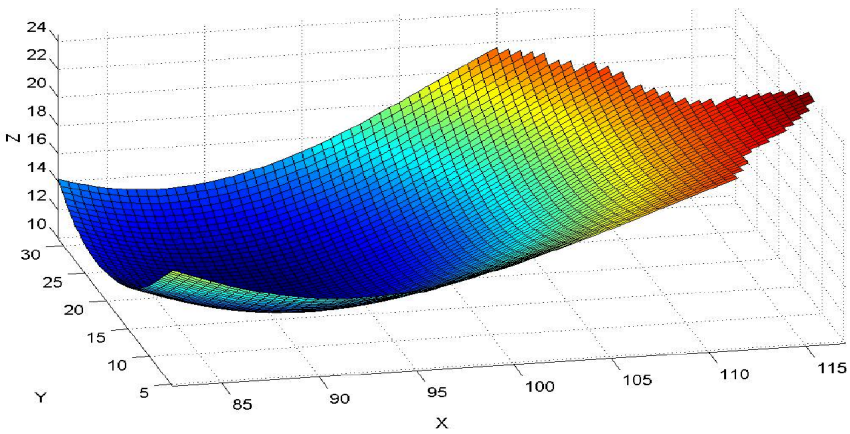

Figure 2. Proximity plot of Acromiohumeral interface

Table 3. Origin of Normal vectors. Decrease in joint space during push task is indicated by a negative value.

	Normals from Humeral Head (HH)	Normals from Acromion (AC) or Glenohumeral Face (GH)
HH-AC (n=4 trials)	-0.25 ± 0.25	-0.27 ± 0.21
HH-GH (n=4 trials)	-0.01 ± 0.34	-0.09 ± 0.30

Table 4. Differences between subjects. Decrease in joint space during push task is indicated by a negative value.
**Statistically significant difference (p=0.01)*

	Subject 1 (N= 4 trials)	Subject 2 (N=3 trials)
HH-AC	-0.27 ± 0.21	0.82 ± 0.50*
HH-GH	-0.09 ± 0.30	-0.04 ± 0.15

(The Mathworks Inc., Natick, Ma) program that reduced the data to several smaller output files, each reflecting a particular bone surface of interest.
A thin plate spline (TPS) method [2] was applied to the cloud of data points derived from the MRI and the modeled surfaces were resampled with a grid spacing of 0.5mm (Figure 1). Some of the data sets extended onto a vertical slope, which is not acceptable for the TPS technique, so an automatic method of discarding resampled points was used. There were possible solutions to this problem, including using cylindrical and spherical coordinate systems, however, the variable shape of the three surfaces of interest (one flat, one spherical, and one concave surface) necessitated an alternative method. By examining two surfaces at a time, either the superior aspect of the humeral head and the A/C surface, or the medial aspect of the humeral head and the glenohumeral surface, it was possible to utilize the standard Cartesian coordinate system. In the Cartesian coordinate system with respect to the midline of the body, the x-axis represents the lateral-medial direction, the y-axis represents the anterior-posterior direction and the z-axis represents the superior-inferior direction.
Proximity measures between the bone surfaces were completed utilizing the following method. Utilizing a Matlab (The Mathworks Inc, Natick, Ma) program written by Boyd et al. [2], the proximity was defined as the distance along the normal, $\vec{n}$, projected from a resampled point on the humeral head TPS surface to its intersection with the second TPS bone surface (either the acromion or the glenohumeral surface). Resampling of the TPS surface with a 0.5 mm grid allows for the interpolation of distances between individual voxels. Similar to what was mentioned by Boyd et al., [2], the distance at which the normal vector from the bone intersects with the second bone surface is a direct measure of the proximity at one point on the surface. Several such measures taken together created a proximity map of the distances between the two bone surfaces (Figure 2). The mathematical equations required to do this are discussed in detail in [2]. A reduced proximity map of the 1200 lowest proximities, representing 300 mm^2 for the acromiohumeral (HH-AC) interface, and a reduced proximity map of 1800 points (450 mm^2) for the glenohumeral (GH-HH) interface was generated since the closest proximities are the ones that are most relevant for impingement or joint contact, respectively. From these, the mean, median, and minimum proximities were calculated, as well as the differences between active and passive trials.

Recalling the three purposes of the study stated earlier, validation of the proposed methodology required that the reliability and variability be examined by testing the:

- Variability due to digitization (one trial, digitized 4 times),
- Variability between trials (one subject, 4 trials),
- Projection of normal vectors from the humeral head versus normal vectors projected from the acromion or glenoid fossa. This was done since it was thought that the extreme curvature of the humeral head might influence the distribution and orientation of the normal vectors, thus rendering a less accurate proximity map.
- Differences between two healthy subjects (subject 1: n=4 trials, subject 2: n=3 trials).

Results

Repeated analysis of a single trial of the push test (Table 1) showed a decrease of 0.21 ± 0.21 mm in the median proximity of the HH-AC joint space. Also, there was a decrease of 0.10 ± 0.11 mm in the GH-HH joint space. The mean and minimum values showed a similar trend as the median measure. Multiple trials in the same subject showed a decrease of 0.25 ± 0.25 mm in the AC-HH joint space. Examination of the four tables above indicated that the median values showed the least amount of variability, although not significantly different from the mean values. As a result, the median value was chosen as the variable of interest.

In table 3, the change in the median proximity depending on whether the normal vectors were projected from the humeral head or from the acromion or glenoid surfaces was examined. As may be noted in the table, when the normal vectors were projected from the second surface there was slightly less variability in proximity measures. Examination of Table 4, a comparison between two different healthy subjects, showed an increase in acromiohumeral joint space of 0.82 ± 0.50 mm in subject 2 versus a decrease in joint space of 0.27 ± 0.21 mm in subject 1. This difference between the two subjects was statistically significant (p= 0.01).

Discussion

The median value was used as the most accurate measure of proximity change, as it tended to have slightly lower variability, 0.21 mm over multiple digitisations, and 0.25 mm over multiple trials. The variations between trials were only slightly larger in subject 1 than the variability due to digitization (Tables 1&2). Most of the variability appears to stem from the digitization process, which suggests that possible improvement on the technique would include improving the digitizing software, or utilizing a higher strength magnetic resonance scanner. There may be other variables at play, such as fatigue, and variation in muscle coordination between the trials. A possible effect of fatigue or skill was seen in the data from the second subject where the variability between the trials was double that of subject 1, at 0.5 mm. Muscle activation patterns may account for the differing manner in which the joint space changed between the two subjects. The results also showed a change in acromiohumeral joint space that was different in the two subjects: 0.27 mm decrease in joint space in subject 1, and a 0.82 mm increase in joint space in subject 2. The statistical significance to this difference in joint spaces indicates that this method has the potential to detect differences between the active stabilizing mechanisms in different subjects. This would be a valuable tool since there are potentially larger abnormalities in patients with shoulder impingement.

Conclusions

From this study it may be concluded that this methodology can accurately measure in-vivo joint space change during a push task. From this study it may also be concluded that the most accurate measure of the shoulder joint space change is the change in the median proximity values generated by the analysis of the magnetic resonance data. It may also be concluded that the digitization process has an important influence on the source of variability. The ability to detect a statistically significant difference between two subjects suggests that this method has the potential to detect functional abnormalities in the shoulder joint. it also suggests that this method is robust enough to warrant further examination of shoulder joint function.

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