

SPECIAL ARTICLE  
MOTION ANALYSIS

# Motion analysis of the shoulder in adults: kinematics and electromyography for the clinical practice

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## ABSTRACT

In this paper, the principal aspects of kinematic and electromyographic (EMG) analysis of the shoulder and their potential for the every-day clinical practice are described. The text reports a brief description of standard recommendations for movement assessment, an overview of the main quantitative motion analysis protocols and a description of the most commonly investigated scapulothoracic muscles. To assess the possibility of using these protocols for clinical applications, reliability and repeatability of kinematic and EMG measures were investigated and reference data for scapulothoracic joint kinematics were provided. The last part of the manuscript reports the integration of the quantitative analysis of scapula dyskinesia within the widely accepted Constant-Murley clinical score. In addition, examples of assessment of muscles activity and recruitment patterns are discussed since they are crucial for the clinical evaluation of common shoulder pathologies.

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The scapulohumeral joint is central in the complex shoulder structure. In particular, coordinated movements of the scapula relative to the thorax, and the scapular movements relative to the humerus are essential to efficiently complete an activity,<sup>1</sup> and require proper function of scapulothoracic and glenohumeral muscles.<sup>2-4</sup> This coordination permits the elevation of the arm overhead, which is a critical component of normal shoulder behavior.<sup>5</sup>

From a clinical viewpoint, motion analysis of the shoulder is typically conducted by assessing the scapulohumeral coordination (SHC), *i.e.* the coordinated kinematics of the scapula and humerus with respect to the thorax during arm elevation in the sagittal, scapular and/or frontal plane.<sup>6</sup> The scapulothoracic movements that occur during elevation include medio-lateral rota-

tion (ME-LA), which is the predominant movement, posterior-anterior tilting (P-A) and protraction-retraction (PR-RE).<sup>5</sup> For each elevation plane, the SHC can be visualized by means of three angle-angle plots,<sup>7-9</sup> whereby scapular ME-LA, P-A and PR-RE, are plotted against humeral elevation. The latter angle is most commonly calculated with respect to the thorax.

Scapulothoracic muscles are the main contributors to correct scapulothoracic movement patterns while glenohumeral muscles, such as the rotator cuff, provide the dynamic stability at the level of the glenohumeral joint. Large humerothoracic and glenohumeral muscles like *pectoralis major*, *lattissimus dorsi* and deltoid subsequently provide the actual arm movement. A change in scapulothoracic, glenohumeral or humerothoracic muscle coordination can induce aberrant scapulotho-

racic and glenohumeral movement patterns. Deficient movement is thus assumed to be characterized by an asynchronous pattern of muscle activation or termination. Specifically for the shoulder complex, early activation of the scapular stabilizers and a correct temporal sequence of scapular musculature in relation to prime mover activity and actual arm movement at the glenohumeral joint are essential for proper scapular position and coordinated scapulohumeral motion.<sup>10, 11</sup> As such, only the concurrent assessment of both kinematic and muscle activity parameters enables clear result interpretation.<sup>9, 12</sup>

The assessment of SHC plays a central role in the clinical management of patients with shoulder disorders.<sup>13</sup> The alteration of SHC, also known as scapula dyskinesia,<sup>2</sup> has been described in association with various shoulder pathologies, including rotator cuff tear, adhesive capsulitis, post-stroke patients,<sup>13</sup> impingement syndromes and hemiplegia.<sup>14</sup> Knowledge of the kinematics and muscle activity parameters of pathological SHC has been shown to improve rehabilitation techniques, sport performance and injury prevention in shoulders with clinical disorders.<sup>9, 12, 14</sup> Importantly, despite debate on the possible causative or compensatory nature of scapula dyskinesia, consensus exists on the importance of addressing the dyskinesia to assure a more effective treatment of patients with shoulder injuries.<sup>13</sup>

The aim of this paper is to review the principal aspects of kinematic and EMG analysis of the shoulder and show their potential for the every-day clinical practice.

