Scand J Med Sci Sports 2011: 21: 352–358
doi: 10.1111/j.1600-0838.2010.01274.x

SCANDINAVIAN JOURNAL OF MEDICINE & SCIENCE IN SPORTS

Review

Scapular positioning and movement in unimpaired shoulders, shoulder impingement syndrome, and glenohumeral instability

F. Struyf[1,2], **J. Nijs**[1,2,3], **J.-P. Baeyens**[4], **S. Mottram**[5], **R. Meeusen**[2]

[1]Department of Health Sciences, Division of Musculoskeletal Physiotherapy, Artesis University College Antwerp, Antwerp, Belgium, [2]Department of Human Physiology, Faculty of Physical Education and Physiotherapy, Vrije Universiteit Brussel, Brussels, Belgium, [3]University Hospital Brussels, Brussels, Belgium, [4]Department of Biometry and Biomechanics, Faculty of Physical Education and Physiotherapy, Vrije Universiteit Brussel, Brussels, Belgium, [5]KC International, Portsmouth, UK

Corresponding author: Jo Nijs, PhD, Department of Health Sciences, Division of Musculoskeletal Physiotherapy, Artesis University College Antwerp, Campus HIKE, Van Aertselaerstraat 31, 2170 Merksem, Antwerp, Belgium. Tel: +32 364 18265, E-mail: jo.nijs@artesis.be

Accepted for publication 9 November 2010

The purpose of this manuscript is to review the knowledge of scapular positioning at rest and scapular movement in different anatomic planes in asymptomatic subjects and patients with shoulder impingement syndrome (SIS) and glenohumeral shoulder instability. We reviewed the literature for all biomechanical and kinematic studies using keywords for impingement syndrome, shoulder instability, and scapular movement published in peer reviewed journal. Based on the predefined inclusion and exclusion criteria, 30 articles were selected for inclusion in the review. The literature is inconsistent regarding the scapular resting position. At rest, the scapula is positioned approximately horizontal, 35° of internal rotation and 10° anterior tilt. During shoulder elevation, most researchers agree that the scapula tilts posteriorly and rotates both upward and externally. It appears that during shoulder elevation, patients with SIS demonstrate a decreased upward scapular rotation, a decreased posterior tilt, and a decrease in external rotation. In patients with glenohumeral shoulder instability, a decreased scapular upward rotation and increased internal rotation is seen. This literature overview provides clinicians with insight into scapular kinematics in unimpaired shoulders and shoulders with impingement syndrome and instability.

The position of the scapula at rest is mainly defined by the shape of the thorax. The convexity of the thorax, together with muscular activity and the acromioclavicular articulation defines scapular positioning. Scapular positioning is important to center the humeral head and thus create a stable base for shoulder movements during daily activities and sport participation (Kibler & McMullen, 2003; Von Eisenhart-Rothe et al., 2005; Veeger & van der Helm, 2007; Ludewig et al., 2009).

Scapulothoracic movement analysis was first studied by Inman et al. (1944) during shoulder elevation in the coronal plane on asymptomatic subjects. By means of inserting bone pins into the scapula, scapula movement was analyzed. Twenty-two years later, Freedman and Munro (1966) examined the scapular movement in the scapular plane using roentgenograms. Because shoulder impingement syndrome (SIS) and glenohumeral joint instability are the most frequent shoulder disorders, much research has been focused on the scapulothoracic motion in patients with these shoulder disorders (Ellenbecker & Derscheid, 1989; Michener et al., 2003).

Knowledge of scapulothoracic motion is considered important for creating preventive strategies in asymptomatic subjects, the development of clinical tests, for the assessment of patients with shoulder disorders, and as a basis for establishing treatment programs. Scapular movements can be measured in different ways. It can be observed visually, using clinical tests, or by means of sophisticated technical equipment. This literature review focuses on measurements with reliable technical equipment. Firstly, scapular movements in asymptomatic subjects are addressed. Secondly, scapular movements in patients with SIS and glenohumeral instability were reviewed and are discussed.

