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Validity and reliability of 3D marker based scapular motion analysis: A systematic review

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Abstract

Methods based on cutaneous markers are the most popular for the recording of three dimensional scapular motion analysis. Numerous methods have been evaluated, each showing different levels of accuracy and reliability. The aim of this review was to report the metrological properties of 3D scapular kinematic measurements using cutaneous markers and to make recommendations based on metrological evidence.

A database search was conducted using relevant keywords and inclusion/exclusion criteria in 5 databases. 19 articles were included and assessed using a quality score. Concurrent validity and reliability were analyzed for each method.

Six different methods are reported in the literature, each based on different marker locations and post collection computations. The acromion marker cluster (AMC) method coupled with a calibration of the scapula with the arm at rest is the most studied method. Below 90-100° of humeral elevation, this method is accurate to about 5° during arm flexion and 7° during arm abduction compared to palpation (average of the 3 scapular rotation errors). Good to excellent within-session reliability and moderate to excellent between-session reliability have been reported. The AMC method can be improved using different or multiple calibrations. Other methods using different marker locations or more markers on the scapula blade have been described but are less accurate than AMC methods.

Based on current metrological evidence we would recommend (1) the use of an AMC located at the junction of the scapular spine and the acromion, (2) the use of a single calibration at rest if the task does not reach 90° of humeral elevation, (3) the use of a second calibration (at 90° or 120° of humeral elevation), or multiple calibrations above 90° of humeral elevation.

Keywords

Shoulder, accuracy, reliability, validity, scapular kinematics

1. Introduction

The measurement of shoulder kinematics during movement provides relevant information for the diagnosis and treatment of clinical disorders (Fayad et al., 2008b), rehabilitation techniques (Hanratty et al., 2012), sports performance (Meyer et al., 2008) and injury prevention (Shaheen et al., 2013). Calculation of shoulder joint kinematics using 3D upper-limb motion analysis is usually carried out with the shoulder considered as a virtual thoraco-humeral joint. The scapulo-thoracic (ST) and gleno-humeral (GH) joints are not considered individually despite the fact that scapular motion is a vital component of shoulder function. Indeed, during arm elevation in healthy subjects, there is significant motion of the scapula relative to the thorax with a mean 2° decrease in protraction, 39° increase in upward rotation and 21° increase in posterior tilt (Ludewig et al., 2009). Moreover abnormal 3D shoulder kinematic patterns have been found in frozen shoulder (Fayad et al., 2008a), hemiplegia (Meskers et al., 2005), impingement syndrome (McClure et al., 2006), children with cerebral palsy (Brochard et al., 2012) and obstetrical plexus palsy (Duff et al., 2007). This highlights the importance of 3D dynamic analysis to improve understanding of shoulder movement both in the biomechanical field and the clinical environment. Tracking of ST motion allows GH motion to be computed, which provides even more complete information on the dysfunction of the whole shoulder girdle.

The main obstacle to performing such a detailed analysis is the difficulty in finding a valid and reliable method to record scapular motion. Among the various techniques available (radiography, magnetic resonance imaging, fluoroscopy, inertial sensor, goniometer, etc.) for the measurement of in vivo scapular kinematics, cutaneous marker based methods (electromagnetic (Johnson et al., 1993; van der

Helm and Pronk, 1995; Barnett et al., 1999; Meskers et al., 1999; Karduna et al., 2001; McClure et al., 2001; Borstad and Ludewig, 2002; Ebaugh et al., 2005; Ludewig et al., 2009) and optoelectronic methods (Bourne et al., 2007; Lovern et al., 2009; van Andel et al., 2009; Lempereur et al., 2010; Senk and Cheze, 2010; Brochard et al., 2011b; Jaspers et al., 2011a; Shaheen et al., 2011; Lempereur et al., 2012) systems) have been the most studied and are the most used techniques for the measurement of scapular motion in the laboratory setting. However, marker based techniques are subject to inaccuracies relating to the placement of markers or soft tissue artefacts (STA) (Leardini et al., 2005). This is particularly true for the tracking of scapular motion: a difference of 87 mm has been found between the position of markers along the medial border of the scapula and the actual position of the scapula with the shoulder in full elevation (Matsui et al., 2006). This may question the validity and reliability of the use of marker based techniques for the recording of scapula motion. In order to standardize the analysis of shoulder kinematics, the International Society of Biomechanics (ISB) has published recommendations for the definition of joint coordinate systems and rotation sequences for the upper limb including the scapula (Wu et al., 2005). Recently, many methods have been described for the estimation of scapular motion such as the acromial method (a sensor is attached directly over the acromion and bony landmarks are digitalized to transform coordinates from the acromial sensor to the scapula coordinate system) (Karduna et al., 2001; van Andel et al., 2009; Brochard et al., 2011b), or the surface mapping approach (estimation of scapular motion using a cluster of markers over the scapula) (Jacq et al., 2008; Mattson et al., 2012). The placement of the sensor over the flat part of the acromion (Shaheen et al., 2011) and the cluster of markers covering the scapula (300 in the study by Mattson et al. (2012) and 120 in the study of Schwartz et al. (2013)) differ according to the methods. The method of computation of scapular motion also varies, such as the Calibrated Anatomical System Technique (CAST) (van Andel et al., 2009), and the double (Brochard et al., 2011a) or multiple (Prinold et al., 2011) calibrations. More complex algorithms can be used to compute scapular motion from marker maps such as the IMCP algorithm (Jacq et al., 2008) which is a robust, simultaneous and multi-object extension of the classic algorithm of registration, Iterative Closest Point (ICP). Moreover, the local coordinate system used affects the scapular rotations obtained. Significant differences between the original coordinate system (TrigonumSpinae (TS), acromioclavicular (AC) joint and

Angulus Inferior (AI)) and the system currently used (AngulusAcromialis (AA) instead of AC) have been found (Ludewig et al., 2010). The current standard interprets the same scapular motion with less internal rotation and upward rotation and more posterior tilt than the original.