### Motion analysis systems for the assessment of the scapulohumeral coordination

Quantitative motion analysis protocols have been developed to examine the multi-planar SHC, based on a variety of measurement systems, e.g. electromagnetic, optoelectronic, inertial.<sup>15-19</sup>

Protocols can also be differentiated based on the scapular tracking technique. The current gold standard procedure requires fixing cortical pins into the scapular bone to remove all soft-tissue artefacts.<sup>20</sup> This method is however highly invasive, and thus of limited applicability in clinical routine. Consequently, noninvasive approaches have been developed, namely the palpation technique,<sup>21, 22</sup> the scapula locator,<sup>23, 24</sup> the scapula-

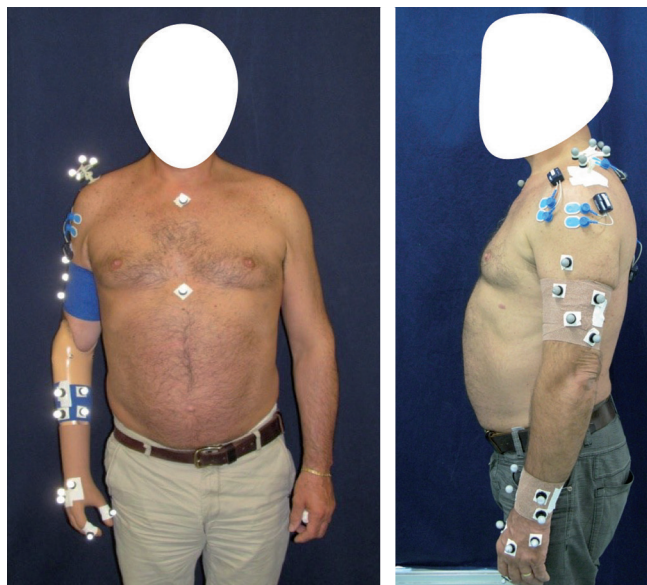


Figure 1.—An example of marker-set for the motion analysis of the upper limb by a stereophotogrammetric system, with an acromion cluster for the tracking of scapula movements. Simultaneous application of EMG sensors is possible (anterior and middle deltoid, upper and lower trapezius in this case).

lar tracker<sup>20</sup> and the acromion marker cluster (Figure 1).<sup>25, 26</sup>

To facilitate and encourage communication among researchers and clinicians, Wu *et al.* published in 2005 the ISB recommendations for the definition of standard joint coordinate systems,<sup>27</sup> focusing on the terminology, the definition of body segment coordinate systems, and joint coordinate system and motion for the constituent joints. Moreover, to further create a consensus regarding protocols for the analysis of shoulder kinematics and reporting of results obtained from anatomical and functional frames, Kontaxis *et al.* published a review article providing guidelines for standardized protocols with specific standardized descriptions and general recommendations.<sup>18</sup> This article offers the definition of a motion analysis protocol, a description on how to build such protocol, an overview of current standardization and issues to be addressed, as well as guidelines for the analysis of parameters.

### Muscle activity assessment of scapulohumeral coordination

The level or timing of muscle activity is mostly recorded by means of electromyography (EMG). Surface

