ACTA UNIVERSITATIS CAROLINAE,
KINANTHROPOLOGICA Vol. 47, 2 – 2011 Pag. 148–158

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BIOMECHANICAL RELATIONS AMONG SHAPE AND MOBILITY OF SHOULDER COMPLEX

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SUMMARY

The aim of this work is to describe the biomechanics of the shoulder complex. The shoulder is the most complicated joint of the body. In biomechanical point of view the scapula is the most important part of modeling the shoulder girdle and it is the best indicator of setting joints. This work describes shape and mobility of the shoulder complex (especially the scapula) in healthy individuals and patients. In case of the shoulder pathology the scapula changes the position and reduces the mobility. The human shoulder can be seen as a perfect compromise between mobility and stability. The article discusses the stability and instability of the shoulder girdle too.

Key words: joint model, scapulothoracic kinematic, winging scapula, scapulohumeral rhythm

INTRODUCTION

The human shoulder girdle is made up of the clavicle, scapula and the humerus as well as associated muscles, ligaments and tendons. The shoulder complex consists of four articulations: the sternoclavicular (SC) joint, the acromioclavicular (AC) joint, the glenohumeral joint (GH) and the scapulothoracic articulation (Čihák, 2003; Petrovický 2001). These four articulations act simultaneously to provide a greater range of motion than any individual articulation and than any other joint complex in the human body (Lovern, 2009). Shape and mutual position of individual muscles and of whole regions is called configuration (Véle, 1995; Véle, 1997). Biomechanics of the shoulder complex is influenced by wide range of factors: the structure and state of muscles, ligaments, joints, nerves and vessels, age... (Otáhal et al., 2010). In my opinion the scapula is the most important part of the shoulder complex which influences its configuration, shape and mobility.

Animation and modeling of joints is very often uses for the biomechanical research. **Models** of the musculoskeletal system depend on accurate skeletal dimension and muscle architectural inputs (Altobelli, 2005; Borst, 2011). The special role of muscles for stabilization and the importance of propriocepsis makes it clear that biomechanical models should not only include all necessary parameters to correctly describe mechanical behavior, but should also include stabilization constrains and feedback and moreover, should focus on the relationship between reflexes and stability (Veeger, 2007).

Table 1. Anatomical landmarks proposed by the ISB (Lovern, 2009)

Thorax	C7	Spinous processus of the seventh cervical vertebra
	T8	Spinous processus of the eighth thoracic vertebra
	IJ	Deepest point of Incisura Jugularis
	PX	Processus Xiphoideus, most caudal point on the sternum
Clavicle	SC	Most ventral point on the SC joint
	AC	Most dorsal point on the AC joint
Scapula	TS	Trigonium Spinae, the midpoint of the triangular surface on the medial border of the scapula in line with the scapular spine
	AI	Angulus Inferior, most caudal point of the scapula
	AA	Angulus Acromialis, most laterodorsal point of the scapula
	PC	Most ventral point of processus coracoideus
Humerus	GH	GH rotation centre (estimated)
	EL	Most caudal point on the lateral epicondyle
	EM	Most caudal point on the medial epicondyle
Forearm	RS	Most caudal-lateral point on the radial styloid
	US	Most caudal-medial point on the ulnar styloid

Shoulder is the most complicated joint of the body. Proposed joint models are based on the dynamic use of common animation parameter of stiffness. During joints movement there are a lot of influences which are described as stiffness. During the movement the mobility of the joints is changed so stiffness is dynamic parameter. This dynamic stiffness is composed from any number of influences using the fuzzy-logic operators. In biomechanical point of view the scapula is the most important part of modeling the shoulder girdle and it is the best indicator of setting joints (Štěpán, 2009). Due to the presence of overlying soft tissue, accurate measurement of the kinematics of the scapula is problematic and very difficult using noninvasive methods (Lovern, 2009). In 2005 the International society of biomechanics (ISB) issued a set of recommended standards for modeling the shoulder complex. The recommendations were based on the work of Grood and Suntay who developed a methodology to calculate relative movement of two body segments. The bones of the body can be viewed as a series of rigid links whose positions can be defined by the location of a point on the bone and the bone's orientation in space.

The bony landmarks for modeling the shoulder complex as recommended by the ISB are thorax, clavicle, scapula, humerus, forearm and their segments (Lovern, 2009). Acromion can be palpated well that's why it is important for the measurement movement of the shoulder girdle (Štěpán, 2009).

