Measuring Three-Dimensional Thorax Motion Via Biplane Radiographic Imaging: Technique and Preliminary Results

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Measures of scapulothoracic motion are dependent on accurate imaging of the scapula and thorax. Advanced radiographic techniques can provide accurate measures of scapular motion, but the limited 3D imaging volume of these techniques often precludes measurement of thorax motion. To overcome this, a thorax coordinate system was defined based on the position of rib pairs and then compared to a conventional sternum/spine-based thorax coordinate system. Alignment of the rib-based coordinate system was dependent on the rib pairs used, with the rib3:rib4 pairing aligned to within 4.4 ± 2.1 deg of the conventional thorax coordinate system. [DOI: 10.1115/1.4032058]

Introduction

Motion of the shoulder is accomplished through a complex coordination of the glenohumeral, scapulothoracic, and acromioclavicular joints. Scapulothoracic motion is of significant clinical interest, with scapular dyskinesis (i.e., altered motion of the scapula) believed to be a nonspecific response to pain due to various shoulder pathologies [1–4]. Consequently, nonoperative clinical interventions such as physical therapy exercises often target the scapular stabilizing muscles in the belief that restoring normal scapulothoracic motion will help to alleviate symptoms [5,6].

Extensive research efforts have focused on characterizing scapulothoracic motion in healthy shoulders (e.g., Refs. [7–9]), as well as understanding how scapulothoracic motion is affected by factors such as fatigue (e.g., Ref. [10]), pathology (e.g., Refs. [11–13]), and treatment (e.g., Ref. [14]). Scapulothoracic motion is typically expressed in terms of anterior/posterior tilt, upward/downward rotation, and internal/external rotation. Previously reported values for scapulothoracic motion often vary considerably between research studies, but it is generally understood that upward/downward rotation is the scapula's predominant motion, with approximately 50 deg of upward rotation in healthy shoulders during scapular-plane elevation [9]. McClure et al. have also reported that scapular motion involves approximately 30 deg of posterior tilt and 24 deg of external rotation during scapular-plane elevation in healthy subjects [9].

The primary experimental approach for measuring scapulothoracic motion has involved the use of optical or electromagnetic motion capture systems with skin-mounted markers or sensors (e.g., Refs. [11,15–17]). More recently, scapular motion has been measured by recording radiographic images of the shoulder with biplane X-ray [18,19], dual-plane fluoroscopy [20], and single-plane fluoroscopy [21,22] systems, and then tracking the scapula's pose by registering a 3D bone model to the radiographic images based on its 3D shape and radiographic density [19,22,23]. These radiographic-based techniques typically offer higher in vivo accuracy compared to conventional motion capture systems, but the relatively small imaging volume is a significant limitation of this approach. Specifically, the imaging volume of currently available radiographic image intensifiers is typically not large enough to simultaneously visualize the sternum and spine medially—i.e., the anatomical landmarks that are commonly used to define the thorax coordinate system with conventional motion capture systems—and enough of the humeral shaft laterally to enable shape-based tracking with high accuracy. Consequently, these radiographic approaches have assessed only glenohumeral joint motion [20,24–26] or have reported scapulothoracic motion by expressing motion of the scapula relative to an external reference (e.g., the ground [27]) instead of the thorax. These alternative approaches for reporting scapular motion limit the physiological meaning of the rotations as they are not described relative to an anatomical coordinate system and also incorporate thoracic motion into their values.

To overcome the difficulty in quantifying scapulothoracic motion from radiographic images in a limited imaging volume, our research team has recently developed an approach for measuring motion of the thorax by tracking the 3D position and orientation of multiple ribs. Thus, the primary objectives of this paper are to describe the use of this radiographic-based technique for measuring thorax motion and to assess the accuracy of this approach. As a secondary objective, we also present preliminary data on scapulothoracic motion using this new approach.