Despite existing literature on scapular kinematic measurements, a systematic review, pooling existing knowledge in order that a general consensus can be reached, is lacking in literature.

Therefore, the aim of this review was to report the existing marker based methods used to estimate 3D scapular movements and their metrological properties (concurrent validity and reliability). Based on this review, recommendations for ST motion analysis tracking and future research are formulated.

2. Method

A systematic search of the following electronic databases was performed: Pubmed, Web of Science, Cochrane Library, Academic Search Premier and Psych Info. Keywords for the search included (1) Scapula, (2) keywords relative to the concept of accuracy: “accuracy”, “validity”, “agreement”, (3) keywords relative to reliability: “reliability”, “repeatability”, “reproducibility”. Only full papers (original articles, short communications or technical notes) published between 1990 and December 2012 were retained. In this paper, validity refers to the general concept of the validity of a measure (including content validity, concurrent/criterion validity and reliability), accuracy refers to the concurrent/criterion validity and reliability refers to the within/between rater/session reliability.

The titles and abstracts of articles retrieved from the search were assessed independently by two reviewers (ML and FL). Consensus for inclusion and exclusion was reached by discussion in the case of disagreement. Papers were included if they satisfied the following criteria: (1) the study included human participants, (2) the study evaluated a marker based method for the estimation of 3D scapular motion, (3) concurrent validity and/or reliability were evaluated, (4) full scientific papers. Papers were excluded if they were not published in English or were cadaver studies. The references in the selected articles were screened to complete the review process.

All studies included were assessed by two reviewers for their methodological quality. Since no validated quality assessment tool exists for the evaluation of articles in this field, a customized quality assessment tool was developed and based upon the STROBE statement (STrengthening the Reporting of OBservational studies in Epidemiology) (Vandenbroucke et al., 2007) and a systematic review in biomechanics (Peters et al., 2010). Table 1 presents the different items. Each item was rated as zero (no description), one (limited description) and two (good description).

3. Results

3.1. Selection of articles

The electronic database search identified a total of 335 papers. 15 articles were included for the title and abstract screening. Screening of references identified another 4 papers. Details of the reviewed articles are summarized in tables 2, 3, 4 and 5.

3.2. Quality of reviewed articles

The quality of the reviewed articles is summarized in table 6.

Six of the reviewed studies had a quality assessment score above 80% (Hebert et al., 2000; van Andel et al., 2009; Bourne et al., 2011; Brochard et al., 2011a; Lempereur et al., 2012; Warner et al., 2012). Five studies had a quality score between 70% and 80% (Meskers et al., 2007; Bourne et al., 2009; Lempereur et al., 2010; Senk and Cheze, 2010; Chu et al., 2012) and 8 between 60% and 70% (Karduna et al., 2001; Lovern et al., 2009; Brochard et al., 2011b; Prinold et al., 2011; Shaheen et al., 2011; Mattson et al., 2012).

Most of the articles were of high quality regarding research objectives, the experimental protocol (subject number, motion analysis system, position of markers, movements, definition of a reference method, computation of accuracy), results of concurrent validity, interpretation of the results and the conclusions. Many articles had limited subject characteristic descriptions, evaluation of reliability and results. Limitations of the studies were not always discussed. No study performed sample size calculations.

3.3. Population

Most of the studies assessed the accuracy of 3D scapular motion in healthy young adult subjects. Lempereur et al. (2012) and Jaspers et al. (2011b; 2011a) also included children with hemiplegic cerebral palsy. Karduna et al. (2001) included one subject with subacromial impingement syndrome.

3.4. Motion analysis system

The first studies of accuracy used electromagnetic systems which make direct measurements of the orientations and positions of the sensor in 3D space (Karduna et al., 2001; Meskers et al., 2007). Among the selected papers, optoelectronic systems have been the most used systems for the estimation of scapular motion (table 3).

3.5. Concurrent validity and reliability

3.5.1. Marker placements other than on the acromion

Three studies put the markers on the anatomical landmarks of the scapula recommended by the ISB (AA, AI and TS) (Lovern et al., 2009; Lempereur et al., 2010; Brochard et al., 2011b). Bourne et al. (2009) used 6 surface marker configurations on the scapula whereas Mattson et al. (2012) fixed 300 markers on the scapula. Lempereur et al. (2010) showed that the use of markers on the scapula produced an error (in comparison with palpation) of up to 15° with increasing humeral elevation Lovern et al. (2009) found an under-estimation of 50° of upward rotation at full arm elevation. However, in both of these studies, a correlation between the skin marker method and palpation (reference method) was performed. Lovern et al. (2009) found a correlation above 0.7 between the 2 approaches, suggesting that it may be possible to predict scapula-thoracic upward rotation using skin-mounted scapula markers. The model of rotation correction determined by Lempereur et al. (2010) improved the accuracy to less than 4°. However, the proposed models are not valid for all upper limb movements but only for the directions of movement measured in these studies. In the study by Bourne et al. (2011), two surface marker configurations (the six most superior markers and all eight markers of the model) gave the most accurate scapular motion. However, they indicated that the scapular joint angles required correction using a skin correction factor due to the low accuracy of skin markers (Bourne et al., 2009).

Two studies assessed the within-session reliability (Lempereur et al., 2010; Brochard et al., 2011b). In both cases, the reliability was excellent (ICC between 0.88 and 0.98 in Lempereur et al. (2010) and ICC between 0.90 and 0.94 in Brochard et al. (2011b)). In the study by Bourne et al. (2011), the between session reliability ranged from 2.6° to 9.1° (RMS differences) showing a good agreement between the 2 sessions.