SHAPE OF SHOULDER

The **scapula's position** in natural stance often reflects an individual's daily lifestyle and stress level. For example, many people stand naturally with the shoulder girdle in an abducted position. The neutral anatomic position of the scapula is flat and flush on the rib cage and centered on the upper back of the rib cage, with the inside border of the scapula between 2.5 and 3 inches from the spine. The scapula lies between the second and seventh thoracic vertebra. In ideal alignment, the scapula lies directly over the posterior ribcage with the upper back in good neutrally alignment (Bryan, 2003). The 3D orientation of the scapula was determined at static positions 0° of humeral elevation in the scapular plane. Muscle lines of action relative to the scapula were described for the trapezius, rhomboids, and levator scapulae. Contributors to scapular tipping moments included the rhomboid major (posterior tipping). Contributors to internal, external rotation moments included the upper and middle trapezius (internal rotation) (Ludewig, 1997).

In case of a **dysfunction** the scapula can be oriented protracted and retracted. Average retraction angle is −7.7° from neutral position 0°, and average scapular protraction is 7.6° from neutral position. Protracted and retracted scapula positions reduce isometric shoulder flexion force. Upward strength is reduced with the scapula retracted (99N) compared to a neutral posture (109N). Neutral scapula postures generate higher force than protracted postures. The influence of scapular orientation is shoulder muscular activity levels. When tension relationships and joint congruity are optimal, the mechanical sequence of muscle firing works efficiently. If a muscle is chronically contracted or hypertonic it becomes a poor mover (Bryan, 2003).

Muscles act together to keep the basic position of the segment of the body. Muscular tone primarily depends on actual state of the central nerve system. Lower or higher muscle tone is a symptom of pathology. Normal muscle tone is described as a reflex which is important for realization and coordination of motion. Muscle tension is a reflection of the whole human body, including manifestation of sensibility, irritability, character of the person. A normotonic muscle is stretchy and elastic and resists a change of shape. Hypotonic muscle is flat, it is linked with hypermobility which leads to a lower protection of joints. A hypertonic muscle changes the shape of the shoulder. Hypertonic muscle is bigger than other muscles. The hypertonic m. trapezius causes that the scapula goes up to head (craniomedial) and the contour of the shoulder girdle is changed which is called the gothic arms (Janda, 1982; Čemusová, 2008). Superficial muscles change the trajectory of the motion and global shape of the region. (i.e. levator scapulae pulls scapula up cranially and medially) (Otáhal et al., 2010).

In case of a **shoulder pathology** the scapula changes the position and reduces the mobility. Winging scapula is the most common scapulothoracic disorder which can be either static or dynamic. Static winging is due to a fixed deformity in the shoulder girdle, spine or

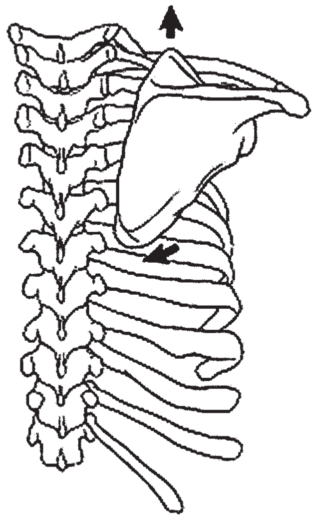

Figure 1. The winging scapula as a result of palsy of serratus anterior caused by injury to the long thoracic nerve (Atasoy, 2000)

ribs and is characteristically present at rest with arm at the side. Dynamic winging is caused by muscular imbalance during active or resisted shoulder movement. Winging can be classified as primary or secondary. Primary winging occurs after neurological injury, usually involving the long thoracic, spinal accessory, or dorsal scapular nerves and in association with a tumour of the ribs or scapula, with fractures of the scapula and with rupture or absence of the periscapular muscles. Secondary winging is due glenohumeral and subacromial disorders such as tears of the rotator cuff, adhesive capsulitis or impingement which produce abnormal scapulothoracic movement. The position of the winged scapula depends on the specific nerve injury and the resulting pattern of muscle paralysis. Injury of the long thoracic nerve causes paralysis of serratus anterior. The scapula assums a high position with the upper medial corner rotated laterally and the inferior pole medially because of the unopposed action of trapezius, levator scapulae and the rhomboid muscles. Injury to the spinal accessory nerve causes paralysis of trapezius and the scapula adopts a lower position. Contraction of the intact serratus anterior results in rotation of the lower pole laterally and the upper medial corner medially. The shoulder is depressed with lateral translation of the scapula and lateral rotation of the inferior angle. Paralysis of the levator scapulae and the rhomboid muscles may occur as a result of injury to the dorsal scapular nerve. The resultant winging is usually mild and similar to that caused by paralysis of the trapezius. The most common cause is paralysis of the serratus anterior which is innervated solely by the long thoracic nerve, a mainly motor nerve arising from the C5, C6 and C7 roots. Winging of the scapula can be a disabling deformity. The functional disability results from diminished abduction and forward flexion of the shoulder, principally because of loss of muscle control of the scapulothoracic articulation. Active abduction and flexion of the shoulder is 80°. Further abduction induced winging of the scapula, discomfort and instability (Atasoy, 2000).