Methods: literature search

Papers were selected from following electronic databases: PubMed, Cochrane Library, and Web of Science (up to January 6, 2009), using keywords for impingement syndrome ("impingement syndrome," "subacromial impingement," "impingement"), shoulder instability ("glenohumeral instability," "anterior instability," "instability"), and scapular movement ("scapulathoracic," "scapula," "scapular"). To focus the search results, these keywords were combined from the following keywords: "biomechanics, motion, movement, positioning or kinematics." To ascertain that all relevant studies were selected, one researcher screened the reference lists of all included papers. Inclusion criteria were: (1) original research reports of data collected on adult humans or human cadavers; (2) original research reports of data collected on asymptomatic subjects; (3) original research reports of data collected on patients with SIS; (4) original research reports of data collected on patients with glenohumeral instability; (5) full papers. For inclusion into the literature review, papers had to meet at least one of the first four criteria. Inclusion criteria number 5 was obligatory. Studies describing scapular kinematics by means of clinical measures, or studies including children were excluded. Studies were also excluded if they were not published in English or were not published as a full paper in a peer reviewed journal. The database search identified 51 relevant articles; six additional articles were retrieved from the reference screening. Based on the predefined inclusion and exclusion criteria, 35 articles were selected for inclusion in the current review.

Defining movement planes of the scapula and scapulohumeral rhythm

The movement of the scapula can be described by rotations in relation to the thorax. The scapula moves around a dorso-ventral axis, resulting in a rotation in the frontal plane. In this movement the glenoid cavity is turned cranially (upward rotation) or caudally (downward rotation). In the sagittal plane, around a latero-lateral axis the scapula rotates posteriorly (posterior tilting) or anteriorly (anterior tilting). External and internal rotation occurs around a cephalo-caudal (longitudinal) axis. The external rotation brings the glenoid cavity more into the frontal plane, whereas the internal rotation turns the glenoid cavity more to the sagittal plane. Although different terminology has been used, the majority of researchers describe the scapular movements in these terms.

In two-dimensional studies (e.g, x-ray – frontal plane), the scapulothoracic angle is most commonly used. This scapular angle is formed by the axis on the glenoid and a vertical line (Freedman & Munro, 1966; Poppen & Walker, 1976; Talkhani & Kelly, 1997). In addition, the scapular plane is defined as 40° (± 10°) anterior to the frontal plane (Fung et al., 2001; Ludewig et al., 2009).

Most scapular movements were described by use of Cardan and Euler angles. These are unfamiliar to most clinicians, but they enable the unique description of three-dimensional angular rotations, as sequential rotations about each of the three anatomical axes (Ludewig et al., 2009). Cardan and Euler angles are the current standard for description of shoulder motion in research testing. These three-dimensional results therefore differ from two-dimensional clinical goniometric measurement. Within the scope of this literature overview, only the extracted angular values for each of the scapulothoracic motions are reported.

A term often used in describing scapulothoracic movement is the scapulohumeral rhythm. The scapulohumeral rhythm is described as the relative movement between the scapula and the humerus during arm movements. The scapulohumeral rhythm is therefore defined as the ratio of the glenohumeral movement to the scapulothoracic movement during arm elevation. This is most often calculated by dividing the total amount of shoulder elevation (humerothoracic) by the scapular upward rotation (scapulothoracic).

Scapular positioning and movement in asymptomatic subjects

Rest position of the scapula

A variety of scapular rest angles have been reported. The scapulothoracic angle with the arm relaxed at the side ranges from 5.4° (Ludewig et al., 2009), 3° (Fung et al., 2001), – 2° (Mandalidis et al., 1999), – 4.7° (Poppen & Walker, 1976) to – 5.3° (Freedman & Munro, 1966). Negative values refer to downward scapular rotation. In addition, the study of Talkhani and Kelly (1997) reported scapular rest angles for a younger (mean age of 35 years) and older (mean age of 70 years) group. The resting scapular angle in the older population showed a significantly different scapular angle (+4.6°) compared with the younger group (– 9.4°). Consequently, the glenoid faces relatively downwardly in the younger group, whereas it faces more upward in the older group. Oyama et al. (2008) quantified the differences in resting scapular posture between the dominant and nondominant sides in healthy overhead athletes. Whereas the dominant shoulder demonstrated 3.46° scapular upward rotation, the nondominant shoulder demonstrated 2.0° of scapular upward rotation. Internal rotation angles ranged from 26.5° (Oyama et al., 2008; nondominant shoulder), 30.3° (Oyama et al., 2008; dominant shoulder), 40° (Fung et al., 2001) to 41.1° (Ludewig et al., 2009). In addition, anterior tilt angles ranged from 2° (Fung et al., 2001), 13.5° (Ludewig et al., 2009), 14.0° (Oyama et al., 2008; nondominant shoulder) to 15.9° (Oyama et al., 2008; nondominant shoulder).

