Capturing three-dimensional clavicle kinematics: a validation of surface sensor measurements

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Abstract: Despite conclusions from previous research that clavicle rotation is necessary for normal shoulder motion, dynamic clavicle rotations are rarely included in shoulder studies. This is likely due to the difficult nature in capturing clavicle motion. The purpose of this study was to determine the validity of non-invasive electromagnetic measures of dynamic clavicle motion against bone pin measurements. 3D rotations of the clavicle were collected simultaneously from a surface sensor and bone pin mounted sensor from six cadaveric shoulders. Intraclass correlation coefficients (ICCs) were calculated to determine the validity of the surface sensor measurements compared to the bone pin measurements. It was determined that the electromagnetic surface sensor accurately tracks retraction and elevation, but underestimates axial rotation. A mathematical equation was developed to improve the fit of surface sensor values for axial rotation. The strong ICC values for each clavicle rotation suggest that the surface sensor has utility in future shoulder research.

Keywords: clavicle kinematics; shoulder kinematics; validation; correction equation; intraclass correlation coefficients; ICCs.

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1 Introduction

Inman et al. (1944) reported that clavicle rotation at the sternoclavicular (SC) joint is necessary for full humerothoracic motion. Using bone pins and 2D radiographs, they determined that scapula rotation on the thorax is a combination of clavicle rotations at the SC joint and rotation of the scapula at the acromioclavicular (AC) joint. They also discovered that restricting motion of the clavicle resulted in reduced arm elevation angles. Despite the authors' conclusions as to the importance of the clavicle in shoulder motion, relatively few shoulder studies collect clavicle rotations in addition to scapular and humeral kinematics. One main reason for this lack of inclusion is that capturing dynamic three-dimensional clavicle rotations is difficult due to the slender, curved shape of the bone and skin motion artefact. The classic study by Inman et al. (1944) and a more recent study by Ludewig et al. (2004) described motion of the clavicle using transcortical bone pins. While both of these studies provide accurate values of normal clavicle rotation, bone pin measurements cannot be implemented as a standard data collection method due to the invasive nature of the procedure and the risks it imposes on study participants. Other studies have used an indirect method to calculate clavicle elevation and retraction based on scapular and thoracic landmarks, but this indirect method cannot calculate the third rotation, axial rotation (Ebaugh and Spinelli, 2009; Karduna et al., 2001; McClure et al., 2006). Once validated, a skin-based sensor would be more applicable than the above mentioned options for capturing 3D clavicle rotations in shoulder biomechanics research.

Currently, a common method for collecting 3D kinematics at the shoulder is a skin-based (surface) tracking sensor (Fayad et al., 2008; Hebert et al., 2002; Lin et al., 2005; Ludewig and Cook, 2000; McClure et al., 2006; Rundquist et al., 2003). Surface sensor measurements *for scapular and humeral rotations* have been established as valid when compared to measures from sensors attached to bone pins (Karduna et al., 2001; Ludewig et al., 2002). *Validity of surface sensor measurements for clavicle rotations in comparison to bone pin measurements has not yet been established.* Bone pin measurements are considered the gold standard since transcortical pins track bone motion without interference from skin motion artefact. Skin motion artefact occurs as the bone rotates under the skin and the skin does not fully move with the bone. A sensor taped to skin overlying a bony prominence may be limited in tracking bone rotation due to the skin 'lagging' behind the bone. *Due to the slender curved shape of the clavicle, it is possible that* skin *motion artefact will be present with surface sensor measurements. A comparison between surface sensor and bone pin measurements will demonstrate the amount of skin motion artefact that occurs with the skin-based sensor.*

Surface sensor measurements for the clavicle have previously been demonstrated to be reliable (Ludewig et al., 2004). The reliability study by Ludewig et al. (2004) demonstrated intra-class correlation coefficients (ICCs) for intra-rater reliability for the 3D clavicle rotations ranging from 0.94 for clavicle elevation/depression to 0.98 for long-axis rotation. For trial to trial reliability, arm elevation angles above 90° demonstrated increasing standard error of measurement (SEM) for axial rotation: 1.8° at 100° of elevation, and 2.1° at 115° of arm elevation. Between-day reliability, calculated with SEM, ranged from 2.7° for elevation/ depression to 4.0° for long-axis rotation during Sagittal plane abduction. While satisfactory reliability of the surface sensor is important the more significant test of the sensor's utility is the accuracy of the measurements (Karduna et al., 2001; Lundberg 1996).

