Abstract

Background. Recording movement of the scapula by non-invasive techniques is fraught with technical difficulty. One convenient method involves placing a single marker on the skin overlying the acromion. The purpose of this study was to compare translatory discrepancies between marker and underlying bone for seven markers affixed to the skin overlying different parts of the scapula.

Methods. The markers were small plastic spheres filled with machine oil, clearly visible on magnetic resonance imaging (MRI), placed over seven loci of the scapula, including the acromion, spine, medial border, lateral border, and inferior angle. Nine healthy men participated, assuming three positions in the MRI apparatus: (1) arm at the side of the trunk (starting position); (2) arm in full elevation over the head; and (3) hand placed behind the back at the thoracolumbar area. Visible markers and three loci of the scapula itself were digitized on each MRI scan, enabling calculation of changes in location of each marker relative to the scapula between the starting position and either of the other two positions.

Results. Among the seven loci examined, the marker placed atop the acromion deviated least from its target, 39 ± 15 mm (mean ± standard deviation) for full elevation and 15 ± 11 mm for moving the hand behind the back. Markers along the medial border and at the inferior angle exhibited relatively large deviations, on the order of 87 mm for full elevation and 33 mm for moving the hand behind the back.

Conclusions. For the two movements studied, involving full range of motion in the shoulder complex, translation of the scapula is most accurately recorded if the marker is placed over the acromion, but the systematic error is too large for such tracking to be deemed precise.

Introduction

In some studies on shoulder function, movement of the scapula has been tracked by recording the kinematics of a module placed on the skin overlying the acromion of the scapula.1-5 In other studies, the module has been put on a platform that contacts the skin over the scapula in more than one place.6-9 Technology has enabled both translation and angular orientation of the module itself to be accurately recorded, but the extent to which movements of the module are congruent with movements of the scapula is more problematic. A marker on the skin that is supposed to indicate the position of an underlying structure may deviate appreciably from its target during movement if the target structure slides underneath the skin. The scapula can easily be seen to move underneath the skin when, for example, the arm moves upward from the side of the body or when the hand is placed behind the back. If a single marker were to be placed over the scapula in an easily palpable location, is the acromion really the best place for movements of the scapula to be accurately followed by recording the movements of the marker? What about other locations over the scapula? These questions motivated the present study.

As a small part of a study on scapulohumeral rhythm, McQuade and Smidt measured distances between bony landmarks and the module on the acromion in a single subject, using roentgenograms obtained at nine arm positions throughout the full range of maximum overhead elevation.1 Error due to skin slippage of the acromial module was reported to be 4.2 mm.

Karduna et al. looked at the problem in greater detail, comparing movement of a “skin” module, placed either atop the acromion or on a platform over the scapular spine, to movement of a “bony” module, placed on an outrigger attached directly to the spine of the scapula.2 They found that, for elevation of the arm up to 120°, disparities in orientation between the two modules were generally less than 5°. Beyond 120° of elevation, however, the error increased precipitously. When the skin module was placed directly over the acromion, discrepancies in translation between that...
module and the module connected to bone were reported to be small in the two surface dimensions of a spherical coordinate system and were ignored as irrelevant in the remaining axial dimension.

The acromion provides a convenient location for affixing a tracking module to the overlying skin because it is flat and immediately underneath the skin. The acromion additionally appears to be a reasonable location because of its proximity to the acromioclavicular joint, rendering that portion of the scapula less likely to slide underneath the skin than other parts of the same bone during movement of the arm. In the present study we explored discrepancies in translation between module and scapula for markers placed on the skin overlying several parts of the scapula. Our intent was to confirm whether the acromion was the most suitable locus for placing a module to track translation of the scapula during full movement of the arm.

Given that both linear translation and angular orientation of the module are recorded in studies of scapular motion, assaying the accuracy of the recording should include evaluation of both translation and orientation. In the present study, we used magnetic resonance imaging (MRI) to track movement of the scapula itself and of several overlying passive markers. Locations of the markers could be determined on the MRIs but not their orientations. Recording from an electromagnetic module simultaneously with MRI recording of the scapula and module was not feasible because such modules are metallic and would interfere with the MRI recording. We thus examined the accuracy of skin markers over the scapula only in terms of translation.

Methods

Nine healthy men volunteered for this study. Eight of them were 21–37 years old, and the remaining one was 56 years old. Their height ranged from 165 to 174 cm and their weight from 55 to 87 kg. The oldest subject had a past history of frozen shoulder and of nerve root impingement of the sixth cervical spinal nerve but currently had no symptoms of pain or functional limitations of movement. No other subject reported having a present or past history of pathology in the cervical spine or in the shoulder complex. Prior to participating in these experiments, all subjects read and signed an informed consent form approved by the ethics committee on research involving human participants in this university.

