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Dynamic Measurements of Three-Dimensional Scapular Kinematics: A Validation Study

The validation of two noninvasive methods for measuring the dynamic three-dimensional kinematics of the human scapula with a magnetic tracking device is presented. One method consists of simply fixing a sensor directly to the acromion and the other consists of mounting a sensor to an adjustable plastic jig that fits over the scapular spine and acromion. The concurrent validity of both methods was assessed separately by comparison with data collected simultaneously from an invasive approach in which pins were drilled directly into the scapula. The differences between bone and skin based measurements represents an estimation of skin motion artifact. The average motion pattern of each surface method was similar to that measured by the invasive technique, especially below 120 degrees of elevation. These results indicate that with careful consideration, both methods may offer reasonably accurate representations of scapular motion that may be used to study shoulder pathologies and help develop computational models.
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1 Introduction

The scapula is a flat, triangular shaped bone that sits posteriorly on the rib cage at rest and moves in a complex three-dimensional motion pattern with humeral elevation. There is evidence that alterations of this motion pattern are associated with shoulder pathologies, such as impingement syndrome, instability, and rotator cuff disease [1–4]. However, due to the unique shape and anatomical location of the scapula, it has been difficult to study the motion of this bone in vivo. Traditionally, scapular rotation with respect to the thorax has been studied with goniometers [5,6] and x-rays [7,8]. While it may be possible to adjust the measurement plane for a goniometric measurement, x-rays are subject to errors of projecting a three-dimensional object in two-dimensional space [9]. In either case, only one rotation can be measured.

Several investigators have attempted to develop methods for measuring three-dimensional scapular kinematics. Earlier bone based studies have utilized biplanar radiographs, both with [10] and without [11] implanted markers. This method is attractive in that direct access to bony landmarks is available, however, experimental protocols must be relatively limited in order to minimize exposure to potentially harmful radiation. Three-dimensional imaging modalities, such as open configuration MRI, look very promising, although cost and availability may present a problem [12]. Recently, several investigators have used a skin based approach that involves digitizing discrete bony landmarks that are palpable through the skin [13–15]. Another skin based approach involves capturing three-dimensional scapular orientation directly with a magnetic tracking device. This has been tried statically by coupling a magnetic sensor to an alignment jig [16–18] and dynamically by attaching a magnetic sensor directly to the acromion [1,19]. Although most of these skin based methods have demonstrated satisfactory reliability, only McQuade and Smidt [19] have addressed the issue of accuracy, which may be the most critical test of a technique's utility [20].

Since it has become standard practice to study motion of the lower extremity with skin based methods, a number of studies have attempted to assess the accuracy of these methods by comparison to a bone based system using bone pins or x-rays. This approach has been attempted in vivo for the hip [21], knee [22–26], ankle [25,27,28], and foot [27,29]. Beyond the lower extremity, this approach has also been used for the finger [30] and jaw [31]. Although, results indicate relatively small errors for some measurements, average errors may exceed 50 percent of the actual motion [28]. Errors of this magnitude highlight the importance of documenting the accuracy of any proposed kinematic measurement tool.

The purpose of the current investigation was to assess the accuracy of measuring three-dimensional dynamic scapular kinematics with a magnetic tracking device. Two skin based approaches of attaching a sensor to the scapula were investigated. Technique accuracy was assessed by simultaneously measuring kinematics with these noninvasive skin based methods and an invasive bone based measurement using a sensor attached to bone pins drilled into the scapula.

2 Methods

2.1 Subjects. Eight volunteers (five men and three women) free from shoulder pathology on the side tested were recruited for this study (mean age 33 years). An additional male subject diagnosed with subacromial impingement syndrome by an orthopaedic surgeon was tested on his affected side (age 25 years). Approval for this study was obtained from the internal review board of MCP Hahnemann University. All subjects read and signed a consent form prior to participation in this study.