The purpose of this study was to determine the validity of surface sensor measurements of clavicle rotation compared to bone-mounted measurements. *A key goal of this project is to determine the accuracy of using a surface sensor to measure clavicle rotations so that clavicle motion can be included in studies of human subjects. Describing the normal movement patterns of the clavicle will provide insight into potential pathology mechanisms.* Clavicle rotations were recorded simultaneously with both sensors to assess the concurrent validity, a form of criterion-related validity. It was hypothesised that skin motion artefact would influence the agreement between the sensors for all clavicle rotations at higher arm elevation angles. For clavicle rotations demonstrating a statistically significant difference between sensors, a correction equation was developed to improve the fit of the surface sensor values.

2 Methods

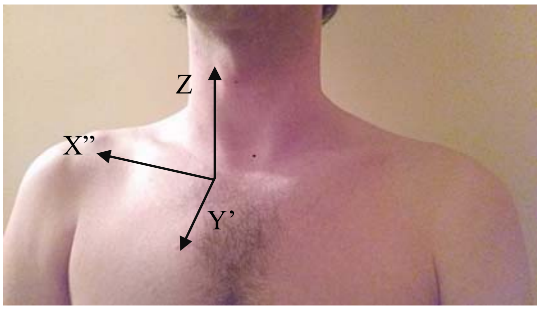
2.1 Subjects

Data were collected from nine shoulders of five fresh-frozen cadavers. Cadavers were thawed prior to testing. Cadaver specimens were full torsos with bilateral upper extremities not separated from the body. All specimens were male with a mean age of 75.0 years (±5.3 SD). Shoulders were taken through a full range of motion to assess movement limitations or joint crepitus and the tested shoulders were determined to be free of gross deformities and motion limitations. Exclusion criteria included a history of shoulder surgery or visible surgical scars on the shoulder. One extremity was excluded due to a humeral fracture.

2.2 Instrumentation

Three-dimensional kinematic data were collected from the thorax, humerus, and clavicle with the Flock of Birds electromagnetic tracking system (Ascension Technologies, Burlington, VT) and associated MotionMonitor software (Innovative Sports Training, Chicago, IL). A 0.8 cm Minibird sensor was secured to the skin overlying the sternum below the sternal notch with double-sided tape. The humeral sensor was contained in non-ferrous housing and inserted with a bone screw into the lateral humerus distal to the insertion of the deltoid muscle. The clavicle bone sensor was secured in non-ferrous housing and inserted with a bone screw near the midpoint of the bone. The clavicle surface sensor was taped to the skin overlying the clavicle, lateral to the bone pin (Figure 1). The skin around the bone pins was cut to minimise tension on the pins as the bones rotated. The sensors and housings were visually monitored during arm elevation to ensure the housings were not rotating on the bone pin. Housings were also checked before removal from the bony segments to ensure they had not loosened on the bone pin. A fifth minibird sensor was used to digitise anatomical landmarks to establish local coordinate systems for the thorax, humerus, and clavicle.

Figure 1 Clavicle sensor set-up (see online version for colours)