3.5.2. Acromion Marker Cluster and single calibration

An alternative method is to position a cluster of markers or an electromagnetic sensor on the flat upper surface of the acromion as first described by Karduna et al. (2001). Table 4 presents the different results of the studies which used an acromion marker cluster. The CAST, with a single calibration and a cluster of markers or an electromagnetic sensor on the acromion, was the most used method to estimate scapular rotations. During upper limb flexion, this method was accurate to 5° (averaged across rotations) except for the studies by Brochard et al. (2011b; 2011a) and Karduna et al. (2001). During upper limb abduction, the accuracy was slightly lower but was above 7°. During elevation in the scapular plane, the method was accurate to 6°, whatever the axis of rotation measured. Despite a low average error in both flexion and abduction, many studies found that accuracy was reduced when the AMC method was used above 90° of arm elevation (Meskers et al., 2007; van Andel et al., 2009; Brochard et al., 2011b; Brochard et al., 2011a; Shaheen et al., 2011). This is a strong limitation when analyzing large amplitude shoulder movements. Above 90° of humeral elevation, the deltoid muscle contraction may create skin movement, increasing soft tissue artifacts although this link has to be proven. The error is generally greater on the Y-axis (protraction) than the other axes.

The placement of the AMC on the flat part of the acromion also influences accuracy. Shaheen et al. (2011) showed that Position C (Position A: near the anterior edge, Position B: just above the acromial angle and Position C: the meeting point between the acromion and scapula spine) was the least affected by soft-tissue deformation and therefore the best position for attaching the AMC.

The within-session reliability of the AMC method has been more studied than the between-session reliability. A good to excellent within-session reliability has been reported (ICC > 0.90 in Brochard et al. (2011b; 2011a), ICC > 0.80 in Jaspers et al. (2011b; 2011a) and inter-trial mean error < 5.5° in Shaheen et al. (2011) and inter-trial variability < 2.33° in Meskers et al. (2007)). The good level of within-session reliability of ST measurement found in Lempereur et al. (2012) for large ranges of shoulder motion and those found by Jaspers et al. (2011b; 2011a) for within and between-session ST kinematics provides evidence that the level of reliability of the use of an AMC in children with hemiplegic cerebral palsy and in typically developing children is good. However, the between session reliability was moderate to excellent (ICC between 0.56 to 0.92) when using the AMC in Brochard et al. (2011a).

3.5.3. Acromion Marker Cluster and multiple calibrations

The estimation of scapular rotations using the AMC and multiple calibrations was evaluated in 2 studies (Brochard et al., 2011a; Prinold et al., 2011). The error between the proposed methods and palpation was estimated between 6.00° and 9.19° with a single calibration versus 2.96° to 4.48° with a double calibration (Brochard et al., 2011a), and between 4° and 7.9° with single calibration versus 1.9° to 2.5° with four calibrations (Prinold et al., 2011). Bourne et al. (2009) also improved the accuracy of scapular tracking using several digitizations of scapula landmarks (Bourne et al., 2011). However, no marker configurations were able to accurately estimate the 3 scapular rotations simultaneously.

The between-session reliability of multiple calibrations has been studied only once. It was slightly lower (ICC ranged from 0.49 to 0.78) than for the single calibration, probably because of the two measurements of scapular postures for the double calibration (Brochard et al., 2011a).

3.5.4. Scapula Tracker

A scapula tracker consists of a base, which is attached to the mid-portion of the scapula spine, and an adjustable arm that positions a footpad onto the meeting point between the acromion process and the scapula spine. Two studies (Karduna et al., 2001; Prinold et al., 2011) used a scapula tracker. They found that it gave an accurate estimation of scapular rotations, particularly in the study by Prinold et al. (2011) (accurate to 3° with a single calibration and to 2° with multiple-calibrations during elevation in the scapular plane). Significant differences were found between the scapula tracker and an acromion marker cluster with a better accuracy with the scapula tracker for upper limb elevation above 100°.

Neither within-session nor between-session reliability have currently been assessed for the scapula tracker.

3.5.5. Synthesis

The AMC or the scapula tracker used with a calibration at rest provides an accurate estimation of ST. Above 90° of thoraco-humeral elevation, the scapula tracker seems to be more accurate, particularly for protraction (Karduna et al., 2001).

Among the different methods, the AMC is the most used method for the estimation of ST and is a reliable tool to quantify scapular rotations in children and adults (Brochard et al., 2011a; Jaspers et al., 2011b; Jaspers et al., 2011a).

A single calibration with the arm at rest and the use of an AMC gives a good estimation of scapular rotations with an excellent within-session reliability, as long as thoraco-humeral elevation remains below 90° during the movement (van Andel et al., 2009; Brochard et al., 2011b; Lempereur et al., 2012). The association of the AMC with double or multiple calibrations improves accuracy, especially at high degrees of humeral elevation (Brochard et al., 2011a; Prinold et al., 2011). Reliability ranges from good to excellent for within session reliability and from moderate to good for between session reliability (Brochard et al., 2011a).

3.5.6. Method of reference

The scapula locator was the device most often used to estimate the 'real' position of the scapula. It allows the position of 3 anatomical landmarks (generally AI, AA and TS) to be obtained simultaneously, in contrast with the palpation method (in which the 3 landmarks are palpated one after the other) used in 4 studies. The studies by Karduna et al. (2001) and Bourne et al. (2009) used intra-cortical pins implanted into the scapular spine. More recently, medical imaging such as X-rays combined with a video-based motion analysis have been used to validate data (Chu et al., 2012).

3.5.7. Tasks

The tasks most used for the estimation of concurrent validity were flexion and abduction of the upper limb, although some studies assessed elevation in the scapular plane (Prinold et al., 2011; Shaheen et al., 2011; Chu et al., 2012; Warner et al., 2012) or shoulder internal/external rotation (Karduna et al., 2001; van Andel et al., 2009; Chu et al., 2012; Mattson et al., 2012). To assess reliability, tasks relating to activities of daily living such as hand to mouth, hand to neck or forward reaching were also evaluated (Jaspers et al., 2011b; Jaspers et al., 2011a; Lempereur et al., 2012).

3.5.8. Statistical tools and methodology designs

The Root Mean Square (RMS) error between the tested method and the method of reference was generally used to quantify errors. In most of the studies, an ANOVA with the independent variables: measurement method and humeral elevation was then performed to show if there was a significant difference between the method and the reference method. One study used Pearson's correlation coefficient and RMS to evaluate the accuracy. No studies performed sample size calculations.

