**Skin-fixed scapula trackers: a comparison of two dynamic methods across a range of
calibration positions**

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Abstract

The aim of this study was to establish the optimal methodology for skin-fixed measurement of the scapula during dynamic movement. This was achieved by comparing an optimally positioned Scapula Tracker device (ST) to a previously described palpation device; taken as the true measure of scapular kinematics. These measurements were compared over a range of calibration positions, including a heterogeneous 'multiple' calibration, in order to establish an optimal calibration approach. 10 Subjects' scapular motion was measured using this ST and an acromial method. The two datasets were compared at a standard, an optimal and a 'multiple' calibration position, thus allowing a direct comparison between two common skin-fixed methods to track the bony kinematics of the scapula across different calibration positions. A comparison was also made with a bone-fixed technique from the literature. At both the standard and optimal calibration positions the ST was shown to be the more accurate measure of internal rotation and posterior tilt, particularly above 100° of humerothoracic elevation. The ST errors were found to be acceptable in relation to clinically important levels. Calibration positions have been shown to have a significant effect on the errors of both skin-fixed measurement techniques and therefore the importance of correct calibration is highlighted. It has thus been shown that a ST can be used to accurately quantify scapular motion when appropriately calibrated for the range of motion being measured.

Introduction

Measuring the 3-D kinematics of the scapula during dynamic movement provides important information for the diagnosis and treatments of clinical disorders (Fayad et al., 2008; Ludewig and Reynolds, 2009; Solem-Bertoft et al., 1993), for rehabilitation techniques (Michener et al., 2004), sports performance (Meyer et al., 2008) and injury prevention (Bell-Jenje and Gray, 2005; Kibler and Sciascia, 2010; Prinold and Bull, 2010). However, the thick layer of soft tissue covering the scapula leads to movement artefacts of about 5° below 120° humerothoracic elevation and far greater above in surface measurement techniques (Karduna et al., 2001; Matsui et al., 2006). Palpation (de Groot, 1997; Johnson et al., 1993; Meskers et al., 1998) (Figure 1) helps overcome skin artefacts but is impractical for dynamic and large volume movements. However, palpation methods have recently been extended to slow movements, and the addition of pressure sensors on the Palpator feet shown to improve repeatability (Shaheen et al., 2010b). Invasive methods such as bone pins (Karduna et al., 2001) allow accurate measurement in a dynamic movement but are impractical for the wider population.

Of the two skin-fixed methods presented in the literature, the Scapula Tracker (ST) has greater accuracy than the Acromial Method (AM) (Figure 1) (Karduna et al., 2001). However, a more recent paper has shown that the position of the AM can be optimised (Shaheen et al., 2010a) and therefore a comparison between the ST and AM at the optimal positions is required. In addition to the position of attachment, the position of calibration can theoretically influence accuracy (Cappello et al., 2005). Therefore the aim of this study is to compare the ST and AM at an optimal fixation position and across a range of calibration positions during a dynamic activity.

Methods

Subjects

Ten healthy male subjects with no history of shoulder pathology participated in the study (age = 27 ± 4 years). Informed consent was obtained from each subject.

Measurements

Kinematic data was collected using a 10 camera optical motion tracking system (Vicon), running at 200Hz.

A lightweight ST (Karduna et al., 2001) was created (27.5g) that incorporated a cluster of three retro-reflective markers (Figure 1). This consisted of a base which was attached to the mid portion of the scapula spine, and an adjustable arm that positioned the 'foot' onto the meeting point between the acromion process and the scapula spine. A previously described AM (Shaheen et al., 2010a) was used (4.8g) with a cluster of three retro-reflective markers (Figure 1). The base of the AM was also optimally placed on the meeting point between the acromion process and the scapular spine (Shaheen et al., 2010a). Both methods were attached to the skin with double-sided tape.

Here, a Palpator with pressure sensors is used as the gold standard measurement of scapula rotations as errors associated with static palpation of landmarks are approximately 2° (de Groot, 1997). A set of twenty one retro-reflective markers were used to track the other body segments (Shaheen et al., 2010a; Wu et al., 2005).

Procedure

After appropriate rehearsal subjects performed slow, controlled bilateral abduction over their full

range of motion in the scapular plane whilst seated on a backless stool. The Palpator and ST measurements were recorded simultaneously for three trials. The trials were then repeated with the AM and Palpator measurements recorded simultaneously (as presented previously; Shaheen et al., 2010a). A visual inspection showed no interaction between the Palpator and the skin-fixed techniques. One observer attached the skin-fixed methods to the subject then positioned and controlled the Palpator throughout the trials. Seven subjects from a previous parallel study (Shaheen et al., 2010a) were used as well as three additional subjects; measurements were taken during the same experimental session.

Data Analysis

The co-ordinate frames for the thorax, humerus, forearm and scapula were defined as described in the ISB recommendations (Wu et al., 2005). Euler rotations were used to calculate the humerothoracic rotations in the sequence $x-z'-y''$ (abduction, flexion, axial rotation), while scapulothoracic rotations were calculated using the sequence $y-x'-z''$ (internal rotation, upward rotation, posterior tilt).