EMG is an accurate, reliable, and non-invasive method to measure muscle activity and muscle timing of superficial muscles.<sup>28</sup> Deeper muscles can be evaluated by means of fine-wire or indwelling EMG. Most common scapulothoracic muscles currently investigated are the superficial m. *serratus anterior* and the m. *trapezius*, consisting of an upper, middle and lower part.<sup>2, 9, 12, 29, 30</sup> The m. *serratus anterior* acts as the main stabilizer of the scapula on the thorax and works in a force couple together with upper and lower part of the m. *trapezius* to laterally rotate the scapula and elevate the shoulder girdle. Humerothoracic muscles with a clear role in glenohumeral movement include the m. *pectoralis major*, m. *latissimus dorsi* and m. *deltoid anterior*. These are large superficial muscles that can be easily assessed using surface electrodes. Only very recently, research focused towards more deeply-lying scapulothoracic musculature, which are also considered important for scapulothoracic movement and that are believed to be prone to tightness and adaptive shortening, and cause muscle imbalances.<sup>31</sup> These non-superficial scapulothoracic muscles are the m. *rhomboid major*, m. *pectoralis minor*, and m. *levator scapulae*.<sup>32-35</sup> M. *levator scapulae* is a scapular elevator and retracts the scapula together with the m. *rhomboid major*, and both muscles additionally medially rotate the scapula.<sup>36</sup> As such, normal scapular lateral rotation can be hampered by shortened or hyperactive m. *levator scapulae* and m. *rhomboid major*.<sup>37</sup> M. *pectoralis minor* is a synergist of the m. *serratus anterior* and both contribute to the protraction of the scapula. Furthermore, m. *pectoralis minor* is responsible for anterior tilting and scapula depression and internal rotation,<sup>38</sup> and might as such hinder correct posterior tilting and external rotation.<sup>39, 40</sup> Increased muscle activity might result in adaptive shortening of the muscle, leading to an aberrant scapulothoracic position and movement.

### Reliability and repeatability of kinematic and EMG measures

The SHC is typically evaluated assessing ranges of motion (ROM) of humerus or scapula angles, *i.e.* single numerical values, comparable by mean of classic statistical tools such as the root mean square error (RMSE), intraclass correlation coefficient (ICC), standard error of measurement (SEM), minimum detectable differ-

ence (MDC), means (Me), standard deviations (SD), etc. For example, Van Andel *et al.*<sup>24</sup> quantified the SEM of scapula rotations based on two different protocols: the acromion tracker *vs.* the scapula-locator. These authors considered humerus at resting position and at 90° and 120° elevation in the sagittal and frontal plane, and humerus at 60° internal and 90° external rotation. Test-retest variability following replacement of the acromion tracker was also assessed. These authors reported that while the acromion tracker generally under-estimated scapula motion compared to scapula-locator, differences in motion tracking were small and results support the use of the acromion-tracker as a valid method of measuring scapular movement.

A second parameter of interest when investigating SHC entails the coordination between humerus and scapula. This coordination is typically analyzed by means of “coordination plots” or “angle-angle plots”, *i.e.* plots where the x-axis reports the humerus elevation angle, and the y-axis one of the scapular angles. In this case, the movement is described by a curve, which represents the kinematic pattern of the “scapulohumeral joint”. The repeatability or reliability of such kinematic patterns can be assessed using the Coefficient of Multiple Correlation (CMC) which varies from 0 (low correlation) to 1 (perfect correlation), which some exceptions as described by Ferrari *et al.*<sup>41</sup> Kadaba *et al.*<sup>42</sup> defined the calculation of the CMC to evaluate both intra-session consistency (formulation “with-in day”, CMC<sub>1</sub>), and inter-session agreement (formulation “between-day”, CMC<sub>2</sub>). For example, Thigpen *et al.*<sup>43</sup> assessed the repeatability of scapular rotation measures for different humeral elevation planes between trials, sessions, and days, using an electromagnetic system. They reported a range of CMC<sub>2</sub> mean values from 0.82 to 0.94 for the sagittal plane and from 0.74 to 0.91 for the scapular plane, with SD varying from 0.08 to 0.28. McGinley *et al.*<sup>44</sup> have suggested to additionally report the MDC, since CMC and MDC provide information on different aspects of intra- and inter-operator agreement. This methodology was applied by Parel *et al.*,<sup>45</sup> for the ISEO protocol (“INAIL Shoulder & Elbow Outpatient protocol”), proposed by Cutti *et al.*<sup>16</sup> This system is based on inertial and magnetic sensors (Xsens Technologies, Enschede, The Netherlands), and the tracking of the scapula is performed using a sensor positioned directly on the skin, just above the scapular spine. Mean

CMC<sub>2</sub> values ranged between 0.85 and 0.96 and between 0.87 and 0.95 for the sagittal and scapular plane respectively (SD 0.04 to 0.11). Concurrent MDC values ranged from 4.48 to 8.68 for the inter-operator agreement and between 4.98 and 8.58 for the intra-operator agreement.