The intra-class coefficient was generally used to assess reliability with the standard error of measurement.

4. Discussion

Advances in motion analysis systems have made the recording of 3D ST joint motion possible, thus providing a more physiological measurement of shoulder kinematics. This systematic review included 19 studies which evaluated the metrological properties of 6 different marker based methods and showed the difficulty of setting one method as a reference for everyday clinical and research practice. The most evaluated method was the AMC with a calibration of the scapula with the arm at rest. Below 90-100° of humeral elevation, this method is accurate to 5° for flexion and 7° for abduction compared to palpation and depends highly on the position of the AMC on the acromion process (Shaheen et al., 2011), the number of calibrations and the degree of humeral elevation when calibrating (Prinold et al., 2011). Other methods using different marker locations or more markers on the scapula blade have been described but they are less accurate than AMC methods and are more relevant for research than clinical use.

4.1. Recommendations of the International Society of Biomechanics

To facilitate comparison of results between studies of scapular motion, the International Society of Biomechanics recommends the use of AA, AI and TS for the definition of the scapular joint coordinate system and the YXZ Euler sequence for the calculation of joint angles (Wu et al., 2005). This sequence is consistent with both research- and clinical-based two-dimensional representations of scapular motion (Karduna et al., 2000). Indeed, Karduna et al. (2000) found that changing the sequence results in significant alterations in the description of motion, with differences up to 50°. The use of the proposed scapular landmarks (AA, TS and AI) compared to the original ones (AC, TS and AI) reduces the risk of gimbal-lock and results in less internal rotation and upward rotation, and more posterior tilt (Ludewig et al., 2010). The tracking method used is also important when estimating 3D kinematics. The ISB advises to digitize anatomical landmarks with reference to a technical coordinate system instead of using skin mounted markers during movement. Lempereur et al. (2010) and Lovern et al. (2009) confirmed that large errors occur when tracking scapular landmarks without a technical coordinate system especially above 90° of humeral elevation.

4.2. AMC

The association of an AMC and single calibration creates errors of less than 5° for flexion, less than 7° for abduction and less than 6° for elevation in the scapular plane. The AMC has been shown to create small errors up to 90° of humeral elevation in many studies and above this threshold the errors are significantly larger. In specific cases, individual subject differences reach extreme values of approximately 25° (van Andel et al., 2009). Shaheen et al. (2011) advocated the attachment of the AMC at the meeting point between the acromion and the scapular spine since this placement created the smallest errors (below 90° of humeral elevation).

No standardized AMC has been developed and therefore, each motion analysis laboratory which carries out measurements of shoulder and scapular motion has created its own. Moreover, there is no consensus regarding the design and dimensions, the diameter of the markers or its weight. We recommend a light AMC with 3 well spaced out markers or electromagnetic receiver, which do not contact the skin during movements, placed at the meeting point between the acromion and the scapular spine.

For measurements of upper limb elevation above 90°, the AMC yields good results if the calibration is performed at 90° or 120° (Shaheen et al., 2011). The double or multiple-calibrations reduce errors by at least 50% in comparison to a single calibration and especially, they improve accuracy at high degrees of humeral elevation (Brochard et al., 2011a; Prinold et al., 2011). The limitations of these techniques are the time needed for the calibration and post data processing and the potential errors generated by multiple palpations. Further studies are needed to reach a compromise between the number of calibrations and the level of error.

4.3. Validation issues

Studies of concurrent validity were generally performed on healthy young adults and on typically developing children and children with hemiplegic cerebral palsy. The AMC has not been validated in pathological populations other than children with cerebral palsy, neither has it been validated in athletes with a large muscle mass. The validation is also generally performed during flexion and abduction. However, the validation of the AMC during functional movements such as hand to pocket, hand to head or hand to mouth might generate other results regarding accuracy.

The scapula locator is the method generally used to validate the different methods and is considered as 'silver standard' (Cutti and Veeger, 2009). Indeed, de Groot (1997) stated that there is a palpation error of about 2° which could increase the risk of validity errors.

The gold standard remains intra-cortical pins and has been used, for instance, to evaluate typical scapula-thoracic joint kinematics (Ludewig et al., 2009). Less invasive, the fluoroscopy or dynamic X-ray, such as that used in the study of Chu et al. (2012), appears to be an alternative method to evaluate validity. Another limit of the proposed methods is that static positions are compared to dynamic measurements. Cutti and Veeger (2009) suggest that it is important to compare both the quasi-static and the dynamic measurements with a gold standard. However, currently the only invasive technical solution is fluoroscopy which could be a good candidate for a gold standard status.

4.4. Reliability

Only a few studies performed both validations of accuracy and reliability even though these metrological properties represent different qualities of a measurement (Meskers et al., 2007; van Andel et al., 2009; Lempereur et al., 2010; Bourne et al., 2011; Brochard et al., 2011b; Brochard et al., 2011a; Shaheen et al., 2011; Lempereur et al., 2012). Results for reliability show good to excellent within-session reliability whereas the inter-session errors are higher. These differences might be related to palpation inaccuracies, differences in marker placement, lack of control of the plane of arm elevation (Ludewig et al., 2009) or the speed of the movement (Prinold et al., 2013). The knowledge of measurement error magnitude (whatever the accuracy and/or the reliability) is important in clinical decision making. Indeed, clinicians must be able to identify significant deviations from the values of healthy subjects and to differentiate between measurement errors and ‘real’ changes.

4.5. Limits and recommendations for future research

4 research teams published 10 of the 19 papers included. Since it is known that reliability is very observer dependent, the good to excellent results found in most of the reliability studies may be lower

when using the method for the first time. This may also affect the generalization of the results of this review.

Only 6 papers had quality scores above 80%. Although we highlighted the main results of the high quality papers we did not exclude low quality papers. One statistical issue which was common to all studies was the lack of sample size calculation. Recommendations exist for power and a priori sample size calculation for reliability studies that could be used in ST measurement validation studies (Eliasziw et al., 1994). Future studies should carry out such calculations in order to produce high quality studies.