Scapular movement during shoulder elevation

During shoulder elevation in the sagittal plane, several studies reported an initial setting phase, in which the scapula has little contribution to the total shoulder elevation (Inman et al., 1944; Fung et al., 2001; McClure et al., 2001). A consensus on either the presence or duration of the setting phase has not been established (linearity of the movement). The setting phase ranges from 0° to 90° (Fung et al., 2001), 0° to 60° (Inman et al., 1944), to 30° (McClure et al., 2001). In addition, some studies reported that the greatest relative amount of scapular rotation occurs between 80° and 140° (Bagg & Forrest, 1988), or between 30° and 60° (Mandalidis et al., 1999) of humeral elevation. However, some studies reject such a setting phase (Van der Helm & Pronk, 1995; Ludewig et al., 2009). Most researchers agree that the scapula rotates upwardly in a linear fashion, externally rotates nonlinearly, and tilts posteriorly in a nonlinear way (Inman et al., 1944; Van der Helm & Pronk, 1995; Fung et al., 2001; McClure et al., 2001; Ludewig et al., 2009). External rotation and posterior tilting occurs around 90° of arm elevation (Ludewig et al., 2009) or until after 90° of arm elevation (McClure et al., 2001).

Different anatomic planes demonstrate a different scapular movement pattern. During shoulder elevation, the scapula is more upwardly rotated at 60° in the frontal plane compared with the other two planes (Fung et al., 2001; Ludewig et al., 2009). At 90° and 120° angles of shoulder elevation, greater upward rotation angles are seen in the frontal plane compared with both the sagittal and scapular plane elevation (Ludewig et al., 2009). Internal rotation of the scapula decreases throughout elevation in all three planes. However, the scapula is more internally rotated in the sagittal plane and less internally rotated in the frontal plane compared with scapular plane abduction (Fung et al., 2001; Ludewig et al., 2009). According to Ludewig et al. (2009), no difference are detected among the three planes of humeral elevation for scapulothoracic tilting. However, Fung et al. (2001) reported significant differences in posterior tilt at 30° and 40° of shoulder elevation. The scapula demonstrated larger posterior tilting in the sagittal plane than in the other two planes. McClure et al. (2001) concluded that although some differences may be noted between the different anatomical planes, the pattern does not differ substantially.

Table 1 displays different degrees in upward rotation, external rotation, posterior tilting, and scapulohumeral ratio during shoulder elevation in the scapular plane in asymptomatic subjects. Finally, asymptomatic throwing athletes demonstrated with significantly increased upward rotation, internal rotation, and retraction of the scapula during humeral elevation compared with nonathletes. No differences in anterior/posterior tilting and elevation/depression were found (Myers et al., 2005).

Scapular positioning and movement in patients with SIS

Rest position of the scapula

The literature reviewed did not identify differences in the rest position of the scapula between patients with

Table 1. Scapular movements during shoulder elevation in the scapular plane

Study	Method used	Study sample	Upward rotation (°)	External rotation (°)	Posterior tilting (°)	Scapulohumeral ratio	Study interval (°)
Freedman and Munro (1966)	Static radiographs	61 right shoulders; 17–24 years	59.67	–	–	1.35/1	0–167
Poppen and Walker (1976)	Static radiographs	15 shoulders 22–63 years	–	–	40	1.25/1	0–150
Ludewig et al. (1996)	Electromagnetic surface sensors	23 right shoulders; 18–40 years	34	13	7	–	0–140
Graichen et al. (2005)	Supine static MRI	12 subjects; 21–33 years	–	–	3	2.3/1	30–150
Fung et al. (2001)	Electromagnetic surface sensors	6 cadaveric shoulders; mean age: 76 years	40	14	9	2.1/1	20–150
Ludewig et al. (2009)	Electromagnetic surface sensors	12 shoulders; 22–41 years	39	2	21	2.2/1	15–140
McClure et al. (2001)	Electromagnetic sensors on inserted bone pins	8 shoulders; 27–37 years	50	24	30	1.7/1	25–150
Ebaugh et al. (2005)	Electromagnetic surface sensors	20 shoulders; 18–30 years	54.7	2	3	–	0–180

SIS and unimpaired subjects (Lukasiewicz et al., 1999; Ludewig & Cook, 2000; Endo et al., 2001; Hébert et al., 2002).