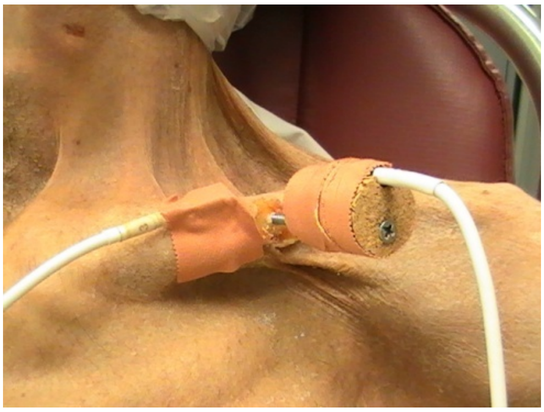
2.2.1 Clavicle surface sensor placement

Correct placement of the clavicle surface sensor required multiple attempts for the majority of the data collection procedures. The clavicle surface sensor was taped at the midpoint of the clavicle where the bone begins to turn concave. Before data collection, the arm was taken through passive range of motion and the surface sensor monitored to ensure that it was following the motion of the clavicle. For the majority of the specimens, the sensor demonstrated difficulty tracking the clavicle with the first attempt at placing the sensor. It was visually observed that if placed on different areas of the clavicle, the surface sensor would rotate anteriorly while the clavicle was rotating posteriorly. This issue was corrected in some specimens by changing the position of the surface sensor to a more anterior and lateral position on the clavicle where the bone is concave and the muscle mass is less bulky. When placed on the midpoint of the clavicle, where the bone begins to turn concave, and on the more anterior aspect of the bone, as opposed to the more cranial aspect, this position gives more consistent and physiologically representative data from the surface sensor (Figure 1).

2.3 Procedures

The cadaveric specimens were propped in an upright seated position on a gurney and secured to either a wooden support or the back of the gurney with all segments of the shoulder complex free to move. Three-dimensional kinematic data of the thorax, humerus and clavicle were collected as the specimen's arm was passively elevated five times each in the scapular plane. This plane was chosen as it is the functional plane of reach and regularly used for data collection in shoulder studies. Three-dimensional clavicle rotations (elevation/depression, retraction/protraction and anterior/posterior rotation) (Figure 2) were captured simultaneously from the surface sensor and bone pin sensor. Data were collected at a sampling rate of 100 Hz per sensor.

Figure 2 Clavicle coordinate system for three-dimensional rotations (see online version for colours)



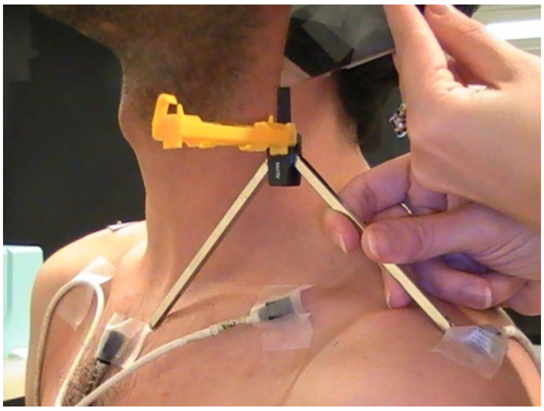
Notes: Rotation about Z axis: retraction/protraction. Rotation about Y’: elevation/depression. Rotation about X”: axial (anterior/posterior) rotation.

2.4 Data reduction

For the trunk, humerus, and clavicle, local coordinate systems were defined following the recommendations of the International Society of Biomechanics (Wu et al 2005). For the clavicle, the most superior aspect of the SC joint and the most dorsal aspect of the AC joint defined the laterally-oriented longitudinal axis. To create the anteriorly-oriented y-axis, the plane of the clavicle is established by digitising a third point. However, due to the shape of this bone, the third point cannot be digitised on the clavicle itself. To find the third point, an adjustable length triangle was constructed similar to that used in a previous study by Ludewig et al. (2004). The two ends of the base of the triangle were placed at the SC and AC joints and the triangle was levelled in the vertical plane (Figure 3). The apex of the levelled triangle was digitised as the third point (Teece et al., 2008). The plane of the clavicle is then created using the third point and the points digitised at the SC and AC joints. The anteriorly-oriented y-axis was mathematically calculated as perpendicular to the plane of the clavicle. The superiorly directed z-axis is the cross product of the clavicular x- and y-axes. The origin of the clavicle axis system was positioned at the SC joint (Figure 2).

Based on previously described recommendations (Wu et al., 2005), the clavicle z-axis was oriented vertically, aligned with the thoracic z-axis in the resting position. The custom designed triangular reference frame-oriented the clavicle z-axis near vertical; however for situations where the clavicle z-axis deviated from the thoracic z-axis, post-processing was done to realign the axes (Teece et al., 2008). To post-process this axis, the resting value of clavicle axial rotation was calculated and the inverse of this value was used to develop a correction rotations matrix. The direction cosines of clavicle axial rotation were multiplied by the correction rotation matrix and the resulting values were subsequently used for data analysis to represent clavicle axial rotation.