Most of the validation studies have been carried out in healthy populations and may not be valid in pathological or sports populations. Shoulder bone deformities which occur in some pathologies (arthritis, hemiplegia or obstetrical brachial plexus palsy) or differences in muscle mass may affect the validity of the tracking method. Further validations should be carried out in the specific populations that are targeted by these methods.

It is also difficult to compare studies due to the different Euler sequences used for thoraco-humeral elevation (both flexion and abduction), the different levels of maximal humeral elevations and the standardization or not of humeral elevation between subjects, and the placement of the AMC. For validity studies, we recommend the use of the ZXY Euler sequence for the calculation of TH during flexion and the XZY Euler sequence for abduction with a standardization of the humeral elevation angles across subjects by fitting spline functions through the raw data of consecutive trials.

Tracking ST joint kinematics based on cutaneous markers remains a challenge and it is highly probable that the most accurate method would be a marker-less approach. However, a 3D dynamic approach has not yet been described. Biplanar fluoroscopy (Zhu et al., 2012) or 3D video cameras (Jacq et al., 2010) may help to produce more accurate recordings. Other static radiological methods (low-dose stereoradiographic imaging (EOS) (EOS imaging, France) (Dubousset et al., 2005), open MRI (Graichen et al., 2000)) might also serve as reference methods to avoid STA or/and to quantify them. Combining static imaging and motion analysis is also a way to explore shoulder motion (Chu et al., 2012).

4.6. Recommendations for practice

Currently, the marker based approach remains the best compromise for measuring shoulder kinematics based on a two joint model: ST and GH. Based on the results of this review regarding measurement of ST motion we recommend (1): the use of an AMC located at the junction of the spine of the scapula and the acromion, (2) use of a single calibration at rest if the task does not reach 90° of humeral elevation in abduction and flexion, (3) use of a second calibration at 90° or 120° of humeral elevation, multiple calibrations or a scapula tracker for movements above 90° of thoraco-humeral elevation. Others methods may have some research applications such as the estimation of STA.

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Conflict of interest

None of the authors have any conflicts of interest in conducting the experiment or in preparing this article for publication.

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Table 1: Quality analysis form used in systematic review

Q1	Is there in the abstract an explication of what has been done and found?
Q2	Is the scientific context clearly explained?
Q3	Are the objectives clearly stated?
Q4	Is the sampling size stated?
Q5	If yes, is the sampling size statically justified?
Q6	Are the characteristics of the subjects (height, weight, sex, healthy or pathologic subject) described?
Q7	Is the motion analysis system described?
Q8	Are marker locations including thorax and humerus accurately described?
Q9	Are the movement tasks defined?
Q10	Is the gold standard defined?
Q11	Is the accuracy computation described?
Q12	Is the reliability computation described?
Q13	Are the statistical tools used to show significant differences?
Q14	Are the results about the accuracy described?
Q15	Are the results about reliability described?
Q16	Are the results interpretable?
Q17	Are the limitations of the study discussed?
Q18	Is the conclusion clearly stated?

0 (no description), 1 (limited description) and 2 (good description)

Table 2: Description of the study population for the selected papers

Study	Subjects (number)	Mean age (std)	Gender
Chu et al. (2012)	Healthy (5)	27.8 (6.9)	5M
Warner et al. (2012)	Healthy (26)	18-43; 26.1 (6)	11M & 15F
Mattson et al. (2012)	Healthy (12)	NR	2M & 10F
Lempereur et al. (2012)	Healthy (10) // CP (10)	11.2 (3.1) // 11.8 (3.6)	5M & 5F // 5M & 5F
Shaheen et al. (2011)	Healthy (7)	23.9 (3.9)	7M
Prinold et al. (2011)	Healthy (10)	27 (4)	10M
Brochard et al. (2011a)	Healthy (12)	18-41; 26 (6.18)	NR
Brochard et al. (2011b)	Healthy (12)	18-35; 26.1 (NR)	NR
Bourne et al. (2011)	Healthy (8)	30 (5)	5M & 3F
Jaspers et al. (2011a)	Healthy (10)	10.3 (3.2)	6M & 4F
Jaspers et al. (2011b)	CP (12)	10.2 (3.2)	6M & 6F
Senk & Chèze (2010)	Healthy (5)	31 (NR)	4M & 1F
van Andel et al. (2009)	Healthy (13)	22-33	6M & 7F
Lovern et al. (2009)	Healthy (10)	27.5 (5.1)	6M & 4F
Bourne et al. (2009)	Healthy (8)	NR	NR
Bourne et al. (2009)	Healthy (8)	30 (5)	5M & 3F
Meskers et al. (2007)	Healthy (8)	29 (10)	4M & 4F
Karduna et al. (2001)	Healthly (8) // Impingement (1)	33 (NR) // 25	5M & 3F // 1M
Hébert et al. (2000)	Healthly (1) // anatomical model of scapula	46	1M