The ST coordinate frame was calibrated to the anatomical coordinate frame of the scapula, defined using the ISB recommended anatomical landmarks (Wu et al., 2005); measured directly by the Palpator. Calibration was performed at 30°, 60°, 90° and 120° of humerothoracic elevation in the scapular plane. Each of the four calibrations was performed and the resulting coordinate frame transformation applied over the full range of motion, giving four sets of errors corresponding to these four calibration positions. All calibrations were done during the simultaneous measurements with the ST (or AM) and Palpator. At the position of calibration the two coordinate frames are made to coincide. As subjects move their arm the two coordinate frames diverge due to soft tissue deformations. 30° humerothoracic elevation was the smallest

angle common to all subjects and was thus used as the neutral position. A 'multiple' calibration was performed where the calibration position was changed throughout the motion: below 45° humerothoracic elevation the calibration at 30° was used, between 45° and 75° the calibration at 60° was used, etc. with calibration at 120°, used from 105° upwards, the maximum.

Errors were found by subtracting the scapula coordinate frame rotations as defined by the Palpator from the same rotations as defined by the ST. The equivalent RMS errors found in this study were compared to those of a previous bone pin study (Karduna et al., 2001) and the parallel study with the AM (Shaheen et al., 2010a) at the standard calibration position (Meskers et al., 2007). The effect of calibration angle on the ST and the AM was analysed with respect to the actual error and the mean RMS errors across the range of motion. A one-way repeated measures ANOVA test was used to determine significant differences between the RMS errors across the five calibration positions ($p < 0.05$). Once the optimal, single calibration position was found the errors of the two skin-fixed methods were compared at this calibration angle. A two-way repeated measures ANOVA test was used to compare these RMS errors across the full range of motion to determine the more accurate of the two methods. Where there was a significant difference and a significant interaction between method and humerothoracic elevation, a paired t-test was used to find the specific humerothoracic elevations that showed significant differences.

Results

The RMS errors of the ST are equivalent to previous studies and are lower than the AM in internal rotation and posterior tilt (Figure 2 & Table 1). Calibration is performed at the neutral position (30° of humerothoracic elevation here). Results calibrated at 90° of humerothoracic elevation are optimal for both measurement techniques (Figure 3 & Table 1).

Calibration angle led to a significantly different pattern of error in the ST (Figure 3). The results of the statistical analysis comparing the two skin-fixed methods are shown in Table 1. This comparison is made at the optimal, neutral and 'multiple' calibration positions.

Discussion

At both a standard and an optimal calibration position the ST was a significantly more accurate measure of internal rotation and posterior tilt than the AM, particularly above 100° of humerothoracic elevation (Figure 2 & Table 1). No significant differences were found between the two skin-fixed methods for upward rotations at any calibration angle. The ST showed a more consistent pattern of error in upward rotation.

The different orientation of the skin-fixed methods' planes of attachment can be used to explain the variation seen in measurement accuracy across the three rotations.

Less RMS errors were seen for upward rotation and posterior tilt for the ST in this study when compared to a previous bone-pin study (Karduna et al., 2001; Figure 2). The differences seen at higher angles of elevation could be explained by the different placement of the 'foot' of the ST between the two studies. Increased error at higher angles of humerothoracic elevation has been shown to exist with alternate, non-optimal attachment sites on the acromion (Shaheen et al., 2010a). It has also been shown, however, that the reliability and thus potentially the accuracy of the Palpator may decrease at higher angles of elevation (Shaheen et al., 2010b).

Altering the calibration angle changes the errors; reducing the mean error (Table 1) and distributing it more evenly over the full range of motion (Figure 3). Multiple calibrations can therefore be effectively used for a full range of motion study. The optimal single calibration position was at 90° humerothoracic elevation for both methods (Table 1). This could in future be found for other motions. Previous studies have only considered a single, neutral calibration angle, thus rejecting results above about 100° as not accurate (Karduna et al., 2001; van Andel et al., 2009).

For clinical application an accuracy of approximately 3° is sufficient to detect clinical abnormalities (Ludewig and Cook, 2000; Lukasiewicz et al., 1999; Meskers et al., 2005).

In summary, it has been shown that a ST can be used to accurately quantify scapular motion in scapular plane elevation when appropriately calibrated for the range of motion being measured.

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Figure legends

Figure 1 – Schematic drawings of the scapula Palpator, Scapula Tracker (ST) and Acromial Method (AM) used in this study; including points of attachment. Descriptions of the Euler rotations used for the scapula are also shown.

Figure 2 – RMS errors for the three rotations of the scapula as measured by the ST, compared to the AM (Shaheen et al., 2010a) and to a previous bone pin study (Karduna et al., 2001) for calibration at 30° and 90° of humerothoracic elevation.

Figure 3 – Error for upward rotation of the scapula measured with the ST at five calibration positions. The different pattern of error across calibration angles is demonstrated.

Table 1 – Mean RMS errors with respect to the Palpator over the range of motion. Significant differences between RMS errors of the ST and AM with a two way repeated measures ANOVA test across the range of motion: - denotes no significance and * denotes significance, both at $p < 0.05$. Localised significance was then found with a paired t-test where a significant difference and a significant interaction between method and humerothoracic angle was found. In all cases of significance the ST was the more accurate measure.

Figure 1

Figure 2

Figure 3

Table 1

Calibration Euler rotation angle		30° (neutral position)		60°		90° (optimal position)		120°		Multiple calibration	
Internal	ST	3.8	*	3.4	2.6	*	3.7	1.8	-		
	AM	7.9	> 70°	6.7	5.9	< 40°	6.1	2.2			
Upwards	ST	4.8	-	3	2.8	-	3.2	1.7	-		
	AM	4		3.7	3.2		4.8	1.9			
Posterior	ST	3.8	*	3.1	2.5	*	3	1.6	-		
	AM	7	> 100°	7	6	40-50° > 100°	5.9	2.5			

***Conflict of Interest Statement**

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The authors declare that there are no financial or personal relationships with people of organisations that have inappropriately influenced this work.