The agreement between the Karduna's scapula tracker and the ISEO-protocol has also been assessed to evaluate the possibility of data sharing between laboratories applying the two methodologies.<sup>45</sup> Parel *et al.* assessed within-protocol repeatability for each protocol separately, as well as between-protocols agreement by means of RMSE and the limits of agreement analyses. Results showed that the two protocols had comparable repeatability and that the agreement between protocols met the stringent criteria for scapula medio-lateral rotation (ME-LA) during humeral sagittal and scapular plane elevations (up to 120° and 100°, respectively).

There are some general remarks to take into account when using EMG in research. Methodological aspects which affect the EMG results are placement of electrodes (inter-electrode distance), electrode types (surface vs fine-wire electromyography) and cross-talk which may occur between superficial and deeper muscles. Furthermore, the definition of muscle activity, type of data processing, calculation of outcome parameters, etc. should always be considered when interpreting EMG results. Since EMG is prone to signal noise, it requires a thorough standardization. Only little is published in literature with regard to reliability results of scapular muscles timing. Reliability of scapular muscle timing relative to anterior deltoid and/or movement start was reported by Phadke *et al.*<sup>46</sup> and Seitz *et al.*<sup>47</sup> in healthy controls and persons with shoulder impingement. They reported highest SEMs and MDC values for lower trapezius. To the best of our knowledge, no reliability data are available regarding the deeper-lying scapulothoracic muscle (m. *levator scapulae*, m. *pectoralis minor* and m. *romboid major*).

### Reference data for the assessment of the SHC

Reference data are fundamental for the assessment of the kinematics of pathologic shoulders and can be divided in two main groups: prediction intervals (PIs) and prediction bands (PBs).<sup>13</sup> PIs are intervals around mean values that contain, with a predefined probability, a new

observation from the same population from which a training sample is drawn. For example, the mean ROM together with a measure of variability (*e.g.* SD) represents the PI of this measure. PBs are similar to PIs, but also apply to continuous data, such as movement patterns (curves and coordination plots). PIs and PBs can be used to test if a new subject is statistically different from the physiological range of a control group.

It is also important to notice that reference data can refer to "monolateral" or "differential" data.<sup>13</sup> Given a sample of asymptomatic control subjects, monolateral reference data are obtained by assessing a single side of each control subject and are used to test the normality of one side of a new subject. On the contrary, differential reference data are obtained from assessing the difference in SHC of the right and left side of control subjects and are used to test if the difference between both sides of a new subject is within normality. Differential reference data can be useful in defining and assessing rehabilitation targets, since the kinematics of the contralateral side of a subject can be a more realistic goal than the pattern from a general population. Indeed, both sides of a subject share the subject's biological and personal history to a considerable extent.<sup>13</sup>

Most literature focuses on confidence intervals for the mean pattern of scapula rotations<sup>5, 8, 39, 48, 49</sup> or reports the mean pattern ± 1 standard deviation, typically for selected humerus elevation angles.<sup>24, 50-52</sup> Cutti *et al.*<sup>13</sup> have additionally generated age-stratified "monolateral" PBIs (Prediction Bands and Intervals), and "differential" PBIs for the SHC assessed with the ISEO protocol. These authors extracted and separately analyzed the scapula orientation in a specific reference posture (ROM offset) and the patterns of coordination (coordination plot). Figure 2 shows an example of application of "monolateral Prediction Bands" for the analysis of scapula kinematic for a patient surgically treated for rotator cuff tear, and assessed at 45, 90 days and 1 year from the surgery.

