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Comparison of Surface Sensor and Bone-Fixed Measurement of Humeral Motion

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A common method of tracking humeral motion involves securing a thermoplastic cuff to the humerus with an electromagnetic sensor attached. The data on the accuracy of this technique are limited. This study addressed two questions: (a) How similar are surface and bone-fixed measurements of 3-D humeral rotations? (b) How similar are surface and bone-fixed measurements of 3-D humeral translations? Electromagnetic motion sensors were secured to a bone-fixed external humeral fixator, a surface humeral cuff, and the skin over the sternum and scapular acromion process. The 3-D data were collected during successive slow velocity (10–20°/second) repetitions of humeral active-assisted scapular plane abduction, sagittal plane flexion, and internal/external rotation with the arm adducted. Root mean square errors of surface measures compared to bone-fixed angular and translational values were calculated, and paired *t*-tests were computed between the two methods. Root mean square errors for humeral rotations ranged from 1° (1%) for humeral elevation during scapular plane abduction to 7.5° (9%) for humeral internal/external rotation. Peak errors were under-representations of 5.7° for internal/external rotation during scapular plane abduction and 15.6° for internal rotation with the arm adducted at the side. Average translation errors ranged from 0.1 to 2.1 mm. Data from this study suggest that dynamic measurement of humeral motion with a surface humeral cuff sensor can be performed for certain slow velocity motions with root mean square errors less than 8°. Caution is called for when interpreting internal/external rotation values, which were underrepresented. Results may vary with one's age, weight, or general physical condition, with different velocities of movement, or with different movements.

Key Words: shoulder, biomechanics, kinematics, helical translations

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Introduction

Measurement of three-dimensional (3-D) humeral motion is important to the study of normal and abnormal shoulder biomechanics (An, Browne, Korinek, Tanaka, & Morrey, 1991; Johnson & Anderson, 1990; Ludewig & Cook, 2000). A commonly employed skin marker method involves securing a thermoplastic cuff to the humerus with an electromagnetic sensor attached (Johnson & Anderson, 1990; Karduna, McClure, Michener, & Sennett, 2001; Ludewig & Cook, 2000; McQuade & Smidt, 1998; Meskers, Vermeulen, de Groot, van der Helm, & Rozing, 1998; Price, Franklin, Rodgers, Curless, & Johnson, 2000). As the underlying bone segment movement is the variable of interest, there is a need for validation of surface marker techniques to invasive bone-fixed techniques (Lundberg, 1996).

McQuade and Smidt (1998) provided some two-dimensional (2-D) radiographic validation data on surface humeral cuff motion from one participant. However, this static 2-D measurement comparison did not allow determination of the error associated with dynamic surface measurement of humeral rotations and humeral head translations about and along all three anatomical axes.

The purpose of this study was to determine the extent to which a surface humeral cuff marker matches the true underlying humeral motion measured with a bone-fixed tracking sensor. This study addressed two questions: (a) How similar are surface and bone-fixed measurements of 3-D humeral *rotations*? (b) How similar are surface and bone-fixed measurements of 3-D humeral *translations*?

Methods

Accuracy of tracking underlying humeral movement with a surface-mounted humeral cuff sensor was investigated on a 48-year-old man (Wt = 78 kg, Ht = 1.75 m) whose activity level included walking but no athletic participation. This participant had an external humeral fixator in place secondary to a previous fracture. The fixator consisted of four stainless steel pins 4-mm in diameter drilled transversely through the skin into the humerus, two above and two below the proximal humeral shaft fracture. The pins were attached externally to a titanium alloy frame. Recent radiographs prior to data collection revealed a stable fracture site and bone growth surrounding the pins. No fixation pins were present in the scapula. The skin over the humerus was intact with the exception of 1- to 2-cm open areas around each pin allowing free skin movement. The university's institutional review board approved the protocol and informed consent was obtained.

The Polhemus FASTRAK (Colchester, VT) electromagnetic motion tracking system was used to monitor the 3-D position and orientation of the participant's thorax, scapula, and humerus at a 30-Hz sampling rate. Manual digitizing of anatomical coordinates uses a sensor attached to a stylus with known tip offsets. Within a 76-cm source-to-sensor collection space, the reported root mean square (rms) accuracy of the system is 0.15° and 0.8 mm (Polhemus, Inc., 1993). Pilot testing verified that the accuracy of the FASTRAK was maintained in the presence of the fixator components when these components were greater than 10 cm from the sensors and not between the transmitter and sensors.