Figure 3 This custom-designed triangular reference frame with bubble level was used to find the third point of the clavicle (see online version for colours)



Clavicle and humeral rotations were described relative to the thorax using Euler angle sequences. The humerus follows a Z, Y', Z" sequence, with rotation around the thoracic Z defining the plane of elevation, about the humeral Y' the angle of elevation, and about the humeral Z" internal/external rotation of the humerus. Clavicle rotations with respect to the thorax follow a Z, Y', X" sequence, with rotation about the thoracic Z describing protraction/retraction, about the clavicular Y' elevation/depression, and about the clavicular X" anterior/posterior rotation (Wu et al., 2005).

2.5 Data analysis

2.5.1 Validity of surface sensor measurements

A one-factor repeated measures analysis of variance (ANOVA) was run with clavicle sensor (bone pin and surface sensor) as the within-subject factor at every 5° of humerothoracic elevation. The dependent variables were the three-dimensional clavicle rotations (retraction, elevation, posterior rotation), recorded simultaneously from the clavicle bone pin sensor and surface sensor. Clavicle rotations were averaged across the 2nd, 3rd, and 4th repetitions of arm motion and pooled across the elevation and lowering phases of arm motion.

To determine the concurrent validity of the surface sensor measurements compared to the bone pin measurements, intraclass correlation coefficients ($ICC_{2,k}$) were calculated using the mean standard error from a one-factor ANOVA. ICCs are a ratio of between subject and total variability and therefore require variance in the data for the ICC to be meaningful (Portney and Watkins, 2009; Shrout and Fleiss, 1979). Post-processing the position of the z-axis greatly reduced the between subject variability, affecting the ICC estimates. Therefore, the ANOVA to calculate the ICCs was run with axial rotation values derived using the original z-axis position, not post-processed with the correction rotation matrix.

As the purpose of this study was to generalise the results of the surface sensor to other sensor types, the two sensor methods (bone and skin) were considered the 'raters' (Shrout and Fleiss, 1979). ICC model 2, k was used (Shrout and Fleiss, 1979) in order to generalise the results of raters (or sensors) to other potential judges. For concurrent validity, correlation values close to 1.0 suggest the untested measurement tool is a valid predictor of the gold standard (Portney and Watkins, 2009). Additionally, ICCs greater than 0.75 are considered good reliability, less than .75 considered moderate to poor reliability.

An overall $ICC_{2,k}$ was calculated across the entire range of arm elevation (30°–120°) for each clavicle rotation. ICCs were also calculated at 15° intervals (30°, 45°, 60°, 75°, 90°, 105°, 120°) of arm motion to develop a more comprehensive picture of how well the surface sensor captures clavicle motion as more error is hypothesised at higher angles of arm motion due to skin motion artefact (Karduna et al., 2001).

Due to instrumentation error, the data from one shoulder was removed from the analysis. Following data analysis, data from two shoulders were identified as outliers, resulting in large between subject variability. These data were removed and the data analysis re-run with six shoulders.

2.5.2 Correcting surface sensor measurements

A second one-factor repeated measures ANOVA was run with axial rotation values derived with the z-axis post-processed. Results from this analysis were used to improve the accuracy of the surface sensor measurements by developing correction equations for clavicle rotations with statistical differences between sensors. In current research of 3D clavicle motion (Teece et al., 2008), it is standard procedure to post-process the clavicle z-axis so using the results from this ANOVA to develop a correction equation is more applicable for future clavicle and shoulder studies.

For rotations with statistically significant differences between sensors ($p \leq 0.05$), determined with this one-factor repeated measures ANOVA, a correction equation was developed using a regression analysis for any clavicle rotation with a statistical effect of sensor.

To evaluate the overall quality of the regression model, the root mean square error (RMSE) was calculated before and after application of the correction equation.

3 Results

3.1 Validity

The results of the one-factor, repeated measures ANOVA used to calculate the overall and individual ICCs are reported in Table 1. The ICC estimates for the three clavicle rotations are presented in Table 2. The overall ICCs are good for each clavicle rotation, though the ICC for axial rotation is notably lower than the other two rotations. Examining the ICCs at 15° increments, it appears that the surface sensor and bone pin measurements are concurrent throughout the range of arm elevation for clavicle retraction. The interval ICCs are good for clavicle elevation and axial rotation through 90°, moderate at 105°, and poor at 120°.