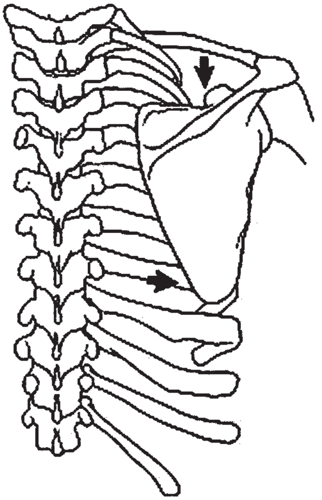

Figure 2. The winging scapula as a result of palsy of trapezius due to injury to the spinal accessory nerve (Atasoy, 2000)

SHOULDER STABILITY

Shoulder function is a compromise between mobility and stability. **The stability** of the joint is mainly based on active muscle control with a role of the glenohumeral capsule, labrum and ligaments. For proper joint stability, the joint translations should be constrained, either by compressing the head in the socket in a spherical joint such as the glenohumeral joint, or by ligamentous structures in other joint types. If large translational forces in parallel to the articular surfaces occur, these forces must be counteracted by ligaments or stabilizing muscle activity, redirecting the joint reaction force towards the articular surface.

The joint congruency of the articular surfaces and the constraint area of the glenoid cavity have effect on the stability and translational stiffness of the GH joint. For joint stability the important parameter to consider is the percentage of enclosed curvature between articular surfaces, or the amount of surface that is covered by the glenoid. A large enclosed curvature will produce a more stable joint, but will allow larger reaction forces. Smaller enclosed curvatures will be less stable intrinsically and, therefore, require more muscle control.

Two congruent curvatures with a small and constant joint gap make sense when joint lubrication is considered. A constant fluid film between the articular surfaces will make almost frictionless motions possible. The pressure in the synovial fluid will be directly related to the joint reaction forces. In a constant joint gap, the intraarticular pressure will be almost constant, except at the end of the gap, where the pressure will be lower. A deformable flap like the labrum will reduce the drop of the intraarticular pressure, and thus improve the lubrication of the joint. Negative intra-articular pressure is one of the stabilizing mechanisms of the GH joint. Traction of the arm produces a negative pressure (force of about 22 N). Intraarticular pressure plays a role in the proprioceptive behavior of capsule and labrum, based on the effect of pressure sensors. An important function of the labrum lies in its role in joint lubrication. The labrum may function as a pressure sensor, whereas its mechanical properties are unlikely to add to joint stability.

From a mechanical point of view, **instability** is the property that a joint will not return to its original position after a perturbation. In clinical terms this is similar to a dislocation of the joint. In mechanical terms this would be considered as a compliant joint, which is still stable if the joint returns to the original position. The GH joint can only dislocate if the resulting joint reaction force vector (summation of muscle, ligamentous, gravitational and other external forces) at the centre of the humeral head points outside the glenoid. The rotator cuff muscles are especially suitable to direct the joint reaction force into the glenoid. Based on mechanical analysis one might conclude that the rotator cuff musculature, arranged in a half circle around the GH joint, is very effective in directing the joint reaction force.

Joint stabilization can be done by continuous co-contraction of muscles, or by the use of a control system based on short-latency and long latency reflexes. The most suitable place for sensors that signal joint force direction is in, or near the glenoid labrum. The Pacini and Ruffini receptors were described in the middle, anterior and superior glenohumeral ligaments, as well as free nerve endings in the lower half of the labrum. The sensors in the ligaments have a signaling function only in the end ranges of motion. These sensors play an essential role in movement control. A nerve conduction velocity is about 1.2–6 m/s, which is typical for Ruffini and Pacini sensors. The muscles controlling the GH joint are based on feedback from muscle spindles – Golgi tendon organs. Due to the glenohumeral motion the orientation of the capsular fibers changes, and that this results in proprioceptive sensoric signals.