Surface sensors were attached with adhesive tape to the sternum and superior scapular acromion process. A thermoplastic cuff was secured to the distal humerus with Velcro straps. Humeral cuff and fixator sensors were attached to rigid plastic extensions from the cuff and fixator, respectively, which placed the sensors at least 13 cm from the metallic components of the fixator. The fixator was not between the transmitter and sensors during any of the motions. The participant stood with both arms at his sides while anatomical landmarks were palpated and digitized, allowing sensor data to be transformed to local anatomically based coordinate systems (Ludewig & Cook, 2000). This surface palpation technique has been shown to be reliable to within 2–3° (Ludewig, Cook, & Nawoczenski, 1996).

Data were collected from all sensors during four successive slow-velocity repetitions of humeral active-assisted scapular plane abduction, sagittal plane flexion, and internal/external rotation with the arm adducted at the side, all within the participant's available range of motion (ROM). The participant's maximum obtained humeral elevation angle relative to the trunk was 111° and the average movement velocity was 10°/second. His internal and external rotation ROM was 75–80% (by visual estimation) of his opposite extremity motion and the average movement velocity was 20°/s.

Anatomical landmarks and development of orthogonal local coordinate systems for each segment have been described previously (Ludewig & Cook, 2000) (Figure 1). The same landmarks were used to determine the humeral coordinate system for both the surface cuff sensor and the bone-fixed sensor so that the coordinate system for the cuff sensor was initially coincident with the coordinate system of the fixator sensor.

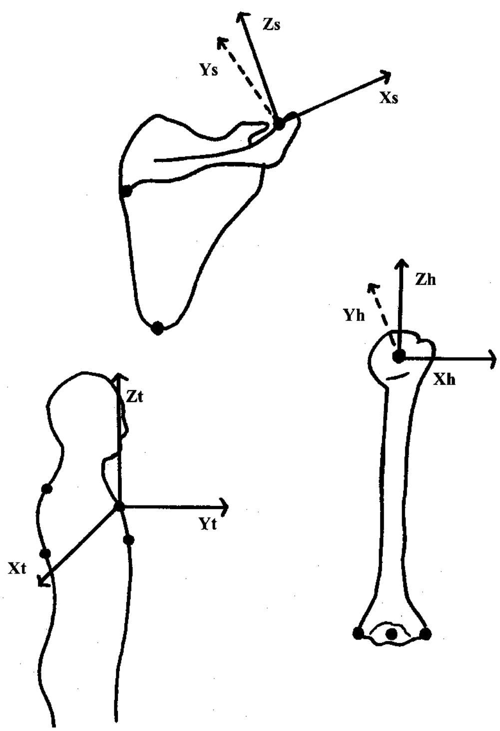

Figure 1 — Local anatomical coordinate systems for the trunk, scapula, and humerus. Trunk axes were aligned with the cardinal planes, with the x-axis directed to the participant's right, y-axis directed anteriorly, and z-axis directed superiorly. The scapular x-axis was directed laterally to the participant's right from the root of the scapular spine to the posterior/superior acromioclavicular joint, the y-axis was directed anteriorly perpendicular to the plane of the scapula, and the z-axis was directed superiorly perpendicular to the x and y axes. The humeral x-axis was directed laterally to the participant's right parallel to a line from the medial to the lateral epicondyle, the y-axis was directed anteriorly perpendicular to the x-axis, and the z-axis was directed superiorly along the long axis of the humerus. Consistent with the right-hand rule, humeral flexion (x-axis), adduction (y-axis), and internal rotation (z-axis) were positive rotations.

To allow clinically meaningful descriptions of humeral rotations, a z, y', z" Euler angle sequence (plane of elevation, elevation, axial rotation) was used to describe humeral orientation relative to the trunk, and a y, x', z" rotation sequence (abduction, flexion, internal/external rotation) was used to describe humeral orientation relative to the scapula (Figure 1). Translations of the humerus were also obtained. Humeral displacements were calculated for 20° increments of humeral motion relative to the thorax.

For each of these increments the finite helical axis translation was determined, representing the minimum translation of any point in the humerus from the initial to the final position (Andrews, 1984). The components of the unit vector defining the helical axis orientation are orthogonal projections onto the axes of the local anatomical coordinate system. The product of the x component of the unit vector and the helical translation is subsequently defined as the medial/lateral translation. Similarly, the products of the y and z components of the unit vector and the helical translation are defined as the anterior/posterior and superior/inferior translations, respectively. This method does not track a fixed point in the segment, such as the estimated humeral head center, but rather tracks the minimal translation of any point in the segment for that interval of motion (Andrews, 1984).