Table 1 ANOVA results for 3D clavicle rotations; mean square values used to calculate the overall and individual ICCs

Clavicle rotation	*Factor*	*Mean square*	*F-ratio*	*p-value*
Retraction	Subject	7,854.03		
	Sensor	371.04	1.93	0.22
	Subject × sensor	192.56		
Elevation	Subject	3,541.58		
	Sensor	379.61	1.35	0.30
	Subject × sensor	280.39		
Axial Rotation	Subject	10,330.05		
	Sensor	8,063.01	7.13	0.04*
	Subject × Sensor	1,131.46		

Note: *Indicates statistical significance at $p < 0.05$.

Table 2 ICCs for each clavicle rotation

Humerothoracic elevation	*Retraction*	*Elevation*	*Axial rotation*
Overall ICC	0.97	0.92	0.80
30°	0.95	0.97	0.91
45°	0.96	0.96	0.91
60°	0.96	0.94	0.90
75°	0.97	0.91	0.87
90°	0.98	0.87	0.82
105°	0.93	0.79	0.69
120°	0.93	0.47	0.30

3.2 Correcting surface sensor measurements

The results of the one-factor, repeated measures ANOVA, run with clavicle axial rotation values with the z-axis post-processed are reported in Table 3. A statistically significant main effect of sensor with this ANOVA was used to determine if a correction equation was necessary for axial rotation. For clavicle retraction and elevation, the results of the ANOVA in Table 1 were used for determining if a correction equation is necessary. There was a statistically significant main effect of sensor for clavicle axial rotation only. The surface sensor underestimated overall axial rotation by 8.1° (Table 4).

The group mean values of each clavicle rotation were graphed to provide a visual representation of the difference between the sensor measurements [Figures 4(a) to 4(c)]. Upon visual inspection, mean rotation values captured with the surface sensor closely follow the bone pin values for clavicle retraction and elevation. For axial rotation, the surface sensor does not track the bone rotation, and the offset between the sensors increases with higher arm angles.

Table 3 ANOVA results for clavicle axial rotation with the z-axis post-process

Clavicle rotation	*Factor*	*Mean square*	*F-ratio*	*p-value*
Axial rotation	Subject	737.00		
	Sensor	7,920.71	29.94	0.003*
	Subject × sensor	264.55		

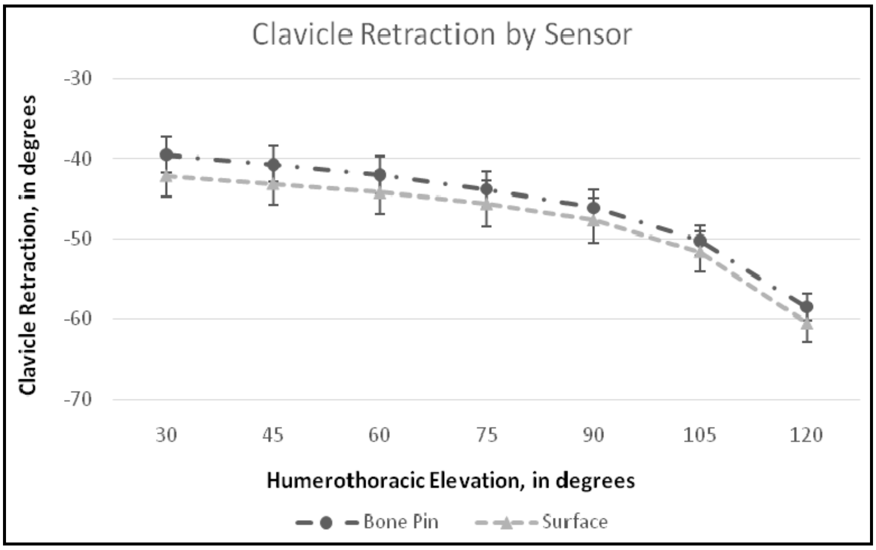
Note: *Indicates statistical significance at p < 0.05.