Methods

To assess the accuracy of a rib-based thorax coordinate system, computed tomography (CT) scans were acquired from five subjects (average age: 59.4 ± 9.9) participating in an IRB-approved

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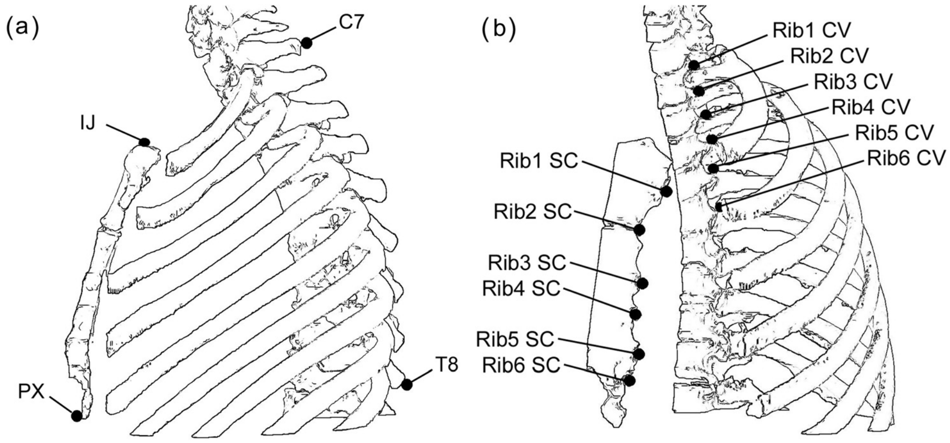

Fig. 1 Anatomical landmark definitions used in thorax coordinate system construction for (*a*) the conventional thorax coordinate system promoted by the International Society of Biomechanics (ISB) [28] and (*b*) rib-based thorax coordinate systems, based on all possible rib-pair combinations of rib1–rib6 (rib1:rib2, rib1:rib3, … , rib5:rib6)

study on the efficacy of physical therapy for patients with a rotator cuff tear. The CT scan encompassed the lateral half of the thorax, including the entire humerus and scapula. Using these CT images, we compared 15 rib-based thorax coordinate systems to a more conventional (i.e., sternum/spine-based) thorax coordinate system. The conventional coordinate system was based on the standard endorsed by the International Society of Biomechanics (ISB) [28]. To create this conventional coordinate system, the first step involved identifying on each CT scan the deepest point of incisura jugularis (IJ) and the most caudal point of the processus xiphoideus (PX) on the sternum and the spinous processes of the seventh cervical (C7) and eighth thoracic (T8) vertebrae (Fig. 1(*a*)). The origin of this coordinate system was defined as the location of the IJ. The superior/inferior (S/I) axis was defined as a line connecting the midpoint between PX and T8 to the midpoint between IJ and C7. The medial/lateral (M/L) axis was defined as the line perpendicular to the plane formed by IJ, C7, and the midpoint between PX and T8. The anterior/posterior (A/P) axis was defined as the cross product of the S/I and M/L axes.

The 15 rib-based thorax coordinate systems were then defined based on every rib-pair combination of rib1–rib6 (i.e., rib1:rib2, rib1:rib3, … , rib5:rib6). These thorax coordinate systems were created from the CT scans by first identifying on each rib the costovertebral (CV) joint (i.e., articulation between the rib and vertebral body) and the sternocostal (SC) joint (i.e., articulation between rib and sternum) (Fig. 1(*b*)). These landmarks were chosen since they are easily identifiable, closely approximate the landmarks used to define the conventional thorax coordinate system, and are minimally affected by inter-rib motion associated with respiration. For each rib pair, the origin of the thorax coordinate system was defined as the SC joint of the superior rib. The S/I axis of the thorax coordinate system was defined as the vector from the midpoint of the inferior rib's CV and SC joints to the midpoint of the superior rib's CV and SC joints. The M/L axis was defined as a vector perpendicular to the plane created by the CV and SC joint of the superior rib and the midpoint between the SC and CV joint of the inferior rib pointing to the right. Finally, the A/P axis was defined as the cross product of the superior/inferior and M/L axes.

To compare the rib-based and sternum/spine-based thorax coordinate systems (Fig. 2), we calculated the three-dimensional transformation matrix necessary to express the rib-based coordinate system relative to the conventional sternum/spine-based coordinate system. Specifically, a Cardan angle rotation sequence was used based on the standard defined for scapular rotation about the thorax [28]. The rationale for this approach is that it would provide an indication of how differences in coordinate system alignment would propagate to measures of scapulothoracic motion. Rotations were performed about the sternum/spine-based coordinate system axes in the following order: S/I-A/P-M/L. Using this approach, the misalignment of each rib-based coordinate system was expressed in terms of anterior/posterior tilt (i.e., rotation about M/L axis), upward/downward rotation (i.e., rotation about A/P axis), and internal/external rotation (i.e., rotation about S/I axis) relative to the sternum/spine-based coordinate system. In addition, we used these three rotational measures of misalignment to determine a single composite measure of coordinate system misalignment. Specifically, we calculated the RMS error between the rib-based and conventional coordinate systems for each rib-pair coordinate system and then averaged these RMS errors across the five subjects.