Humeral rotations and translations relative to the scapula were described from both bone-fixed and surface humeral sensors and directly compared to one another. For angular comparisons, the difference between the bone-fixed measurement and humeral cuff measurement for each sample and each angular rotation was determined, and the rms error value was calculated. For translation data, the helical axis component translations in the x, y, and z directions were determined for each 20° increment of motion and each repetition using both the surface and bone-fixed measurement techniques.

Values for all trials of each increment and technique were averaged (e.g., repetitions of helical anterior/posterior translations between 80 and 100° of humeral elevation relative to the trunk), and the rms value of differences between the two measurement techniques was calculated. In addition, rms differences between the techniques for individual trials were determined. For all angular and translation variables, paired *t*-tests were completed between the two measurement methods using a significance level of 0.05.

Results

The surface-mounted sensor closely represented the underlying angular movements of the bone for most motions (see Table 1 and Figure 2). Scapular plane abduction showed the least deviation between the two measurement techniques. For humeral external rotation (z-axis rotation) occurring during scapular plane abduction, the surface sensor slightly underrepresents the true bone-fixed motion (Figure 2), with a maximum deviation of 5.7°. Slightly greater rms deviations were seen for arm motion into flexion.

Internal/external rotation with the arm adducted demonstrated small differences between the surface and bone-fixed techniques for x- and y-axis rotations (flexion and abduction, respectively), but greater rms differences between the two techniques for the primary motion, internal/external rotation (z-axis). This error predominately results from progressive underrepresentation of the true bone motion by the surface humeral cuff sensor as the arm begins to decrease external

Table 1 Root Mean Square Differences Between Bone-Fixed and Surface Cuff Measures of Humeral Angles During Active-Assisted Motions

	Flexion	Scapular plane abduction	Internal/External rotation
x-Axis rotation	3.8	1.5	1.3
y-Axis rotation	3.1	1.3	2.4
z-Axis rotation	3.5	3.5	7.5

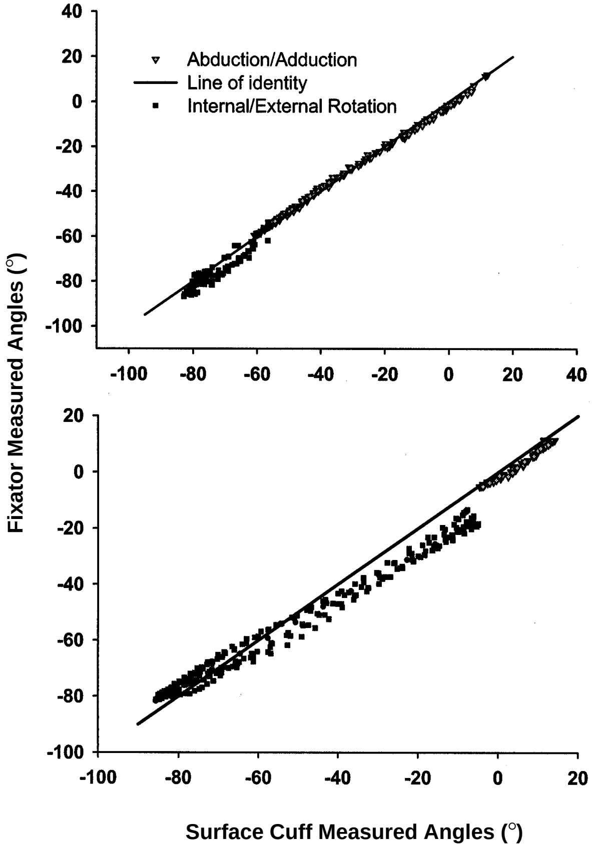

Figure 2 — Humeral fixator internal/external rotation and abduction/adduction angles plotted against angles measured by the surface cuff method. Top graph is scapular plane abduction; bottom graph is internal/external rotation with the arm adducted. Humeral adduction and internal rotation are positive rotations relative to the scapula. Equivalent measurements plot on the line of identity. For internal/external rotation, points falling below the line of identity are underrepresentations of fixator-measured bone motion.