Markers were mounted over the right scapula on the basis of bony landmarks that could be clearly palpated. Plastic fishing bobs, 18 mm in outer diameter with a 1 mm thick wall, were filled with machine oil and taped onto the skin at seven locations with the subject’s arm at the side of the body: (1) over the acromion near its anterior edge; (2) at the posterior edge of the acromion; (3) on the spine of the scapula midway between (2) and (5); (4) midway between (2) and (7); (5) on the spine of the scapula where it spreads out at the medial border; (6) midway between (5) and (7); and (7) at the inferior angle (Fig. 1).

MRI images were used to record positions of the markers (Gyroscan ACS-NT, 1.5 T; Philips). The images were spin echo, T1-weighted, with a time of repetition of 500 ms, time of echo of 17 ms, a flip angle of 90°, and a field of view of 450 × 450 mm. Under these conditions each slice was 5 mm thick with a pixel spacing of 879 µm. Altogether, 17–33 slices were required to obtain sufficient morphological information of the scapula in each position the subject assumed.

An initial image was obtained according to the orientation of the trunk with the arm at the side. Orientation of the MRI planes was then adjusted to approximate the plane of the scapula. An MRI (X, Y, Z) coordinate system was set in this adjusted orientation with the origin at the lateral extremity of the acromion (Fig. 2). This MRI coordinate system could not be used for tracking movements of the markers relative to the scapula because movement of the scapula relative to the thorax was not measured.
Locations and distances were measured using Scion Image software (available at www.scioncorp.com) to examine digitally scanned reproductions of the MRI images. The same individual performed all of these measurements. In a pilot study, this person used Scion Image on test MRI images of markers similar to those used in this study. The markers were arranged so distances could be measured between one marker (the origin) and seven other markers, set both vertically and horizontally away from the origin at distances of approximately 50 and 100 mm. Five MRI images of this array of markers were obtained. With the use of Scion Image, distances were measured 20 times between the origin and each of the other markers per test image. Thus, each of the seven distances was measured 100 times altogether. Standard deviations of measurements of these seven distances ranged from 0.60 to 0.98 mm. Considering that these standard deviations included error attributable to the human operator in addition to the limits of precision of the apparatus used, we concluded that use of Scion Image would be suitable for this study.

In the MRI apparatus, the subject lay recumbent, mainly left side-lying but turned partially toward supine. The scans were obtained with the subject holding the arm in three positions: at the side of the body (starting position), with the hand behind the back, and in full elevation. The starting position was scanned in three planes (Fig. 2) and the other two positions in only the transverse and sagittal planes to curtail the time in which the subject had to remain stationary. To avoid extraneous movements of the scapula and markers during the scanning process, the subject lay on his left side with a wedge-shaped pillow under his lower back and another pillow under his head. When the arm was in elevation, a third pillow was placed under the elevated arm to enable the subject to relax.

A local \((x, y, z)\) coordinate system for the scapula was used to account for translation of the markers relative to the scapula between the starting position of the arm at the side of the trunk and the final position of elevation or of the hand behind the back. This coordinate system was constructed on the basis of three points on the scapula that could be identified in the MRI images: lateral extremity of the acromion \(a\), anterior extremity of the coracoid process \(c\), and bottom of the glenoid \(g\). These three points can be seen in Fig. 1 as a triangle drawn by dashed lines. The origin of the local coordinate system was set at \(a\), identical with the origin of the MRI coordinate system.

The choices of \(a\), \(c\), and \(g\) for constructing the local coordinate system of the scapula were entirely pragmatic. The inferior angle of the scapula would certainly have provided another desirable place for determining the local coordinate system because of its distance from \(a\), \(c\), and \(g\). Unfortunately, no part of the inferior angle could be consistently located as a distinct point on different MRI views.

To transform the coordinates of the MRI system \(M\) to the local coordinate system of the scapula \(M'\), a matrix \(T\) of unit vectors was defined for the transformation so that

\[
M' = T \cdot M
\]

where

\[
T = \begin{pmatrix} \hat{i} \\ \hat{j} \\ \hat{k} \end{pmatrix}
\]

and \(\hat{i}, \hat{j}, \hat{k}\) are unit vectors for the \(x\), \(y\), and \(z\) axes, respectively. The \(z\)-axis ran through the acromion and the glenoid.

\[
\hat{k} = \frac{a - g}{|a - g|}
\]
The $y$-axis was set perpendicular to triangle $\mathbf{a}$ $\mathbf{c}$ $\mathbf{g}$.

$$\hat{j} = \frac{\mathbf{k} \times (\mathbf{a} - \mathbf{c})}{\|\mathbf{k} \times (\mathbf{a} - \mathbf{c})\|}$$

The $x$-axis was set perpendicular to the $y$- and $z$-axes.

$$\hat{i} = \hat{j} \times \hat{k}$$

The $x$-, $y$-, and $z$-axes based on this plane have no functional or clinical significance in terms of describing structure of the scapula or movements of the markers. The position vectors $\mathbf{a}$, $\mathbf{c}$, $\mathbf{g}$ simply provided the basis for a common local coordinate system for the scapula that could be determined on differing MRI views when the arm was placed in each of its three positions, making it possible to determine translatory movements of the markers in relation to the scapula.