Scapular movement during shoulder elevation

Table 2 shows the differences in scapular upward rotation, external rotation, and posterior tilting between SIS patients and unimpaired subjects.

In summary, the majority of researches report a decreased scapular external rotation, decreased scapular upward rotation, and a decreased posterior scapular tilting in patients with SIS (Lukasiewicz et al., 1999; Ludewig & Cook, 2000; Hébert et al., 2002; Endo et al., 2004). In contrast, one study demonstrated greater upward rotation angles and increased posterior tilting in patients with SIS (McClure et al., 2006).

Scapular positioning and movement in patients with glenohumeral instability

Rest position of the scapula

In patients with anterior shoulder instability, the scapula is downwardly rotated compared with asymptomatic subjects (Warner et al., 1992). Differences in scapular internal rotation or tilting have not been reported.

Scapular movement during shoulder elevation

During shoulder elevation in the scapular plane, patients with anterior shoulder instability show significantly greater scapulohumeral ratios from 0° to 90° of shoulder elevation compared with unimpaired control subjects (Paletta et al., 1997; Von Eisenhart-Rothe et al., 2005). The scapulohumeral ratios from 90° to maximal shoulder elevation were significantly lower in the instability group compared with those in the control group (Paletta et al., 1997). This means that scapulothoracic movements are increased from 90° to end range of shoulder elevation. In addition, Illyés and Kiss (2006) studied the first 90° of humeral elevation in the scapular plane in patients with multidirectional instability (MDI). They confirmed the study of Paletta et al. (1997) by reporting a significant greater ratio during this first 90° of humeral elevation in the patient group compared with the control group. The study of Ogston and Ludewig (2007) reported a significant decrease in scapular upward rotation and increased internal rotation up to 120° of shoulder elevation in the scapular plane.

In addition, during shoulder elevation in the frontal plane up to 120°, Ogston and Ludewig (2007) reported that persons with MDI demonstrated a significant decrease in scapular upward rotation in

Table 2. Scapular movements during shoulder elevation in the scapular plane (only significant alterations are presented)

Study	Method used	Study sample	Upward rotation (°)	External rotation (°)	Posterior tilt (°)	Study interval (°)	Plane studied
Lukasiewicz et al. (1999)	Electromechanical digitizer	20 controls; 17 impingement; 25–66 years	No difference	No difference	Decreased at 90° and max SE	0–max	Scapular
Hébert et al. (2002)	Optical surface sensors	10 controls; 41 impingement; 30–60 years	No difference	Increased at 110° SE in sagittal plane	No difference	0–110	Sagittal and frontal
Ludewig and Cook (2000)	Electromagnetic surface sensors	26 controls; 26 impingement; 20–71 years	Decreased at 60° SE	Decreased when loading	Decreased at 120° SE	0–120	Scapular
Graichen et al. (2000)	Supine static MRI	14 controls; 20 impingement; 22–62 years	No difference	No difference	No difference	30–120	Scapular
McClure et al. (2006)	Electromagnetic surface sensors	45 controls; 45 impingement; 24–74 years	Increased at 90° and 120° SE in sagittal plane	No difference	Increased at 120° SE in scapular plane	0–max	Scapular and sagittal
Endo et al. (2001)	Static radiographs	27 impingement (side comparison); 41–73 years	Decreased at 90° SE	No difference	Decreased at 45° and 90° SE	0–90	Frontal

the frontal plane. Likewise, Von Eisenhart-Rothe et al. (2005) confirmed the increased scapular internal rotation in the frontal plane from 30° to 90° of shoulder elevation.

Discussion

Shoulder abduction involves a complex variety of movements that has been the subject of numerous studies and discussions. The present review has attempted to summarize the current knowledge of scapular positioning at rest and scapular movement in asymptomatic subjects and patients with SIS and glenohumeral shoulder instability.