Table 2 Differences Between Bone-Fixed and Surface Cuff Measures of Humeral Translations for 20° Angular Increments

	Scapular plane abduction	Flexion	Internal/External rotation
Translation in x direction	1.4 (1.7)	1.3 (1.6)	0.1 (0.2)
Translation in y direction	2.1 (2.3)	0.4 (0.4)	0.2 (0.3)
Translation in z direction	0.4 (1.1)	0.8 (0.8)	0.5 (0.8)

Note: Measurements are averaged across trials and the root mean square differences between methods are given. Averages of rms differences considering individual trials are in parentheses.

rotation (Figure 2). The maximum deviation between the methods was 15.6°. All angular differences between the two techniques were consistent enough to reach statistical significance ($p < 0.05$).

The humeral helical axis translation measures were also highly similar between the surface humeral cuff as compared to the humeral fixator data (Table 2). Not unexpectedly, in several cases individual trial differences between the two techniques resulted in slightly higher rms differences than when comparing the trial means. The translational differences between the two techniques did not reach statistical significance except for the x-axis translation during flexion ($p < 0.05$).

Discussion

Overall, the humeral rotations are well described by the surface humeral cuff across a variety of arm motions, with the exception of humeral internal/external rotation when the arm is adducted at the side. These differences are likely attributable to the bone moving under the skin and not being fully captured by the surface cuff. Tracking of flexion and abduction angles were the least prone to error. Previous surface marker validation experiments in the lower extremity also demonstrated larger errors in tracking long axis rotations of a bone as compared to flexion/extension (Reinschmidt, van den Bogert, Murphy, Lundberg, & Nigg, 1997a; Reinschmidt, van den Bogert, Nigg, Lundberg, & Murphy, 1997b).

In skin marker validation studies, errors are also commonly expressed as a percentage of the total ROM for that angular rotation. If presenting the data from the current study in percentage format, rms errors range from as low as 1% for abduction to a high of 12% for external rotation when elevating the arm in the scapular plane. The worst-case error for this motion was 19% of the total range for humeral external rotation. When internally and externally rotating the adducted arm, the percent rms errors for internal/external rotation were 9% and the worst-case error was 20%. The mean angular differences between the surface sensors and bone sensors were statistically significant. However, the percent error values compare quite favorably with previously reported errors of 21–70% for 3-D knee rotations and 14–51% for 3-D ankle rotations (Reinschmidt et al., 1997a; 1997b).

Helical axis translation data were also well represented by the surface cuff as compared to the bone-fixed sensor. If using the mean of trials, the translations were described within 2 mm or less of the true translation, with the most caution required for anterior/posterior translation, where the rms overestimation of translation was 2.1 mm. The use of the mean of several trials is recommended, as this generally was found to reduce the measurement error.

Humeral data in this study were described relative to trunk and scapular markers that were skin-based, and reference frames were based on palpation and digitizing of anatomical landmarks. Errors in palpation and errors in thorax and scapular measurements due to skin-slip may occur to some degree (Karduna et al., 2001). However, as both methods of humeral motion tracking are described relative to the same reference frame, these other errors do not impact the rms errors for humeral motion measurement. Using trunk and scapular reference frames rather than a global reference frame allows humeral motions to be described about anatomically relevant axes. The errors described, however, are only for humeral motion measurement. Errors of glenohumeral measurement may be attributable to scapular skin-slip and palpation errors that are not accounted for in the humeral motion measurements.

The obvious primary limitation of this study is the restriction of data to a single participant under specific test conditions. Results may vary with one's age, weight, or general physical condition (Karduna et al., 2001), with different velocities of movement, or at different ranges of joint motion. The person in this study was tested at slow velocities of movement and did not have full ROM. Accordingly, the consistency of motion tracking for the single participant in this study may not be generalizable to others because of different test conditions. External fixation for humeral fractures is an uncommon procedure, and this participant presented a unique opportunity to compare a 3-D analysis between the commonly used surface marker technique and true motion of the underlying humerus.

The results of this study support the notion that certain dynamic measurements of humeral motion using a surface humeral cuff sensor can be performed with minimal error at slow velocities of movement. The largest errors occurred with underrepresentation of internal/external rotation. The extent to which various test conditions across different types of participants influence the consistency between these measurements will require further experimentation. However, these results represent the first presentation of the consistency between 3-D data obtained with surface and bone sensors during humeral movement. The ultimate acceptable accuracy of any measurement technique depends on the specific experimental conditions.

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