M: Male
F: Female
CP: Cerebral Palsy
NR: Not Reported

Table 3: Task and measurement methods for the selected papers

Study	Motion capture system	Study about	Method of reference	Method	Task	Amplitude	Standardization of humeral elevation between subjects	Humerothoracic elevation
Chu et al. (2012)	Opto-electronics - Vicon	Accuracy	DSX	AMC with single calibration	Abd EleScaPlane Int/Ext Rot	30–150 30–150 40–35	NR NR NR	Yes Yes Yes
Warner et al. (2012)	Opto-electronics - Vicon	Accuracy	Scapula Locator	AMC with single calibration	Flex Abd EleScaPlane	0–120 0–120 0–120	NR NR NR	Yes Yes Yes
Mattson et al. (2012)	Opto-electronics - Motion Analysis	Accuracy	Palpation (AA, (TS+AA)/2, TS, (TS+AI)/2, AI	Surface Mapping	Abd HBB Ext Rot Int Rot HtM HtN	NR NR NR NR NR NR	NR NR NR NR NR NR	Yes Yes Yes Yes Yes Yes
Lempereur et al. (2012)	Opto-electronics - Vicon	Accuracy and reliability	Scapula Locator	AMC with single calibration	Flex Abd	20–120 20–120	Yes Yes	Yes Yes
Shaheen et al. (2011)	Opto-electronics - NR	Accuracy and reliability	Scapula Locator	AMC with single calibration (5 calibrations positions) and 3 positions of AMC	EleScaPlane / Pos A EleScaPlane / Pos B EleScaPlane / Pos C	25–140 25–140 25–140	NR NR NR	Yes Yes Yes
Prinold et al. (2011)	Opto-electronics - Vicon	Accuracy	Scapula Locator	AMC / ScaTra with 4 calibration	EleScaPlane	30–120	NR	Yes
Brochard et al. (2011a)	Opto-electronics - Vicon	Accuracy and reliability	Scapula Locator	AMC with single and double calibration	Flex Abd	0–120 0–120	Yes Yes	Yes Yes
Brochard et al. (2011b)	Opto-electronics - Vicon	Accuracy and reliability	Palpation of AA, AI, TS	Markers on AA, AI, TS; AMC; anatomical AMC	Flex Abd	30–110 30–110	Yes Yes	Yes Yes
Bourne et al. (2011)	Opto-electronics - Optotrack	Accuracy and reliabili	Palpation of AA, AI, TS	Clusters of markers	GH Abd GH Horiz Add	NR NR	NR NR	Yes Yes

		ty		on scapula	Forward Reaching	NR	NR	Yes
					HBB	NR	NR	Yes
Jaspers et al. (2011a)	Opto-electronics - Vicon	Reliability	--	AMC with single calibration	3 reach tasks	NR	NR	NR
					2 reach to grasp tasks	NR	NR	NR
					3 gross motor tasks	NR	NR	NR
Jaspers et al. (2011b)	Opto-electronics - Vicon	Reliability	--	AMC with single calibration	3 reach tasks	NR	NR	NR
					2 reach to grasp tasks	NR	NR	NR
					3 gross motor tasks	NR	NR	NR
Senk & Chèze (2010)	Opto-electronics - Motion Analysis	Accuracy	Palpation of AA, AI, TS	Local optimisation procedure built from AC, AA and (TS+AA)/2 and recalculation of TS and AI	Flex	90–180	NR	NR
					Abd	90–180	NR	NR
					Horizontal Flexion	0–90	NR	NR
Lempereur et al. (2010)	Opto-electronics - Vicon	Accuracy and reliability	Palpation AA, AI, TS	Markers on AA, AI, TS	Flexion	0–160	NR	NR
van Andel et al. (2009)	Opto-electronics - Optotrack	Accuracy and reliability	Scapula Locator	AMC	Flex	20–100	Yes	Yes
					Abd	20–100	Yes	Yes
					Int/Ext Rot	60–90	Yes	Yes
Lovern et al. (2009)	Opto-electronics - Qualisys	Accuracy	Scapula Locator	Markers on AA, AI, TS	Flex	NR	NR	Yes
					Abd	NR	NR	Yes
Bourne et al. (2009)	Opto-electronics - Optotrack	Accuracy	Pins	Clusters of markers on scapula and palpation of AA, AI, TS	GH Abd	NR	NR	Yes
					GH Horiz Add	NR	NR	Yes
					Forward Reaching	NR	NR	Yes
					HBB	NR	NR	Yes
Meskers et al. (2007)	Electromagnetics - Flock of birds	Accuracy and reliability	Scapula Locator	AMC	Flex	30–130	Yes	Yes
					Abd	30–130	Yes	Yes
Karduna et al. (2001)	Electromagnetics - Polhemus	Accuracy	Pins	AMC / ScaTra	EleScaPlane	10–150	NR	Yes
					Flex	NR	NR	Yes
					Horiz Add	NR	NR	Yes
					Int/Ext	NR	NR	Yes

					Rot			
Hébert et al. (2000)	Opto-electronics - Optotrack	Accuracy and reliability	Palpation	Markers on AC, AI, TS	15 imposed displacements	0-35	No	No

AMC: Acromion Marker Cluster, SCaTra: Scapula Tracker
AA: Angulus Acromialis, AI: Angulus Inferior, TS: Trigonum Spinae, AC: Most dorsal point on the acromioclavicular joint
Flex: Flexion, Abd: Abduction, EleScaPlane : Elevation in the Scapular Plane, HBB: Hand Behind Back, Ext Rot: External Rotation, Int Rot: Internal Rotation, HtM: Hand to Mouth, HtN: Hand to Neck, GH Abd: GlenoHumeral Abduction, GH Horiz Add: GlenoHumeral Horizontal Adduction.