2.2 Measurement Technique. Kinematic data were collected with a magnetic tracking device (Polhemus 3Space Fastrak, Colchester, VT), consisting of a transmitter, four receivers, a digitizer, and a systems electronic unit [32]. A global coordinate system was established by mounting the transmitter on a rigid plastic base and aligning it with the cardinal planes of the body. The level of the transmitter was adjusted with visual feedback from a bubble level for alignment within the coronal and sagittal planes. The transmitter was rotated about a vertical axis until it was aligned with a rigid support fixed to the floor for alignment within the horizontal plane. The rigid support was used to help position the subject, as discussed later. Receivers were mounted on the thorax, humerus, and scapula. The thoracic receiver was placed at the

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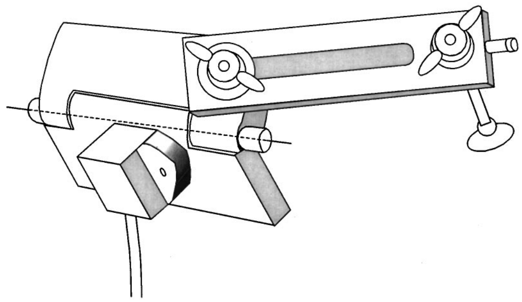

Fig. 1 Schematic drawing of custom designed scapular tracker. The hinge joint on the base allows it to conform to the subject's scapular spine. The arm can pivot and translate on the base so that the location of the footpad can be adjusted. The footpad can be raised or lowered and rotate on a ball and socket joint.

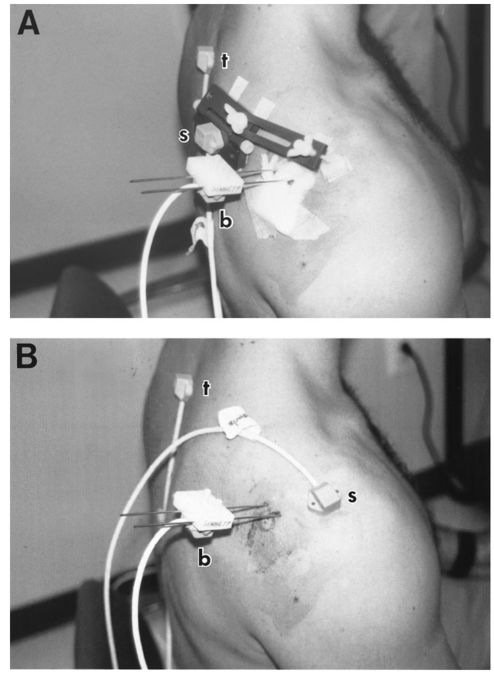

Fig. 2 Photographs of bone and skin base receiver locations. (*A*) Tracker method, (*B*) acromial method.

level of T3 with double-sided tape. The humeral receiver was mounted on a molded cuff strapped to the distal humerus.

Two skin based methods for mounting the scapular receiver were investigated separately. The first was the method utilized by McQuade and Smidt [19] and Ludewig et al. [1], in which a receiver was directly attached to the broad, flat surface of the posterior-lateral acromion with double sided tape—the so-called acromial method. This area is located by having the subject elevate their arm with the investigator palpating the flat area of the acromion just proximal to the origin of the deltoid. The second method involved the development of a custom designed scapular tracker—the so-called tracker method (Fig. 1). This device consists of three parts: a base, an adjustable arm, and a footpad. The receiver is mounted on the base, which has a hinge joint that can be pivoted and locked so that it conforms to the mid-portion of the scapular spine. The arm extends from the base and its length can be adjusted and locked so that it reaches the acromion. The footpad is connected to the arm via a ball and socket joint that can be adjusted and secured so that the footpad sits flush on the same area of the posterior-lateral acromion used for the acromial method. Both the base and footpad of the scapular tracker were attached to the skin with adhesive-backed Velcro strips.

2.3 Validation. In order to independently assess the concurrent validity of the two proposed skin based methods, an additional receiver was rigidly fixed to the scapula with pins. An orthopaedic surgeon cleaned and anesthetized a small region on the lateral scapular spine with lidocaine. Two 1.6 mm K-wires were then drilled into the bone using a plastic alignment jig to keep them parallel and approximately 20 mm apart. Care was taken to ensure that the location of these pins was lateral enough so that they would not contact the scapular tracker. After determining that the pins were secure in the bone, they were fixed to the alignment jig with setscrews. The additional receiver was then secured to this jig so that the receiver was rigidly attached to the scapula via the pins. This configuration allowed for simultaneous data collection from skin and bone based receivers (Fig. 2).