The literature showed no consensus on the scapular rest position. A variety of scapular rest angles have been reported. Regarding the internal rotation angles, all three studies discussed in this review agreed on a approximately 35° internal rotation angle (Fung et al., 2001; Oyama et al., 2008; Ludewig et al., 2009). In addition, anterior tilt angles ranged from 2° (Fung et al., 2001) to 16° (Oyama et al., 2008). However, Fung et al. (2001) included only human cadavers.

Most researchers agreed that during shoulder elevation, the scapula rotates upwardly, rotates externally, and tilts posteriorly, with the majority of tilting and external rotation occurring after 90° of humeral elevation (Inman et al., 1944; Van der Helm & Pronk, 1995; Fung et al., 2001; McClure et al., 2001; Ludewig et al., 2009). No consensus exist on the presence of a setting phase during shoulder elevation. Although some studies reject the presence of a setting phase (Van der Helm & Pronk, 1995; Ludewig et al., 2009), it seems reasonable that downward rotation of the scapula may occur during the first degrees of shoulder elevation, because of the weight of the limb and the resultant muscular forces acting on the scapula and the humerus during movement of the arm. The forces may pull the scapula initially downward in an attempt to create adequate length–tension relationships for the muscles acting on the humerus and scapula.

Another aim of the literature review was to look at the relative contributions of the scapula to upper limb movements in patients with SIS and shoulder instability. However, several discrepancies among studies were noted. Of the studies investigating scapular upward rotation in patients with SIS, two of six found decreased upward rotation (Ludewig & Cook, 2000; Endo et al., 2001), one increased upward rotation (McClure et al., 2006), and three no differences (Lukasiewicz et al., 1999; Graichen et al., 2000; Hébert et al., 2002). Somewhat greater consistency in findings was found for the measurements of scapular posterior tilting, with three of six studies finding decreased posterior tilt in symptomatic subjects (Lukasiewicz et al., 1999; Ludewig & Cook, 2000; Endo et al., 2001), one reporting increased posterior tilting (McClure et al., 2006), and two finding no significant difference (Graichen et al., 2000; Hébert et al., 2002). For scapular external rotation, only one of six studies found a decrease in external rotation in symptomatic subjects (Ludewig & Cook, 2000), one increased external rotation (Hébert et al., 2002), and the remaining four found no significant differences between symptomatic and asymptomatic individuals.

In patients with glenohumeral shoulder instability, moderate consensus can be seen: the scapula demonstrates with a decreased scapular upward rotation and a significant increased internal rotation (Warner et al., 1992; Paletta et al., 1997; Von Eisenhart-Rothe et al., 2005; Ogston & Ludewig, 2007). In addition, scapular internal rotation is frequently found as the most common and defining alteration in the clinical exam in patients with injuries (Ulh et al., 2009).

Comparing data across kinematic studies is difficult because of several important methodological aspects. First, measurement of scapular movements has proved difficult because they occur beneath the skin, inhibiting the fixation of any externally applied measurement system (McQuade & Smidt, 1998). Second, differences across kinematic studies include the choice of anatomical plane and the range of motion studied. Third, some studies only address static positions, while other include dynamic motion. Fourth, a variety of instruments is used to obtain measurements. Fifth, although the degree of stabilization differed substantially, thoracic spine position has shown to affect scapular kinematics significantly during scapular plane abduction (Kebaetse et al., 1999; Finley & Lee, 2003). Sixth, a lack of significant differences between groups also relates to the presumed multifactorial etiology of SIS. In addition, many of the discrepancies in scapular motion among patients with SIS are related to the variety of possible causative factors for the patients impingement symptoms. Finally, some methodological aspects makes comparisons difficult: the number of subjects studied, anthropometric data of the subjects, shoulder pathologies, the choice of bony landmarks, the method used to calculate angles and describe motion, and the specific methods used to reduce and present the data, such as whether the resting position is taken as zero or is given a value based on a defined zero position. Given these differences, it is not surprising that variation exists in the literature relating to scapular motion. In addition, future research should address the impact of factors such as age, arm dominance, gender, and upper extremity "exposure" to occupational or athletic activities on scapular kinematics. It is clear from the methodological problems encountered here that, because of the complexity of assessing three-dimensional motions, it is necessary to train orthopedic surgeons, sports physical therapists, sport physicians, ergonomists, and anatomists in the difficulties and pitfalls in interpreting kinematics (Baeyens et al., 2005).