Table 4: Results of the accuracy for the selected papers

Study	Method of reference	Method	Movement	Accuracy method	Statistical tool	Error			Remark	Amplitude
						Y	X	Z		
Chu et al. (2012)	DSX	AMC with single calibration	Abd	RMSE		3.7	4.6	5.3		30–150
			EleScaPlane			6.2	4.5	7.0		30–150
			Int/Ext Rot			5.9	14.2	6.7		40–35
Warner et al. (2012)	Scapula Locator	AMC with single calibration	Flex	RMSE, mean difference, limits of agreement	ANOVA	3.5	4.3	4.7	RMSE max	0–120
			Abd			4.4	4.8	5.9		0–120
			EleScaPlane			4.0	6.1	7.3		0–120
Mattson et al. (2012)	Palpation (AA, (TS+AA)/2, TS, (TS+AI)/2, AI	Surface Mapping	Abd	RMSE, mean error	ANOVA	3.5	4.6*	3.5	p<0.1	NR
			HBB			2.3	3.2*	*5.0		NR
			Ext Rot			5.1*	4.2	4.7*		NR
			Int Rot			5.3*	3.9	4.1		NR
			HtM			5.1*	4.2	3.2		NR
			HtN			4.2*	5.9*	2.9		NR
Lempereur et al. (2012)	Scapula Locator	AMC with single calibration	Flex	RMSE	ANOVA	3.40	5.23*	4.47	p<0.05	20–120
			Abd			7.69*	4.92	6.26		20–120
Shaheen et al. (2011)	Scapula Locator	AMC with 5 calibrations (0°, 30°, 60°, 90° and 120°) and 3 positions of the acromial cluster (Pos A: near the anterior edge, Pos B: just above the acromial angle, Pos C: meeting point between the acromion and scapula spine)	EleScaPlane / Pos A / Calibration 1 to 5	RMSE		Figure	Figure	Figure		25–140
			EleScaPlane / Pos B / Calibration 1 to 5			Figure	Figure	Figure		25–140
			EleScaPlane / Pos C / Calibration 1 to 5			Figure	Figure	Figure		25–140
Prinold et al. (2011)	Scapula Locator	AMC / ScaTra with 4 calibration (30°, 60°, 90°, 120°, multi)	EleScaPlane / AMC / 30°	RMSE		7.8	4	7		30–120
			EleScaPlane / AMC / 60°			6.7	3.7	7		30–120
			EleScaPlane / AMC / 90°			5.9	3.2	6		30–120
			EleScaPlane / AMC / 120°			6.1	4.8	5.9		30–120
			EleScaPlane / AMC / multi			2.2	1.9	2.5		30–120
			EleScaPlane / ScaTra / 30°			3.8	4.8	3.8		30–120
			EleScaPlane / ScaTra / 60°			3.4	3	3.1		30–120
			EleScaPlane / ScaTra / 90°			2.6	2.8	2.5		30–120
			EleScaPlane / ScaTra / 120°			3.7	3.2	3		30–120

			EleScaPlane / ScaTra / multi			1.8	1.7	1.6		30–120
Brochard et al. (2011a)	Scapula Locator	AMC with single and double calibration	Flex / AMC / single calibration	RMSE	ANOVA	6.87	6.03*	8.92*		0–120
			Abd / AMC / single calibration			6.42*	6.00*	9.19*		0–120
			Flex / AMC / double calibration			4.48*	3.59	2.96		0–120
			Abd / AMC / double calibration			3.74	3.24	3.43		0–120
Brochard et al. (2011b)	Palpation of AA, AI, TS	Markers on AA, AI, TS; AMC; anatomical AMC	Flex / Markers on AA, AI, TS	RMSE	ANOVA	4.94*	6.65*	6.06*		30–110
			Abd / Markers on AA, AI, TS			1.55	7.85*	6.80*		
			Flex / AMC			9.33*	4.47	2.14		
			Abd / AMC			8.87*	3.51	8.79*		30–110
			Flex / anatomical AMC			11.05*	3.52	2.4		
			Abd / anatomical AMC			2.46	8.65*	2.21		
Bourne et al. (2011)	Palpation of AA, AI, TS	6 clusters of markers on scapula	GH Abd	RMSE		Figure				NR
			GH Horiz Add							NR
			Forward Reaching							NR
			HBB							NR
Senk & Chèze (2010)	Palpation of AA, AI, TS	Local optimisation procedure built from AC, AA and (TS+AA)/2 and recalculation of TS and AI	Flex	RMSE		9.7	8.3	10.3	Mean of RMSE from 90° to 150°	90–180
			Abd			5.4	7.5	7.8		90–180
			Horizontal Flexion			5.0	7.7	7.6		0–90
Lempereur et al. (2010)	Palpation AA, AI, TS	Markers on AA, AI, TS	Flexion	Maximal difference	ANOVA	14.86*	14.21*	16.16*		0–160
			Flexion			1.74	3.98	2.75	Correction model	
van Andel et al. (2009)	Scapula Locator	AMC	Flex	Mean difference	ANOVA	Figure ErrorY<6*	Figure ErrorX<3	Figure ErrorZ<5	Mean difference	20–100
			Abd			Figure ErrorY<4	Figure ErrorX<6*	Figure ErrorZ<5		20–100
			Int/Ext Rot			Figure ErrorY<8.4	Figure ErrorX<4	Figure ErrorZ<6		60–90
Lovern et al. (2009)	Scapula Locator	Markers on AA, AI, TS	Flex							NR
			Abd							NR
Bourne et al. (2009)	Pins	Clusters of markers on scapula and palpation of AA, AI, TS	GH Abd	RMSE		9.5	7.5	9.7	Un-correction of the joint angles	NR
			GH Horiz Add			7	6.4	4.8		NR
			Forward Reaching			6	4.2	5.1		NR
			HBB			5.1	7.8	9.7		NR

			GH Abd	RMSE		2.8	2.8	2.4	Correction of the joint angles	NR
			GH Horiz Add			2.3	1.9	1.4		NR
			Forward Reaching			2.2	2	3		NR
			HBB			1.8	1.6	2.3		NR
Meskers et al. (2007)	Scapula Locator	AMC	Flex	Mean difference	ANOVA	Figure 2.5<ErrorY<6	Figure -1<ErrorX<1	Figure -5<ErrorZ<-2		30–130
			Abd			Figure 0<ErrorY<2.5	Figure -9<ErrorX<-3	Figure -4<Error<-1		30–130
Karduna et al. (2001)	Pins	AMC / ScaTra	EleScaPlane / AMC	RMSE		9.4	6.3	6.6		10–150
			Flex / AMC			11.4	5.9	8.6		NR
			Horiz Add / AMC			10.0	4.8	7.3		NR
			Int/Ext Rot / AMC			6.2	4.4	3.7		NR
			EleScaPlane / ScaTra			3.2	8.0	4.7		10–150
			Flex / ScaTra			3.8	8.4	6.2		NR
			Horiz Add / ScaTra			5.0	10.0	3.8		NR
			Int/Ext Rot / ScaTra			4.4	7.2	4.6		NR
Hébert et al. (2000)	Palpation	Markers on AC, AI, TS	15 imposed displacements	Mean difference		1.73 for all movements imposed on the model				0-35

AMC: Acromion Marker Cluster, SCaTra: Scapula Tracker

AA: Angulus Acromialis, AI: Angulus Inferior, TS: Trigonum Spinae, AC: Most dorsal point on the acromioclavicular joint

Flex: Flexion, Abd: Abduction, EleScaPlane : Elevation in the Scapular Plane, HBB: Hand Behind Back, Ext Rot: External Rotation, Int Rot: Internal Rotation, HtM: Hand to Mouth, HtN: Hand to Neck, GH Abd: GlenoHumeral Abduction, GH Horiz Add: GlenoHumeral Horizontal Adduction.