2.4 Kinematics. The arbitrary axes defined by the magnetic tracking device were converted to anatomically appropriate embedded axes derived from digitized bony landmarks (Fig. 3). All landmarks were surface points and could thus be located directly with a digitizer connected to the magnetic tracking device, except for the center of the humeral head. This was defined as the point on the humerus that moved the least with respect to the scapula when the humerus was moved through short arcs ($<$45 degrees) of mid-range glenohumeral motion and was calculated using a least-squares algorithm [33]. The scapular landmarks were only digitized once so that the same points were used to create the axis system for both the skin and bone based receivers, ensuring that they were aligned at the time of digitization. After the digitization process, the raw data from the receivers were converted into anatomically defined rotations that could be displayed in real time using LabView software (National Instruments, Austin, TX).

Standard matrix transformation methods were used to determine the rotational matrix of the humerus and scapula with respect to the thorax [14]. Humeral rotations were represented using a standard Euler angle sequence in which the first rotation defined the plane of elevation, the second rotation described the amount of elevation and the last rotation represented the amount of internal/external rotation [34,35]. Scapular rotations were represented using an Euler angle sequence of external/internal rotation (Z_S axis), upward/downward rotation (Y_S axis), and posterior/anterior tilting (X_S axis) [14,36]. When the second scapular rotation was within 10 degrees of the Gimbal lock position (90 degrees of upward rotation), the results for the other two rotations were not considered reliable.

The scapula is connected to the thorax via the sternoclavicular and acromioclavicular joints, which are both assumed to exhibit ball and socket kinematics. Consequently, the orientation of the scapula with respect to the thorax is not restricted and is modeled with three degrees of freedom, represented by the three Euler angles described above. However, due to the rigidity of the clavicle, which spans these two joints, the distance between them is kept constant. Therefore, the position of the scapula is restricted to only two degrees of freedom that are represented by protraction/retraction and elevation of the clavicle. This is equivalent to representing the position of a point on the Earth with the use of two angles, longitude and latitude. Clavicular angles are derived from the location of the sternal notch and acromioclavicular joint, which are tracked with the thoracic and scapular receivers, respectively. In summary, motion of the scapula with respect to the thorax is described with a total of five degrees of freedom (three for orientation and two for position).

2.5 Experimental Protocol. The following protocol was performed separately for both skin based methods. For each, simultaneous measurements were made with the skin and bone mounted receivers. Subjects stood with their eyes fixed forward, feet at a comfortable width apart, and heels against a rigid support