The distinction between scapula orientation at rest and coordination pattern allows the clinician to assess the subject's posture and movement separately, as commonly reported in literature.<sup>53</sup> Monolateral PBIs were also calculated for 3 age groups (group 1 from 18 to 30; group 2 from 31 to 50; group 3 from 51 to 70 years old), finding differences among groups, in particular between young adults and older subjects: bands from

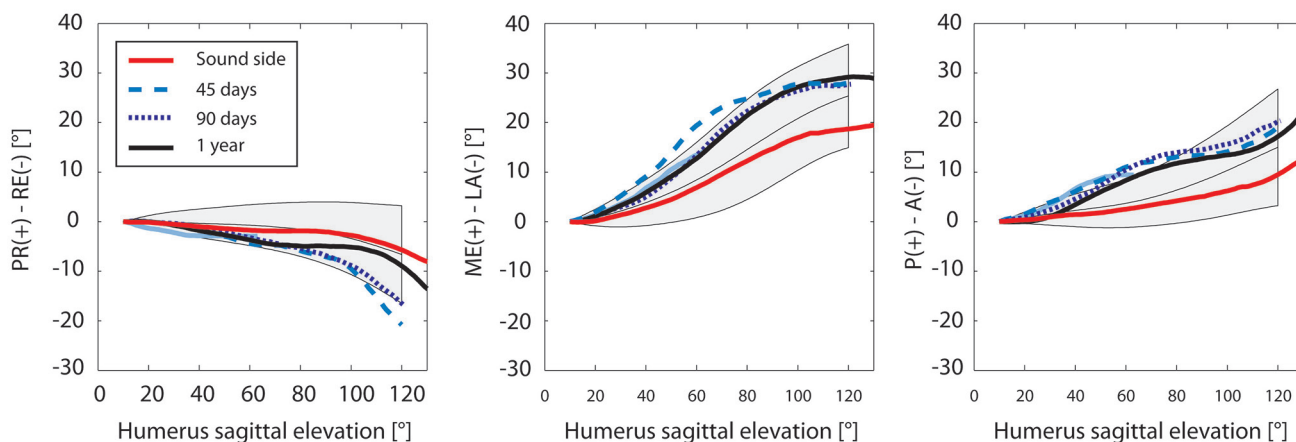


Figure 2.—An example of application of “monolateral Prediction Bands” for the analysis of scapula kinematic for a patient surgically treated for rotator cuff tear. The patient is assessed at 45 (dashed line), 90 (dotted line) days from the surgery, and at 1-year follow-up (black line). Also the controlateral side is assessed (grey line). Subplots report the coordination movement between scapula and humerus during humerus elevation in the sagittal plane. Patterns within bands are considered “physiological”, patterns outside bands are considered “pathological”.

young adults are larger than bands from older subjects. This finding may be explained by the increased stiffness of the glenohumeral joint with age and the related constraint on motion. This observation leads to the indication that the use of non-age-matched PBIs can lead to misclassifications of patients.

Unfortunately, there is no reference data for EMG available yet.

### Applications in clinical practice

Scapula dyskinesia is typically described in association with a variety of shoulder pathologies, including impingement, rotator-cuff tear, adhesive capsulitis, glenohumeral osteoarthritis and post-stroke.<sup>5, 15, 54</sup> Its origin has been related to pain, soft tissue stiffness, altered muscle recruitment patterns, force imbalance, muscle fatigue, poor thoracic posture, and scapula dyskinesia has been reported as either a cause or an effect of shoulder pathologies.<sup>5, 15, 55, 56</sup> Consensus exists that scapula dyskinesia is a potential impairment to shoulder function, that its assessment should be a routine part of the shoulder examination, and that addressing dyskinesia in the framework of a rehabilitation program improves outcomes.<sup>2, 57</sup> Ultimately, the quantitative measure of shoulder dyskinesia, including both kinematics and muscle activity measures, can help in moving away from the generic diagnostic label of ‘shoulder impinge-

ment’, in favor of movement-based diagnostic categories that can help in treatment planning.<sup>58</sup>

The ability to measure the impairment and activity level of patients with shoulder disorders is clinically relevant to manage or refine their expectations during rehabilitation but also to compare the efficacy of alternative treatments. For this purpose, a variety of clinical scores has been proposed in literature,<sup>53, 54, 59</sup> for example the “Scapula Weighted Constant-Murley Score” (SW-CMS).