RMSE: Root Mean Square Error

ANOVA: ANalysis of VAriance

Table 5: Results of the reliability for the selected papers

Study	Method of reference	Number of trials	Reliability coefficient	Within-Session	Between-Session
Lempereur et al. (2012)	Scapula Locator	3	CMC SEM	Excellent for the TH joint Good for the ST joint Good to excellent for the GH joint SEM inferior to 7°	
Shaheen et al. (2011)	Scapula Locator	3	Inter trial mean error	Inter-trial error inferior to 5.5° on average, much smaller than the calculated errors using the acromial tracker	
Brochard et al. (2011a)	Scapula Locator	3	ICC	Simple Calibration: good to excellent (0.75-0.96) Double Calibration: good to excellent (0.63-0.92)	SC: moderate to excellent (0.56-0.92) DC: moderate to good (0.49-0.78)
Brochard et al. (2011b)	Scapula Locator	3	ICC	Flex / Markers on AA, AI, TS : Y (0.94), X (0.93), Z (0.94) Abd / Markers on AA, AI, TS: Y (0.90), X (0.93), Z (0.92) Flex / AMC: Y (0.93), X (0.94), Z (0.94) Abd / AMC: Y (0.93), X (0.94), Z (0.91) Flex / anatomical AMC: Y (0.90), X (0.89), Z (0.91) Abd / anatomical AMC: Y (0.94), X (0.92), Z (0.91)	
Bourne et al. (2011)	Palpation AA, TS and AI	10 Day1 and Day2	ICC RMS		2.6°<RMS<8.1°
Jaspers et al. (2011a)	--	6	ICC SEM CMC	Moderately high to very high (ICC>0.6) SEM < 5°	ICC > 0.6 SEM < 7°
Jaspers et al. (2011b)	--	6	ICC SEM CMC	ICC > 0.7 SEM < 5°	ICC > 0.6 SEM < 5°
Lempereur et al. (2010)	Palpation AA, TS and AI	10	ICC	Good to excellent reliability 0.88 to 0.98	
Van Andel et al. (2009)	Scapula Locator	Day 1 and Day2	ICC SEM	Acceptable to good for protraction and external rotation. ICC low for tilt. Maximal SEM of 8.4°.	
Meskers et al. (2007)	Scapula Locator		RMSE	2.33°	5.0°
Hebert et al. (2000)	Palpation	2 Day1 and Day2	Coefficient of variation		< 10% for most of flexion and abduction task

CMC: coefficient of multiple correlations, SEM: Standard Error of Measurement, ICC: Intraclass Correlation Coefficient, RMSE: Root Mean Square Error

AMC: Acromion Marker Cluster

AA: Angulus Acromialis, AI: Angulus Inferior, TS: Trigonum Spinae

Flex: Flexion, Abd: Abduction

Table 6: Methodological quality of the selected papers

Study	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16	Q17	Q18	Total (Max=36)
Chu et al. (2012)	2	2	2	2	0	2	2	2	2	2	2	0	2	1	0	2	1	2	28
Warner et al. (2012)	2	2	2	2	0	2	2	2	2	2	2	0	2	2	0	2	2	2	30
Mattson et al. (2012)	2	0	2	2	0	1	2	2	2	1	2	0	2	1	0	2	2	2	25
Lempereur et al. (2012)	2	2	2	2	0	2	2	1	2	2	2	2	2	2	0	2	0	2	29
Shaheen et al. (2011)	2	2	2	2	0	1	0	2	2	2	2	0	2	2	0	2	2	0	25
Prinold et al. (2011)	2	2	2	2	0	1	2	1	2	2	2	0	2	1	0	2	0	2	25
Brochard et al. (2011a)	2	2	2	2	0	2	2	2	2	2	2	2	2	1	2	1	1	2	31
Brochard et al. (2011b)	0	2	2	2	0	2	2	2	2	2	2	0	2	2	0	2	0	0	24
Bourne et al. (2011)	2	2	2	2	0	2	2	2	2	2	2	2	2	2	2	2	1	2	33
Jaspers et al. (2011a)	2	2	2	2	0	1	2	1	2	0	0	2	0	0	2	2	2	2	24
Jaspers et al. (2011b)	2	2	2	2	0	1	2	1	2	0	0	2	0	0	2	2	2	2	24
Senk & Chèze (2010)	2	2	2	2	0	1	2	2	2	2	2	0	0	2	0	2	1	2	26
Lempereur et al. (2010)	2	2	2	2	0	2	2	2	2	1	0	0	2	1	1	1	2	2	26
van Andel et al. (2009)	2	2	2	2	0	0	2	2	2	2	0	2	2	2	2	2	2	2	30
Lovern et al. (2009)	2	2	2	2	0	0	2	2	2	2	0	0	0	2	0	2	1	2	23
Bourne et al. (2009)	2	2	2	2	0	0	2	2	2	2	2	0	0	2	0	2	2	2	26
Meskers et al. (2007)	2	1	2	2	0	0	2	2	2	2	1	2	2	2	1	2	1	1	27
Karduna et al. (2001)	1	2	2	2	0	0	2	2	2	2	2	0	0	2	0	2	2	1	24
Hébert et al. (2000)	2	2	2	2	0	1	2	2	2	0	2	2	2	2	2	2	1	2	30