The coracohumeral ligament and the superior glenohumeral ligaments are seen as inferior stabilizers for adducted shoulder. The middle glenohumeral ligament is assumed to be restraining external rotation from 0–90° abduction and to provide anterosuperior stability. The inferior glenohumeral ligament complex is thought to be the most important stabilizer against anteroinferior shoulder dislocation. The stabilizing function is only possible if the ligaments are exerting forces, which implies that they are stretched beyond their rest length. The glenohumeral ligaments consist mainly of collagen fibers, which have a maximal strain of about 3–7%, which is equivalent with a possible rotation in the glenohumeral joint of about 9.5°. The coracoclavicular ligament is strong but not considerably stiff (103 N/mm). It forms a limitedly deformable link between the scapula and clavicle, scapular and clavicular motions, which allows for 8 to 14 mm elongation before failure, which is equivalent to about 20° of AC joint rotation (Veeger, 2007).

MOBILITY OF SHOULDER

Shoulder girdle motion is complex and involves synchronous **movement of the scapula**, clavicule, and humerus. The motion of the shoulder complex is described as the sum of movement contributed by synchronous participation of the sternoclavicular, acromioclavicular, glenohumeral and scapulothoracic articulations (Lovern, 2009). Motion of the scapula on the thorax is essential for normal function of the upper extremity. The orientation of the scapula relative to the thorax and the position of the scapula on the thorax are used to describe 3D scapulothoracic motion (Ebaugh, 2005; Dayanidhi, 2001). The majority of previous biomechanical descriptions of scapulothoracic muscle actions have been limited to two dimensional models describing scapular upward and downward rotation. Three dimensional models describe scapular external, internal rotation, and anterior, posterior tipping (Johnson, 1997). The GH joint can be considered a 6 degree of freedom (DOF) joint, with three translational and three rotational DOF. The kinematic data for scapular orientation and position are described using three scapular rotations and two clavicular rotations. The orientation of the scapula relative to the trunk is described using Euler angle sequence of external, internal rotation, upward, downward rotation, and posterior, anterior tilt. (Ebaugh, 2005; Ebaugh, 2006; Štěpán, 2009). Two clavicular rotations, protraction, retraction and elevation, depression are used to describe scapular position. The shoulder is a closed chain mechanism in which the humeral head is positioned by a closed chain formed by thorax, scapula and clavicle. It is obvious that a decrease in degree-of-freedom of the system due to fusion, or pain, will reduce the function of the system. In addition, changes in dimensions of the elements of the mechanism will also influence the kinematic and dynamic behavior (Otáhal, 2011; Veeger, 2007).

As the arm is raised, the generally accepted pattern of motion at the shoulder is as follows: The scapula upwardly rotates, posteriorly tilts, and externally rotates. The clavicule elevates and retracts, and the humerus elevates and externally rotates (Ebaugh, 2005). This coordinated motion is important for normal function of the shoulder girdle

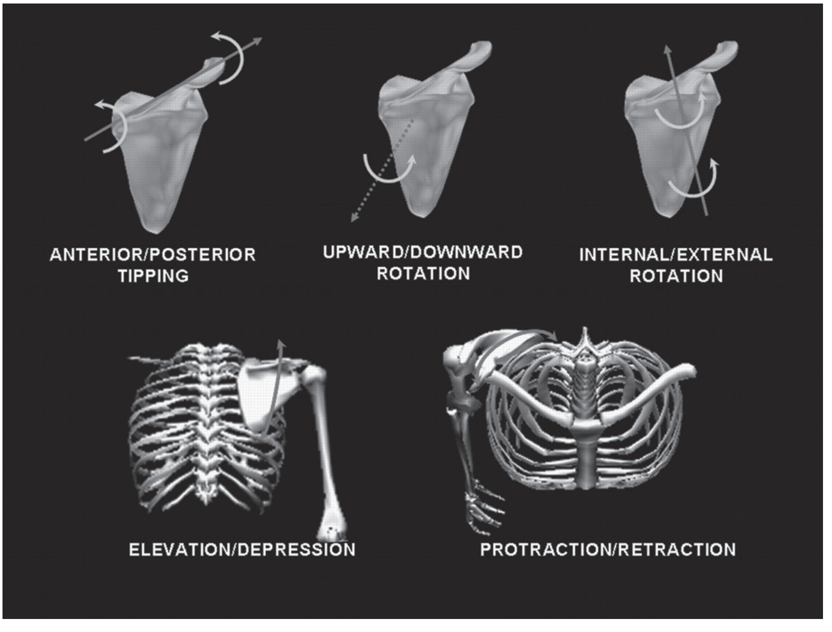

Figure 3. Movement of scapula [http://www.kmle.co.kr, 20. 10. 2011]

and is depend upon capsuloligamentous structures and neuromuscular control. The humerus is able to axially rotate about 135°relative to the scapula, the glenohumeral elevation is up to 120°. The scapular motion is responsible for approximately 1/3 rd of the total arm elevation. This process is coined the scapulohumeral rhythm. Scapulothoracic fusion, as is sometimes performed in paralysis of serratus anterior, results in a maximal elevation capacity of around 100° (Veeger, 2007).