The SW-CMS<sup>54</sup> is a new formulation of the popular “Constant-Murley Score”. CMS includes both self-reported and performance-based items. Score can vary between 0 and 100, and a minimum total score of 80 points is considered in general a good result for the patient (*i.e.* patient recovered). The SW-CMS complies with the necessity to include the assessment of scapula dyskinesia in quantitative clinical tests. This new score includes a quantitative evaluation of the scapulo-humeral coordination collected by the ISEO motion analysis system.<sup>16</sup> Alterations of the scapulo-thoracic joint are detected and used to reformulate the points assigned to the evaluation of the humero-thoracic joint. Reference bands are used to compare and classify the kinematics of the pathologic shoulder with respect to the kinematics of asymptomatic control subjects. If a patient adopts compensatory movements, points relative to the evaluation of the humero-thoracic joint kinematics decrease.

The SW-CMS has been tested in a group of patients surgically treated for rotator-cuff tear. Patients were longitudinally tested both with CMS and SW-CMS during the rehabilitation. Statistical investigations showed that there are differences between CMS and SW-CMS. In particular, the number of patients recovered at 90 days from the surgery (patients with a score higher than 80) decreases if SW-CMS is considered. This result shows that if scapula alterations are assessed there is a lowering of the CMS clinical score, and potentially a reclassification of patients recovered.

The assessment of muscle activity and recruitment patterns has gained increasing attention in various shoulder pathologies, including impingement syndrome and glenohumeral instability. Decreased activation of the middle and lower part of the *m. trapezius* and the *m. serratus anterior*, as well as increased activity of *m. pectoralis minor* has been related to the development of shoulder pain due to subacromial impingement.<sup>34, 55, 60</sup> The role of the upper part of *m. trapezius* is currently still under debate, *i.e.* while some research suggests a link between increased activity of the upper part of *m. trapezius* and shoulder pathology,<sup>55, 60</sup> others suggest to specifically train this muscle as part of the lateral scapular rotation force couple in patients with shoulder pain.<sup>61, 62</sup> Other EMG studies also investigated the role of *m. latissimus dorsi* and *m. pectoralis major* in glenohumeral instability, as these muscles contribute to increased glenohumeral internal rotation and scapulothoracic protraction movement. These studies have suggested that increased activation of *m. latissimus dorsi* plays a role in both anterior and posterior instability and that increased activation of *m. pectoralis major* plays a role in anterior instability.<sup>63</sup> Lastly, a shortened *m. pectoralis major* has been associated with abnormal scapular positioning, increased anterior tilting and internal scapular rotation.<sup>64, 65</sup> These kinematic alterations in turn lengthen the scapular stabilizers and thereby negatively influence their stabilizing function.<sup>2, 57, 65</sup> As such, these alterations are known to lead to glenohumeral joint disorders and subacromial impingement syndrome.<sup>64-66</sup>

### Conclusions

Future investigations should be focused on an actual integration of the motion and muscle analysis in clinical practice, to further help clinicians understanding the

advantage of including these new technologies and procedures in the evaluation of a patient's shoulder. Moreover, research should go beyond the assessment of surface scapulothoracic muscle registration in persons with impingements syndrome, and investigate all surrounding muscles of the scapula which are involved in either scapulothoracic or glenohumeral movement in different patient groups. Relevant patient groups are persons suffering from neck pain, frozen shoulder pathology, glenohumeral instability, but also individuals after stroke with a painful shoulder.

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