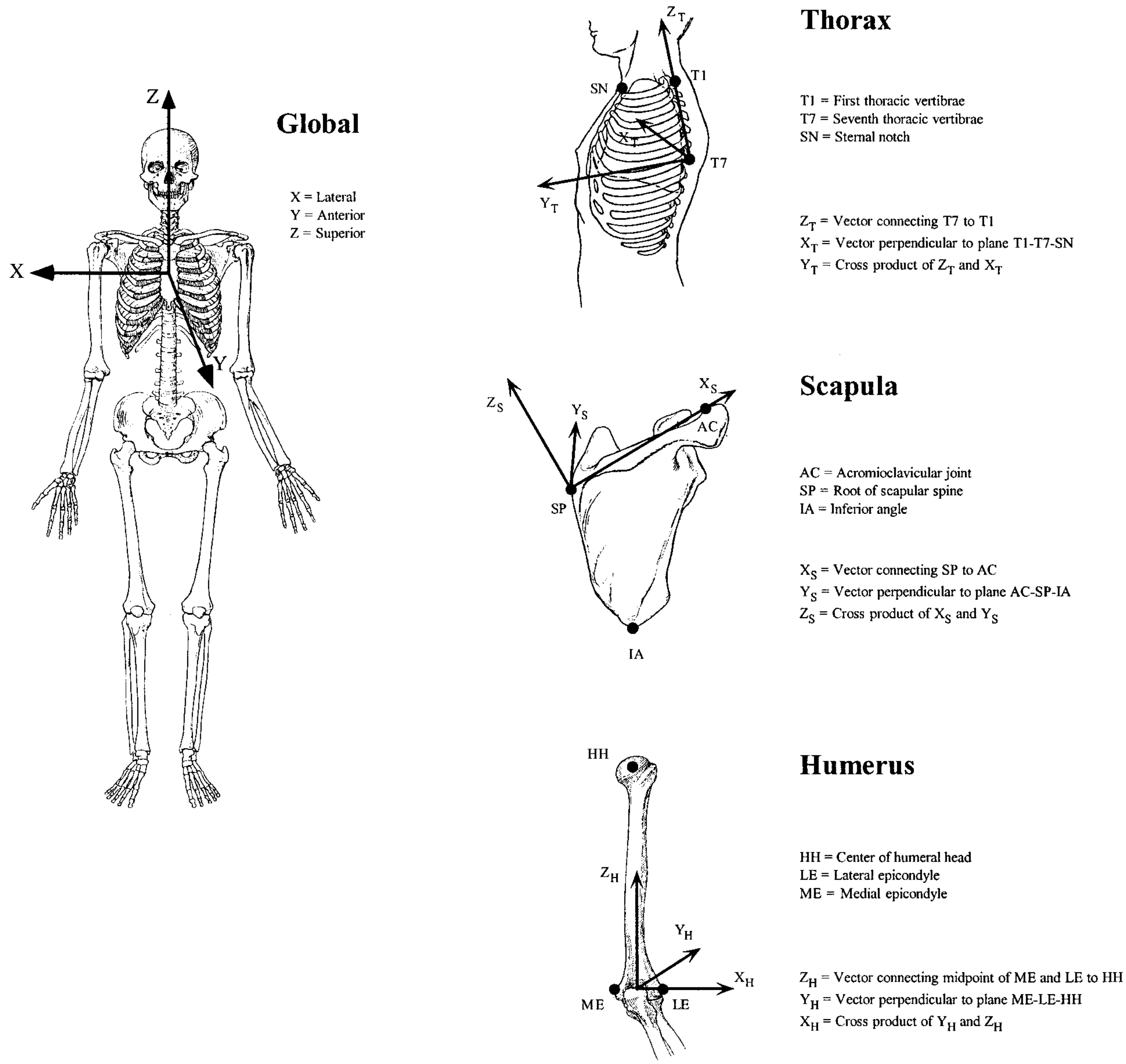

Fig. 3 Landmarks and coordinate axes for the global, thoracic, scapular, and humeral reference frames

that was aligned with the global coordinate system. A total of four active motions were studied: (1) elevation of the humerus in the scapular plane (40 degrees anterior to the frontal plane) with the elbow in full extension, (2) elevation of the humerus in the sagittal plane (90 degrees anterior to the frontal plane) with the elbow in full extension, (3) horizontal adduction (arm at 90 degrees of elevation and the elbow in full extension, arm brought from the posterior to anterior plane), (4) internal to external rotation with the arm elevated 90 degrees in the frontal plane and the elbow in 90 degrees of flexion. This protocol was designed so that all three humeral rotations (plane, elevation, internal/external rotation) were independently controlled for in at least one experiment.

Prior to collecting data for each motion, several practice trials were performed. The investigator monitored real-time humeral motion, which was displayed on a computer screen, and provided the subject with verbal feedback. The subject was instructed to maintain a forward gaze and not to look either at their arm or the computer screen during the experiment. Once the subject could accurately reproduce this motion for two consecutive trials, data collection began. As with the practice trials, the investigator was able to monitor the humeral motion pattern during the data collection.

For each motion, subjects moved their arm through the desired arc to a count of three seconds and then returned along the same path, while data were collected continuously at a rate of approximately 10 Hz. This procedure was repeated for three consecutive trials. For each trial, the minimum and maximum increasing humeral rotation points were measured and data at every five-degree increment were calculated by linear interpolation, with the primary humeral rotation serving as the independent variable. These data were averaged over the three trials. Only the elevation portion of the motion was analyzed.

3 Results

All subjects were able to complete the entire protocol; however, one trial of horizontal adduction was lost due to a computer problem. Over the entire data set, only two positions reached 80 degrees of scapular upward rotation and had to be discarded due to Gimbal lock. The error for a given position was defined as the difference between the angles recorded by the pin and surface mounted receivers. From these data, the root mean square (rms) errors were calculated for all experiments with both methods (Table 1). Since scapular plane elevation is of great interest from

Table 1 Root-mean-square errors for all rotations and experiments for all normal subjects. All data in degrees.

	Tracker method				Acromial method			
Degree of freedom	Scapular plane elevation	Sagittal plane elevation	Horizontal abduction	External rotation	Scapular plane elevation	Sagittal plane elevation	Horizontal abduction	External rotation
Posterior tilt	4.7	6.2	3.8	4.6	6.6	8.6	7.3	3.7
Upward rotation	8.0	8.4	10.0	7.2	6.3	5.9	4.8	4.4
Upward rotation*	4.2	4.1	4.0	4.5	2.0	2.5	4.1	4.0
External rotation	3.2	3.8	5.0	4.4	9.4	11.4	10.0	6.2
Clavicular plane	1.2	1.2	2.0	1.1	2.6	2.6	2.6	2.6
Clavicular elevation	1.5	1.6	1.7	1.3	1.1	1.2	1.5	1.2

*Upward rotation with correction factor applied.