In conclusion, during shoulder elevation in asymptomatic subjects, the scapula rotates upwardly, rotates externally, and tilts posteriorly. In patients with SIS, the scapula demonstrates a decreased upward rotation and a decreased posterior tilt. In patients with glenohumeral shoulder instability, the scapula demonstrates a decreased scapular upward rotation and consequently a significant increased internal rotation.

Perspectives

First, the current literature review provides sports clinicians with insight into scapular kinematics in unimpaired shoulders: clinicians working with athletes can answer the basic question of "what is normal scapular positioning and movement?" Second, sports clinicians, especially those working with overhead athletes, frequently encounter athletes with symptoms of shoulder impingement or glenohumeral instability. Subsequently, this literature review increases our understanding of scapular positioning abnormalities in overhead athletes, which creates the basis for assessment and therapy.

Key words: scapula, movement, impingement, instability, shoulder.

Acknowledgement

This study was financially supported by a research grant (G826) supplied by the Department of Health Sciences, Artesis University College Antwerp, Antwerp, Belgium.

References

Baeyens JP, Cattrysse E, Van Roy P, Clarys JP. Measurement of three-dimensional intra-articular kinematics: methodological and interpretation problems. Ergonomics 2005: 48: 1638–1644.

Bagg Ds, Forrest WJ. A biomechanical analysis of scapular rotation during arm abduction in the scapular plan. Am J Phys Med Rehabil 1988: 67: 238–245.

Ebaugh DD, McCLure PW, Karduna AR. Three-dimensional scapulothoracic motion during active and passive arm elevation. Clin Biomech 2005: 20: 700–709.

Ellenbecker TS, Derscheid GL. Rehabilitation of overuse injuries of the shoulder. Clin Sports Med 1989: 8: 583–604.

Endo K, Ikata T, Katoh S, Takeda Y. Radiographic assessment of scapular rotational tilt in chronic shoulder impingement syndrome. J Orthop Sci 2001: 6: 3–10.

Endo K, Yukata K, Yasui N. Influence of age on scapulo-thoracic orientation. Clin Biomech 2004: 19: 1009–1013.

Finley MA, Lee RY. Effect of sitting posture on 3-dimensional scapular kinematics measured by skin-mounted electromagnetic tracking sensors. Arch Phys Med Rehabil 2003: 84: 563–568.

Freedman L., Munro RR. Abduction of the arm in the scapular plane: scapular and glenohumeral movements: a roentgenographic study. J Bone Joint Surg 1966: 48: 1503–1510.

Fung M, Kato S, Barrance PJ, Elias JJ, McFarland EG, Nobuhara K, Chao EY. Scapular and clavicular kinematics during humeral elevation: a study with cadavers. J Should Elbow Surg 2001: 10: 278–285.

Graichen H, Hinterwimmer S, Von Eisenhart-Rothe R, Vogl T, Englmeier KH, Eckstein F. Effect of abducting and adducting muscle acitivity on glenohumeral translation, scapular kinematics and subacromial space width in vivo. J Biomech 2005: 38: 755–760.

Graichen H, Stammberger T, Bonel H, Haubner M, Englmeier KH, Reiser M, Eckstein F. Magnetic resonance based motion analysis of the shoulder during elevation. Clin Orthop Relat Res 2000: 370: 154–163.

Hébert LJ, Moffet H, McFadyen BJ, Dionne CE. Scapular behavior in shoulder impingement syndrome. Arch Phys Med Rehabil 2002: 83: 60–69.

Illyés A, Kiss RM. Kinematic and muscle activity characteristics of multidirectional shoulder joint instability during elevation. Knee Surg Sports Traumatol Arthrosc 2006: 14: 673–685.

Inman VT, Saunders JB, Abbott LC. Observations on the function of the shoulder joint. J Bone Joint Surg 1944: 26: 1–30.

Kebaetse M, McClure P, Pratt NA. Thoracic position effect on shoulder range of motion, strength, and three-dimensional scapular kinematics. Arch Phys Med Rehabil 1999: 80: 945–950.