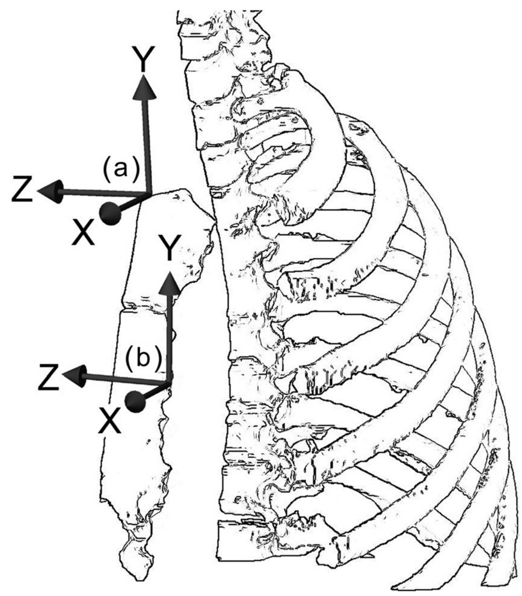

Fig. 2 Comparison of the conventional thorax coordinate system promoted by the ISB (*A*) and the rib-based coordinate system (*B*)

To demonstrate the utility of using a rib-based thorax coordinate system, three of the patients were positioned with their shoulder and upper thorax centered within the 3D imaging volume of a custom biplane X-ray system. X-ray images were acquired at 60 Hz for 2 s using two high-speed video cameras (v9.1; Vision Research, Wayne, NJ). These radiographic images were acquired during coronal-plane abduction, beginning with the subject's arm at his/her side and ending at approximately 120 deg of humerothoracic abduction. Three trials were recorded for each subject's dominant shoulder. As a part of the image-based tracking technique [19], 3D bone models were reconstructed from the CT images for the humerus, scapula, and ribs by segmenting them from surrounding bones and soft tissues (Mimics version 16.0, Materialise Corp., Leuven, Belgium). The bone models were then interpolated and scaled to have cubic voxels with dimensions similar to the pixel size of the X-ray images. Using these bone models, the 3D position and orientation of each bone were determined from the biplane X-ray images using a model-based tracking technique [19]. The accuracy of this technique has been shown to range from approximately 0.5 to 1.0 mm and 0.5 to 1.0 deg for the shoulder [19], knee [29,30], elbow [31], cervical spine [32], and hip [33].

Scapulothoracic and humerothoracic motions were determined by transforming the 3D poses of the humerus and scapula into the rib-based thoracic coordinate system described above. Scapulothoracic motion was expressed in terms of anterior/posterior tilting, upward/downward rotation, and internal/external rotation. Humerothoracic motion was expressed in terms of the plane of humerothoracic abduction, the humerothoracic abduction angle, and the axial rotation. In addition, inter-rib motion was assessed by calculating the relative translation and rotation between rib pairs. To accomplish this, we first determined the midpoint between the SC and CV landmarks for each rib and then calculated the variation in the distance between the inferior and superior rib midpoints for each trial. Relative inter-rib rotation was calculated for each trial as rotation about the S/I axis of the thorax coordinate system.

Results

Alignment of the rib-based coordinate system with the conventional sternum/spine-based coordinate system was highly dependent on the rib pairs used to construct the thorax coordinate system (Table 1). Specifically, misalignment of anterior/posterior tilt ranged from 0.4 ± 2.2 deg posterior (rib1:rib3) to 7.9 ± 3.4 deg anterior (rib4:rib5), with the rib1:rib3 pair being closest to zero (0.4 ± 2.2 deg posterior). Misalignment of upward/downward rotation ranged from 24.8 ± 5.0 deg upward (rib1:rib2) to 2.3 ± 5.5 deg downward (rib2:rib3), with the rib3:rib5 pair being closest to zero (0.1 ± 2.2 deg upward). Internal/external rotation misalignment ranged from 8.0 ± 7.4 deg internal (rib2:rib3) to 37.4 ± 8.2 deg external (rib1:rib2), with the rib4:rib6 pair being closest to zero (0.7 ± 5.4 deg internal). Composite rib-pair misalignment values (reported as RMS) ranged from 4.4 ± 2.1 deg (rib3:rib4) to 26.1 ± 5.4 deg (rib1:rib2).