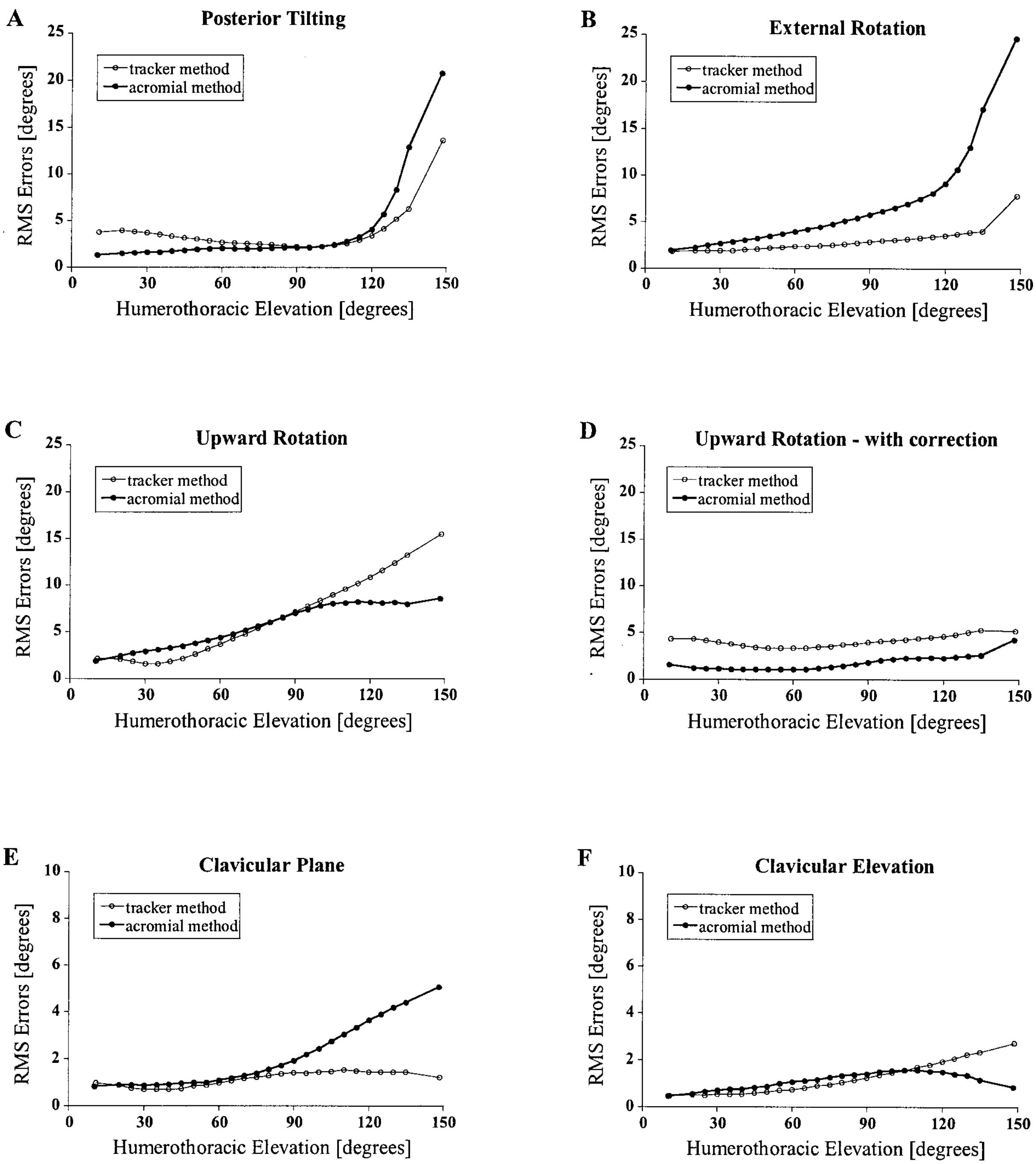

Fig. 4 Comparison of skin and bone based methods during scapular plane elevation. Each data point represents the rms errors of the eight healthy subjects. (*A*) Posterior tilting, (*B*) external rotation, (*C*) upward rotation, (*D*) upward rotation with a correction factor, (*E*) clavicular plane, (*F*) clavicular elevation.

a functional standpoint and is also the most commonly reported motion in the literature, the data from this experiment are presented in more detail.