Kibler B, McMullen J. Scapular dyskinesis and its relation to shoulder pain. J Am Acad Orthop Surg 2003: 11: 142–151.

Ludewig PM, Cook TM. Alterations in shoulder kinematics and associated muscle activity in people with symptoms of shoulder impingement syndrome. Phys Ther 2000: 80: 276–291.

Ludewig PM, Cook TM, Nawoczenski DA. Three-dimensional scapular orientation and muscle activity at selected positions of humeral elevation. J Orthop Sports Phys Ther 1996: 24: 57–65.

Ludewig PM, Phadke V, Braman JP, Hassett DR, Cieminski CJ, LaPrade RF. Motion of the shoulder complex during multiplanar humeral elevation. J Bone Joint Surg 2009: 91: 378–389.

Lukasiewicz AC, McClure P, Michener L, Pratt N, Sennett B. Comparison of 3-dimensional scapular position and orientation between subjects with and without shoulder impingement. J Orthop Sports Phys Ther 1999: 29: 574–583.

Mandalidis DG, McGlone BS, Quigley RF, McInerney D, O'Brien M. Digital fluoroscopic assessment of the scapulohumeral rhythm. Surg Radiol Anat 1999: 21: 241–246.

McClure PW, Michener LA, Karduna AR. Shoulder function and 3-dimensional scapular kinematics in people with and without shoulder impingement syndrome. Phys Ther 2006: 86: 1075–1090.

McClure PW, Michener LA, Sennett BJ, Karduna AR. Direct 3-dimensional measurement of scapular kinematics during dynamic movements in vivo. J Should Elbow Surg 2001: 10: 269–277.

McQuade KJ, Smidt GL. Dynamic scapulohumeral rhythm: the effects of external resistance during elevation of the arm in the scapular plane. J Orthop Sports Phys Ther 1998: 27: 125–133.

Michener LA, McClure PW, Karduna AR. Anatomical and biomechanical mechanisms of subacromial impingement syndrome. Clin Biomech (Bristol, Avon) 2003: 18: 369–379.

Myers JB, Laudner KG, Pasquale MR, Bradley JP, Lephart SM. Scapular position and orientation in throwing athletes. Am J Sports Med 2005: 33: 263–271.

Ogston JB, Ludewig PM. Differences in 3-dimensional shoulder kinematics between persons with multidirectional instability and asymptomatic controls. Am J Sports Med 2007: 35: 1361–1370.

Oyama S, Myers JB, Wassinger CA, Ricci RD, Lephart SM. Asymmetric resting scapular posture in healthy overhead athletes. J Athl Train 2008: 43: 565–570.

Paletta GA Jr., Warner JJ, Warren RF, Deutsch A, Altchek DW. Shoulder kinematics with two-plane x-ray evaluation in patients with anterior instability or rotator cuff tearing. J Should Elbow Surg 1997: 6(6): 516–527.

Poppen NK., Walker PS. Normal and abnormal motion of the shoulder. J Bone Joint Surg 1976: 58: 195–201.

Talkhani IS, Kelly CP. Scapulothoracic rhythm in normal male volunteers. Biomed Sci Instrum 1997: 34: 327–331.

Ulh TL, Kibler WB, Gecewich B, Tripp BL. Evaluation of clinical assessment methods for scapular dyskinesis. Arthroscopy 2009: 25: 1240–1248.

Van der Helm FC, Pronk GM. Three-dimensional recording and description of motions of the shoulder mechanism. J Biomech Eng 1995: 117: 27–40.

Veeger HA, van der Helm FC. Shoulder function: the perfect compromise between mobility and stability. J Biomech 2007: 40: 2119–2129.

Von Eisenhart-Rothe R, Matsen FA III, Eckstein F, Vogl T, Graichen H. Pathomechanics in atraumatic shoulder instability: scapular positioning correlates with humeral head centering. Clin Orthop Relat Res 2005: 433: 82–89.

Warner JJ, Micheli LJ, Arslanian LE, Kennedy J, Kennedy R. Scapulothoracic motion in normal shoulders and shoulders with glenohumeral instability and impingement syndrome. A study using Moiré topographic analysis. Clin Orthop Relat Res 1992: 285: 191–199.