Table 4 Means (±SE) of clavicle rotations in degrees between sensors

Clavicle rotation	*Mean bone pin value (SE)*	*Mean surface value (SE)*	*Difference*
Retraction	–45.1° (±0.91)	–46.9° (±1.0)	+1.8°
Elevation	–12.8° (±0.53)	–11.1° (±0.67)	–1.7°
Posterior rotation	6.3° (±0.44)	–1.8° (±0.28)	+8.1°*

Note: *Indicates statistical significance at p < 0.05.

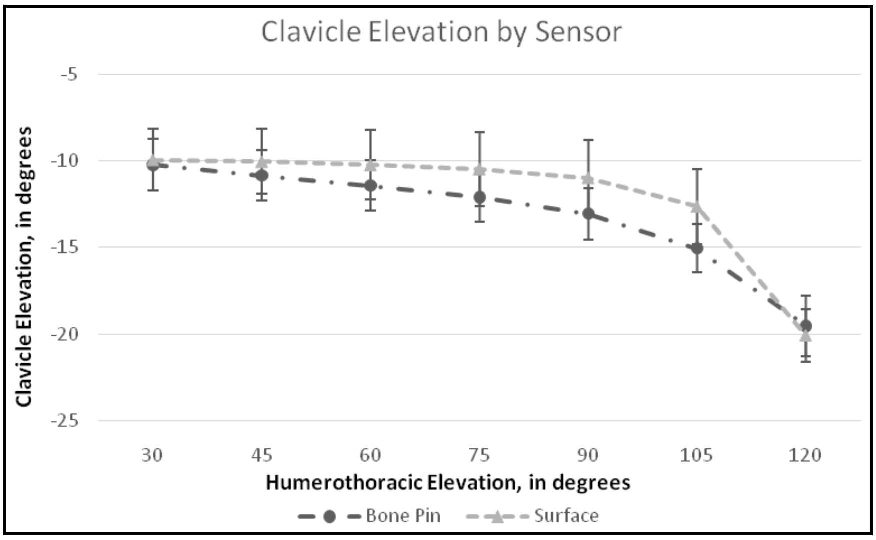
Figure 4 (a) Mean (±SE) clavicle retraction by sensor* (b) Mean (±SE) clavicle elevation by sensor** (c) Mean (±SE) clavicle axial rotation by sensor and with correction equation



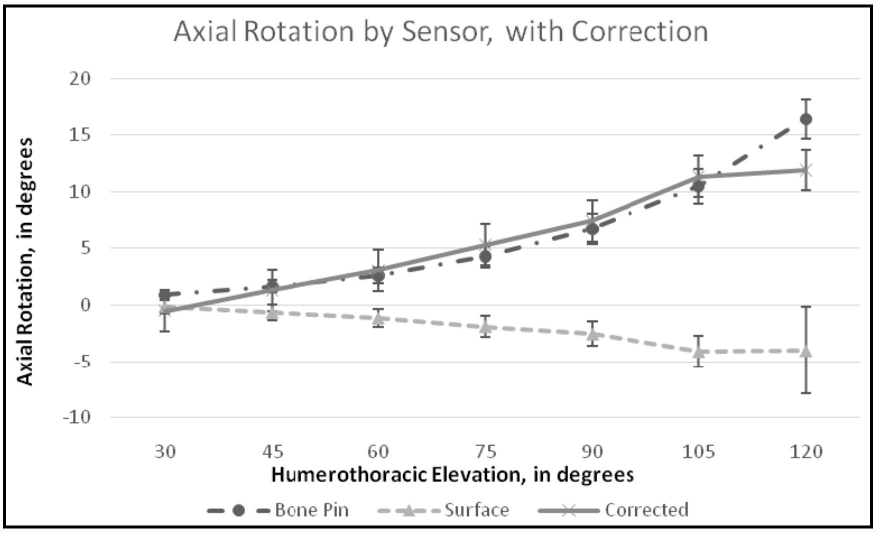
(a)

Notes: *Increasing negative values represent retraction.
**Increasing negative values represent elevation.
***Increasing positive values represent posterior rotation.