**Results**

From a starting position with the arm at the side of the body, the medial border of the scapula (locations 5, 6, and 7 in Fig. 1) moved away from its overlying markers the most and the acromion (locations 1 and 2) the least, whether the movement was elevating the arm or placing it behind the back (Table 1). Failure of the markers to follow underlying displacement of the scapula was clearly greater for elevating the arm than for reaching behind the back. The least discrepancy between the marker and true movement of the scapula was on top of the acromion (location 1). Removing the data for the oldest subject had no appreciable effect on these results.

**Discussion**

The individual markers are referred to by number, corresponding to the numerals in Fig. 1.

| Table 1. Displacements of markers from initial locations over scapula in two movements beginning with arm at the side |
|----------------------------------|----------------------------------|
| Location | Arm behind back (mm) | Arm elevation (mm) |
| 1 | 14.9 ± 11.3 | 38.5 ± 14.6 |
| 2 | 14.7 ± 11.1 | 32.3 ± 14.3 |
| 3 | 21.0 ± 16.1 | 63.2 ± 16.5 |
| 4 | 21.4 ± 14.2 | 58.8 ± 14.9 |
| 5 | 32.0 ± 23.5 | 86.8 ± 28.1 |
| 6 | 30.4 ± 22.1 | 83.2 ± 27.9 |
| 7 | 32.6 ± 22.4 | 85.7 ± 30.7 |

Results are the mean ± standard deviation

Cf. Fig. 1 for interpreting location numbers

Of the seven markers placed over the scapula, the one that best kept its particular position in relation to the scapula, marker 1, nevertheless deviated from its original relative location due to placing the arm behind the back by more than 14 mm, certainly not an error worthy of neglect. The corresponding best case during elevation of the arm, again with marker 1, averaged more than twice as much, exceeding 38 mm. That markers 1 and 2 exhibited less translation than the other markers in either elevation or reaching behind the back might be explained by their proximity to the acromioclavicular joint, where the scapula is tethered to the rest of the skeleton. Our results confirm that the choice of the acromion for a marker in previous studies is indeed the best among the seven locations that we observed. The scapula slipped furthest away from medial markers 5–7, which were relatively distant from the mechanical link between the scapula and the clavicle. The medial part of the scapula was freer to move along the thorax, or even to separate away from the thorax, than other parts of the scapula represented by the markers.

Karduna et al. carefully tracked the movement of an acromial skin marker in relation to a marker rigidly connected to the bone of the scapula itself. During the first 100° or so of elevation of the arm, the skin marker’s angular orientation stayed within 5° of the bony angular orientation. Error increased precipitously beyond 120° of elevation, yielding errors three to four times as large for full elevation. When investigating errors in translation of the acromial skin marker, Karduna et al. characterized scapular translation as movement of a rigid shaft connecting the acromioclavicular joint to the sternoclavicular joint. This motion, constrained along a spherical surface, was recorded in degrees of clavicular movement rather than in millimeters of scapular movement. Their data for full elevation suggest that the error in translation of the acromial marker was about 10% of the spherical radius afforded by the clavicle. If the radius were 150 mm long, for example, error in translation between the acromial marker and the actual acromion would have been 15 mm, about half of what we found for the same movement, yet considerable. Part of this disparity may be that the coordinate system of Karduna et al. made slippage of the acromial marker in a direction toward the sternoclavicular joint irrelevant, whereas our data included that component of translation.

McQuade and Smidt reported translatory slippage of the acromial marker during full elevation of the arm by a single subject to be only 4.2 mm. Not enough technical information is available to determine how they arrived at such a favorable value. Ludewig and Cook, who worked at the same institution as McQuade and Smidt, stated that the analysis was based on two-dimensional radiographic measurements.
Whether the arm was elevated or placed behind the back, the skin was more bunched together, tending to reduce distances slightly among the markers, than when the arm was at the side of the trunk. This effect was probably more than simply squeezing the skin together like an accordion, being a matter of underlying muscles and soft tissue being squeezed together as well and bulging. Because it was initially located over the flat acromion, where little more than skin lay between marker and bone, marker 1 may have been less influenced by this effect than the other markers.

Conclusions

Use of a single marker on the skin to track movements of the scapula is fraught with error if full movement of the shoulder is to be measured. A general indication of scapular movements can best be obtained by placing the marker over the acromion.

References