Using the thorax coordinate system defined by the rib pair with the least overall misalignment (rib3:rib4), scapulothoracic motion was determined from 40 deg to 120 deg of humerothoracic elevation for three of the patients. At 40 deg of humerothoracic elevation, the scapula was in an orientation of 7 ± 2 deg posterior tilt, 11 ± 4 deg of upward rotation, and 36 ± 11 deg of internal rotation (Fig. 3). At 120 deg of humerothoracic elevation, the scapula was in an orientation of 33 ± 3 deg posterior tilt, 35 ± 1 deg of upward rotation, and 43 ± 12 deg of internal rotation (Fig. 3). For rib3:rib4, inter-rib motion was found to be an average of 0.58 ± 0.17 mm and 1.31 ± 0.58 deg across all trials. These data correspond to a coefficient of variation of 2.8 ± 1.0%.

Discussion

The results indicate that the rib3:rib4 pairing produces a rib-based thorax coordinate system that is most closely aligned with the conventional thorax coordinate system when all three rotations are taken into consideration (RMS = 4.4 ± 2.1 deg, Table 1). This finding is fortuitous because ribs 3 and 4 are easily visualized in biplane X-ray images whose fields of view have been optimized to visualize the humerus and scapula during shoulder elevation. Rib-pair combinations rib3:rib5 and rib4:rib5 also produce similar overall misalignment (Table 1) and are viable alternatives because rib5 can be consistently visualized during shoulder elevation. In contrast, while several rib pairings involving rib6 generally produce a well-aligned coordinate system, these pairings are less optimal from a practical perspective as maintaining rib6 in the biplane X-ray system's field of view is unreliable when assessing shoulder elevation.

Previously reported values for scapulothoracic motion often vary considerably between research studies, but it is generally understood that upward rotation is the scapula's predominant motion during shoulder elevation. McClure et al. reported scapulothoracic motion during shoulder elevation in healthy volunteers [9]. Restricting their reported data to 40–120 deg of humerothoracic elevation (i.e., the range over which data in the current study are captured) indicates ranges of scapular motion of approximately 28 deg of upward rotation, approximately 10 deg of

Table 1 Misalignment of rib-based coordinate systems relative to the conventional thorax coordinate system endorsed by the International Society of Biomechanics (ISB) [28] was calculated in terms of anterior/posterior tilt, upward/downward rotation, and internal/external rotation. In addition, the three rotations were used to calculate the RMS error as a single composite measure of coordinate system misalignment.

Rib pairs		Rib-based coordinate system misalignment			
Superior	Inferior	Ant/post tilt (deg)	Up/down rotation (deg)	Int/ext rotation (deg)	RMS error (deg)
rib1	rib2	2.3 ± 5.5	−24.8 ± 5.0	37.4 ± 8.2	26.1 ± 5.4
	rib3	−0.4 ± 2.2	−10.3 ± 4.6	20.4 ± 6.9	13.3 ± 4.7
	rib4	0.5 ± 1.5	−5.9 ± 2.5	15.8 ± 5.1	9.8 ± 3.1
	rib5	2.1 ± 1.1	−4.2 ± 1.6	14.1 ± 4.2	8.6 ± 2.5
	rib6	2.7 ± 2.2	−3.8 ± 1.7	13.7 ± 4.2	8.5 ± 2.4
rib2	rib3	6.6 ± 4.7	2.3 ± 5.5	−8.0 ± 7.4	7.7 ± 2.9
	rib4	5.6 ± 2.3	1.7 ± 2.4	−7.4 ± 5.7	6.1 ± 2.4
	rib5	6.3 ± 1.9	0.7 ± 1.5	−6.6 ± 5.1	5.8 ± 1.8
	rib6	6.1 ± 2.0	−0.1 ± 2.2	−5.9 ± 5.1	5.5 ± 1.8
rib3	rib4	4.7 ± 2.3	1.2 ± 2.5	−4.3 ± 4.8	4.4 ± 2.1
	rib5	6.2 ± 2.6	−0.1 ± 2.2	−3.4 ± 4.3	4.7 ± 1.7
	rib6	6.1 ± 2.9	−0.8 ± 3.2	−2.8 ± 4.6	4.7 ± 2.1
rib4	rib5	7.9 ± 3.4	−1.2 ± 2.4	−1.2 ± 4.8	5.5 ± 1.6
	rib6	6.9 ± 3.3	−1.9 ± 4.0	−0.7 ± 5.4	5.3 ± 2.1
rib5	rib6	5.5 ± 6.0	−2.4 ± 6.5	−1.4 ± 7.1	6.3 ± 3.0