Figure 4 (a) Mean (±SE) clavicle retraction by sensor* (b) Mean (±SE) clavicle elevation by sensor** (c) Mean (±SE) clavicle axial rotation by sensor and with correction equation (continued)



(b)



(c)

Notes: *Increasing negative values represent retraction.
**Increasing negative values represent elevation.
***Increasing positive values represent posterior rotation.

3.2.1 Developing the correction equation

As axial rotation demonstrated decreased agreement between sensors at higher arm elevation angles, the correction equation was developed using multiple linear regression. Arm angle and surface sensor measurement were included as potential predictors.

$$\begin{array}{l}\text{Correction equations}:\\ \text{ClavicleAxial rotation}\\ (-2.28)+(0.05\times\text{Angle})+(-2.02\times\text{Surface value})\end{array}$$

The correction equation was applied to individual mean values and the group means of clavicle axial rotation was then calculated. Figure 4(c) shows the group mean surface values for axial rotation after application of the correction equation and the bone pin measurements.

RMSE values for axial rotation calculated before and after application of the correction equation are presented in Table 5. Application of the correction equation greatly reduced the RMSE for group data.

Table 5 RMSE values before and after correction equation

Humerothoracic angle	*Before correction*	*After correction*
30°	0.42	0.67
45°	0.98	0.19
60°	3.46	1.31
75°	11.30	1.50
90°	30.82	0.42
105°	76.66	0.80
120°	76.27	1.38
120°	114.19	0.72
105°	94.93	3.44
90°	40.32	0.01
75°	16.53	0.31
60°	5.16	0.60
45°	2.00	0.00
30°	1.69	2.18
Overall	5.82	0.98

4 Discussion

In general, the strong ICC values for each of the three clavicle rotations suggest that the surface sensor is an accurate measure for three-dimensional clavicle rotation. The ICC model 2, k includes the between sensor variance, so it is a combined measure of agreement and consistency (McGraw and Wong, 1996; Shrout and Fleiss, 1979), therefore, the generally high ICCs for the three clavicle rotations suggest good agreement and consistency between the two sensors. Despite these strong ICCs, statistical analysis and visual inspection of the data demonstrates that the surface sensor underestimates axial rotation while closely tracking clavicle retraction and elevation.

Due to the statistical difference between the bone and surface sensor for axial rotation, a correction equation was developed to improve the fit of the surface sensor measures. The ICC values for this rotation support developing a correction equation as differences between sensors are consistent between subjects. The correction equation was developed using group mean data and applied to individual mean values to calculate corrected group mean values. Application of the correction equation to the surface sensor measurements improved the fit of these values, as demonstrated by the increased RMSE values. Initially the correction equation was created using individual data, but this method resulted in poor R^2 values in the regression analysis. Using group mean data is consistent with the process and results achieved by Meskers et al. (2007) in creating a correction equation for scapular motion captured with a surface sensor. The correction equation, when applied to individual data, improves group means and allows for between group comparisons.

It was anticipated that the surface sensor would deviate from the bone pin measurements at higher arm elevation angles due to the inability of the surface sensor to follow the bone and skin motion artefact. This was observed for axial rotation in the graphs of the mean values from each sensor and with decreased ICC values at higher arm angles for clavicle elevation and posterior axial rotation. These observations are consistent with the previous reliability study by Ludewig et al. (2004) which demonstrated good reliability of the surface sensor up to approximately 100° of humeral elevation. While this may limit the utility of the surface sensor somewhat, clavicle rotation values up to 90° of arm elevation still provide valuable information. The majority of clavicle elevation and retraction occurs by 90° of arm elevation (Ludewig et al., 2009), so if there are changes in the magnitude of these rotations, it will likely be captured by the surface sensor. Additionally, applying the correction equation to the surface sensor measurements improved the fit of the surface sensor values across the full range of arm elevation and RMSE values.