For posterior tilting, both methods demonstrated good agreement between the skin and bone based receivers for humeral elevation angles up to 120 degrees (Fig. 4*a*). For several subjects, however, there was a large discrepancy between the skin and bone based methods at the end range of humeral elevation, which lead to high rms values. Over the entire range of motion, posterior tilting rms errors were 4.7 degrees for the tracker method and 6.6 degrees for the acromial method.

For the scapular tracker method, rms errors for external rotation were low and essentially independent of humeral elevation angle below maximum elevation. However, for the acromial method, there was a progressive increase in rms error with humeral elevation, up to 25 degrees at maximal elevation (Fig. 4*b*). Over the entire range of motion, external rotation rms errors were 3.2 degrees for the tracker method and 9.4 degrees for the acromial method.

Both skin based methods recorded the same general pattern of scapular upward rotation as the bone based method, with errors increasing with increasing humeral elevation (Fig. 4*c*). However, while the scapular tracker underestimated upward rotation, the acromial method overestimated upward rotation. Over the entire range of motion, upward rotation rms errors were 8.0 degrees for the scapular tracker and 6.3 degrees for the acromial method.

Near identical rotations were observed between the two sensors for clavicular retraction (Fig. 4*e*). The rms error for this rotation was 1.2 degrees for the tracker method and 2.6 degrees for the acromial method. Similar results were found with clavicular elevation (Fig. 4*f*). The rms error for this rotation was 1.5 degrees for the tracker method and 1.1 degrees for the acromial method.

3.1 Upward Rotation Correction Factor. For both skin based methods, a systematic error pattern was found for upward rotation that was consistent across all subjects. Consequently, a correction model based on this systematic error was developed for each. The error (e) is represented as the difference between the bone (U_B) and skin (U_S) receivers:

$$e = U_B - U_S \tag{1}$$

The key assumption of the proposed model is that this error is due to skin movement artifact caused by motion of the underlying scapula. Therefore, upward rotation errors were modeled as a linear function of the scapula position, as represented by the bone based receiver:

$$e = \alpha U_B + \beta \tag{2}$$

where α and β are constants. The combined data from all eight healthy volunteers for upward rotation during scapular plane elevation were used to determine the constants (α and β) using a least-squares fit. In general, the position of the bone based receiver would not be known, so eq (1) and (2) were combined to eliminate the position of this receiver (U_B) and solve for the error as a function of the skin based receiver (U_S):

$$e = [\alpha/(1-\alpha)]U_S + [\beta/(1-\alpha)] \tag{3}$$

The application of this model reduced the rms errors for the tracker method from 8.0 to 4.2 degrees and for the acromion method from 6.3 to 2.0 degrees (Fig. 4*d*). Applying this correction factor with the same coefficients to the data from the other tested motions also reduced the upward rotation errors (Table 1).

3.2 Subject With Impingement Syndrome. During scapular plane elevation, the rms errors for the subject with impingement were less than 2 degrees for all rotations except for the tracker method with upward rotation (7.7 degrees) and external rotation (3.4 degrees) and the acromial method with upward rotation (4.4 degrees). While the application of the upward rotation correction model reduced tracker method rms error to 2.4 degrees, it increased the acromial method rms errors to 5.7 degrees. Note that the data from this subject were not curve fit to find the most appropriate coefficients, but rather the coefficients developed from the data on the normal subjects were used.

4 Discussion

We have presented the accuracy of two skin based methods of attaching a sensor to the scapula for measuring in-vivo kinematics and both methods demonstrated reasonable accuracy for a wide variety of motions. In order to determine the accuracy of any measurement, there must be a direct comparison with a valid measurement. The use of pins as a bone based assessment of in-vivo scapular motion has been used previously by Harryman et al. [37] and Koh et al. [38] and was assumed to be a valid representation of scapular kinematics for the present study. The only difference between these skin and bone based techniques is that the former is sensitive to motion of the skin motion with respect to the underlying bone. Therefore, any numerical difference between the two was attributed to skin motion artifact.

One motivation for developing a valid method of measuring scapular kinematics is to help study the mechanisms associated with shoulder pathologies. Previous investigations in this area have focused on two-dimensional scapular upward rotation patterns [3,8,39]. However, recent studies have demonstrated that in order to completely describe differences between shoulder patients and healthy subjects, a three-dimensional analysis is necessary [1,2]. It is therefore important to examine the accuracy of all kinematic degrees of freedom.