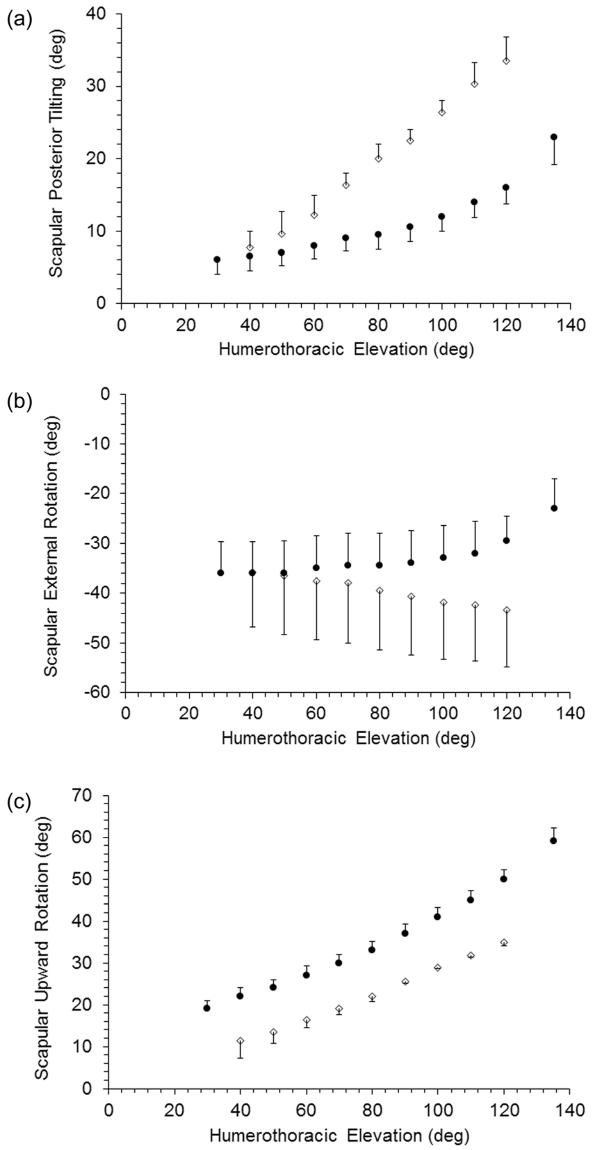

Fig. 3 Comparison of scapulothoracic motion between the current study (◇) and data previously reported by McClure et al. [9] (•) in terms of anterior/posterior tilting (*a*), internal/external rotation (*b*), and upward/downward rotation (*c*). The data from the current study are reported as mean (±SD) of three patients, whereas the McClure data are from eight healthy subjects.

posterior tilt, and approximately 6 deg of external rotation [9]. In comparison, the ranges of scapulothoracic motion in the current study are 23.6 ± 3.3 deg of upward rotation, 25.7 ± 5.3 deg of posterior tilt, and 7.5 ± 0.8 deg of external rotation (Fig. 3) which can be considered to be in reasonable agreement with the data reported by McClure et al. The discrepancies observed between the two datasets can primarily be attributed to differences in measurement techniques (electromagnetic pin/skin-mounted versus noninvasive radiographic) and subject populations (i.e., healthy versus pathologic), with a small offset attributable to differing coordinate system definitions.

This study presents a new approach for assessing thorax motion and describing scapular rotations with physiological meaning during biplane X-ray imaging. The primary advantage of this approach is that it has, for the first time, enabled biplane X-ray kinematic tracking techniques to describe the shoulder's scapulothoracic motion with the same level of physiological meaning as electromagnetic/optical tracking techniques while avoiding the motion errors associated with skin-mounted markers or sensors. Furthermore, establishing a rib-based thorax coordinate system allows us to calculate 3D glenohumeral, scapulothoracic, and humerothoracic motions from a single imaging modality. A limitation of this study is that the accuracy results are likely influenced by the uncertainty of the model-based tracking technique (i.e., rib tracking accuracy has not specifically been validated), but this technique has been shown to be accurate to within $\pm$ 0.5–1.0 deg for a variety of anatomical joints [19,29–33]. The above validation has provided a new technique which can augment existing biplane X-ray kinematic tracking methodologies and improve their ability to assess the effects of pathologic conditions and clinical interventions on scapulothoracic motion.

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