We experienced difficulty with placement of the sensor on the clavicle that affected data collection. It was visually observed that if placed on different areas of the clavicle, the surface sensor would not track the clavicle during axial posterior rotation and instead would rotate anteriorly. This could be corrected in some specimens by changing the position of the surface sensor to a more anterior and lateral position on the clavicle where the bone is concave and the muscle mass is less bulky. But for some specimens, the positioning would not correct the problem and anterior rotation continued to be recorded by the surface sensor. Overall, the best position for the sensor based on our trials is near the midpoint of the bone where it becomes concave. This position prevents interference from muscle bulk as the arm is elevating. Also, placing the sensor on the anterior aspect of the bone as opposed to the superior aspect allows the sensor to track the bone better. Visual observation of both the sensor and real-time data is necessary when setting up the sensor on subjects to ensure that axial rotation is being captured.

A primary goal of this study was to develop a valid measure of clavicle rotations that is easy to incorporate into a typical shoulder data collection protocol. Other measurement options that have been explored for capturing clavicle rotation include MRI (Fung et al., 2001; Sahara et al., 2007) and static palpation techniques (Marchese and Johnson, 2001). Clavicle rotation values obtained by a vertically open MRI are consistent with previous bone pin studies; however this data collection method is not commonly used for 3D kinematic studies of the shoulder. Most current studies capture kinematic data with a motion analysis system similar to the one used for this study. The limited availability and cost of a vertically open MRI system may make it difficult to implement into most study designs (Graichen et al., 2000; Karduna et al., 2001). Some study designs capture 3D kinematics statically versus dynamically (Marchese and Johnson, 2001). To do this with the clavicle, landmarks are palpated and tracked at specific angles of arm elevation. An algorithm is developed to predict the amount of clavicle rotation that occurs over the range of arm motion. This method has not been validated against true bony measurements and the static measurements do not represent smooth dynamic arm motion and are prone to error from repeated measurements of the bony landmarks (de Groot, 1997). In this current study, we captured dynamic, passive rotation with a surface sensor. The clavicle rotation values captured with the surface sensor during passive arm motion were consistent with values reported in the previous study by Ludewig et al. (2004) that tracked active bone rotation with bone pins. This further supports that the surface sensor is an accurate measure of bone rotation.

While the clavicle surface sensor demonstrates some error due to skin motion artefact, the strong ICC values for each clavicle rotation suggest that the surface sensor has utility in future shoulder research. However, for axial rotation especially, further research is needed to determine if it may be possible to instead model this rotation using humeral elevation values or a combination of humeral and scapular rotations.

5 Limitations

The initial power analysis determined nine shoulders were needed to find statistically significant differences at alpha = 0.05 with 80% power; however, due to equipment and measurement issues, only six shoulders were included in the analysis. The small sample size and therefore low power increases the risk of making a Type II error in assuming there was no statistical difference between sensors for clavicle retraction or elevation in the scapular plane.

This study was completed with passive motion therefore it excludes the active tension that affects bony movement. Because bone pin placement is an invasive procedure, with many risks, a reasonable alternative is capturing passive motion using cadaver specimens. Teece and colleagues captured both active (*in vivo*) and passive (cadaver) movement patterns of the AC joint (Teece et al., 2008). The movement patterns of the AC joint were consistent for each rotation (upward rotation, internal rotation and posterior tilting) between active and passive conditions, though there was an offset in the values for upward rotation and posterior tilting which the authors attributed to a lack of active muscle tension. These findings support the use of cadaver specimens in this validation study as the movement patterns will be comparable to active motion, while avoiding the risks associated with transcortical pin placement. However, the use of passive movement may affect the correction equation developed for use with the clavicle surface sensor when applied *in vivo*. To assess the utility of the surface sensor and the correction equation for capturing clavicle rotations, a follow-up study should be completed using the surface sensor to capture active clavicle motion.

6 Conclusions

Based on the calculated ICCs, the clavicle surface sensor appears to be a valid tool for capturing the three-dimensional rotations of the clavicle. However, due to skin slip, the surface sensor measurements for axial rotation in the functional plane need to be corrected. The correction equation developed in this study is based on arm elevation angle so while the correction equation improves the values of axial rotation, it may be possible to instead model these values based on humeral elevation angle. Capturing clavicle motion along with scapular and humeral motion is important in order to develop a more complete picture of shoulder complex motion in both normal and pathology populations. Therefore, follow-up studies are needed to assess the utility of the surface sensor for capturing active clavicle motion in healthy populations for application in pathology populations.

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