A comparison of the mean data from skin and bone based receivers indicates that both methods investigated in the present study are well suited for capturing the essence of the motion patterns, especially below 120 degrees of elevation. When the rms errors for all subjects are examined, both methods demonstrated low errors for clavicular motion. For scapular rotations, the tracker method resulted in lower rms errors for posterior tilting and external rotation. Additionally, maximum individual subject rms errors were much lower for the tracker method in posterior tilting (7 vs. 17 degrees) and in external rotation (6 vs. 19 degrees). However, the acromial method was found to have lower errors for upward rotation. While the addition of a correction factor for the healthy subjects reduced the upward rotation errors for both methods, for the patient with impingement syndrome, the errors were only reduced for the tracker method.

Although palpating surface landmarks in a static environment may provide a more accurate measurement of scapular motion, no study has attempted to document the experimental accuracy of this approach. Only McQuade and Smidt [19] have attempted to validate a method of measuring scapular kinematics (similar to the acromial method in the current paper). In that study, x-ray measurements were used for validation purposes, but only for two-dimensional static measurements of upward rotation in one subject. All other studies have simply made the same measurement more than once with the same technique, which is a measure of reliability or precision of the measurement, not accuracy. This makes it difficult to perform a direct comparison with other scapular kinematic studies.

During scapular plane elevation, the rms errors can be represented as percentages of the total range of motion for that degree of freedom. For posterior tilting, upward rotation, external rotation, clavicular plane, clavicular elevation, those would be 15, 8, 12, 6, and 14 percent for the tracker method and 19, 4, 32, 11, and 10 percent for the acromial method. These results are better than the rms errors reported by Reinschmidt et al. in similar pin studies of 70, 64, and 21 percent for the three rotations of the knee [24] and 35, 51, and 14 percent for the three rotations of the ankle [28].

Due to ethical issues, all but one of our subjects were healthy volunteers. Although it is possible that skin motion patterns may be different in subjects with shoulder pathologies, we did find comparable errors for the one patient with impingement syndrome that we studied. However, while the correction model reduced upward rotation rms errors for the tracker method, it increased these errors for the acromial method. The results from this one subject do not completely rule out the possibility that other patients with impingement or other pathologies may have more exaggerated skin motion errors.

Several previous investigators have attempted to compensate for skin motion artifacts in vivo [40–42]. The correction model in the present study was developed based on an approach originally conducted on horses. Van Weeren et al. noted that for some equine joints the skin motion pattern was fairly systematic [43,44]. In a subsequent paper this error was modeled as a function of the orientation of the bone [45]. A similar approach was adopted in the present study in which the errors were modeled as a function of the actual position of the scapula. We had originally attempted to model the error as a function of humeral elevation, which reduced the errors even further. However, this was simply a phenomenological model without any regard for the cause of the skin motion. By definition, that type of model would predict scapular motion with humeral elevation even in subject that had no scapular motion. The currently proposed model does not have this restriction.

One potential criticism of the surface methods presented is that they may only work well on ''young and lean'' subjects. While all subjects were under the age of 40 years, by observation, several subjects, including the one with impingement, had large amounts of soft tissue surrounding the scapula, both from muscle or subcutaneous fat. This can also be inferred from their body-mass indices (up to 36 kg/m^2). Additionally, although we believe that data from the pin receiver accurately represented scapular motion, it is possible that skin tension may have caused the pins to bend. This tension was probably low, however, since subjects did not complain of any pain or discomfort due to skin tension, despite the fact that the experiment went well beyond the effective time of the anesthesia. With a liberal estimate of fifty pounds of skin tension, simple beam theory predicts that errors due to pin bending are less than 0.2 mm and 0.5 degrees. Additionally, we performed a pilot study on a cadaver specimen in which we simulated this tension by pulling the skin maximally and found negligible errors due to this effect.

5 Conclusions

We have presented a comprehensive analysis of the accuracy of two noninvasive skin based methods for collecting continuous three-dimensional kinematics of the human scapula in vivo. Although rms and percent errors were found to be reasonable, the utility of these techniques may depend on specific experimental effect sizes. These methods have applications in detecting motion abnormalities associated with various shoulder pathologies, as well as assessing changes in kinematics following various treatment interventions.

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