Due to the important role that the shoulder musculature has in producing and controlling shoulder motion, impairments of these muscles could alter the motion of the scapula, clavicule, and or humerus. **Altered scapular kinematics** was identified in individuals with impingement syndrome, rotator cuff tears, and glenohumeral instability. Several variables were identified as risk factors for the development of shoulder pain and include highly repetitive use of the arm (i.e. wheelchair users), work with the arm in an elevated position, and heavy work loads (Morrow, 2011).

The fatigue of the shoulder muscles was shown to result in altered shoulder proprioception. It is possible that muscle fatigue results in changes in muscle spindle sensitivity, activity which then leads to altered feedback to the central nervous system. This altered feedback may result in altered muscle coordination with subsequent alterations in shoulder kinematics. The infraspinatus and deltoid muscles were fatigued to a greater degree than the upper and lower trapezius and serratus anterior. The greater amount of fatigue in these muscles could have resulted in a compensatory response in the scapulothoracic musculature which resulted in increased amounts of scapulothoracic motion. Another possible explanation for the observed changes in scapulothoracic motion could be the decreased amount of humeral external rotation. Perhaps altered glenohumeral motion in and of itself was the primary mechanism for increased scapulothoracic motion. The changes in scapulothoracic motion are a direct result of fatigue in the external rotator muscles (Ebaugh, 2006).

The fatigue of the shoulder girdle musculature results in altered scapulothoracic and glenohumeral kinematics and the shoulder muscle fatigue resulted in increased upward rotation of the scapula. In general, greater scapulothoracic motion and less glenohumeral motion are described following muscle fatigue. Muscle fatigue influences humeral external rotation which decreases. Knowing how muscle fatigue influences humeral external rotation is important since this motion is believed to clear the greater tuberosity from underneath the acrominon thereby preventing excessive compression of the soft tissues located within the subacromial space. Between 60° and 120°elevation, the average decreased humeral external station was between 4° and 7° (Ebaugh, 2005; Ebaugh, 2006). This reduced external station may prevent adequate clearance of the greater tuberosity and subsequently place the soft tissues in the subacromial space at risk for injury. The issue of trauma of soft tissues is also discussed by Jelen (1999). This range of humeral elevation 60–120° is associated with a decrease in the width of the subacromial space and high subacromial pressures (Ebaugh, 2006).

The scapulothoracic kinematic changes may be viewed as compensatory motions in an attempt of offset the effects of decreased humeral external rotation. Upward rotation and external rotation of the scapula are believed to play an important role in maintaining an optimal relationship between the humeral head and glenoid fossa as well as maintaining the size of the subacromial space. The increased upward and external rotation of the scapula may act to rotate the acromion up and back away from the greater tuberosity. Furthermore, the increased amount of clavicular retraction could be an attempt to prevent a reduction in the size of the subacromial space. In individuals who use their hands in a repetitive overhead manner these compensatory motions may prevent narrowing of the subacromial space thereby reducing potentially harmful forces in the subacromial space. The increase in upward rotation of the scapula may be detrimental in that it leads to a reduction in subacromial space.

Another point of view **the orientation and position of the scapula** on the thorax is influenced by whether the arm is elevated actively or passively. In case of active arm elevation the most pronounced change is more upward rotation of the scapula. The upper and lower trapezius and serratus anterior muscles have an important role in producing upward rotation of the scapula. Decreased amounts of scapular upward rotation is noted when the arm was passively elevated. The decreased scapular upward rotation leads to glenohumeral instability and reducing the size of the subacromial space by altering the optimal alignment between the humeral head and glenoid fossa as was written above (Veeger, 2007).

The human shoulder can be seen as a perfect compromise between mobility and stability. Its large mobility is based on the structure of the glenohumeral joint and simultaneous motion of all segments of the shoulder girdle. This requires fine-tuned muscle coordination. The large mobility of the glenohumeral joint is possibly due to the small articular surface of the scapula, the glenoid surface, as well as the loose connecting capsule. The capsule is not tight enough to prevent joint dislocation. Passive tension in ligaments contribute to the motion, i.e. the coracoclavicular and acromioclavicular ligaments contributed to clavicular elevation (Ebaugh, 2005). On the other hand the ligaments can reduce the motion. Capsulorraphy, or thermal shrinking of the glenohumeral capsule to reduce shoulder luxation, can strongly reduce the mobility of the glenohumeral joint (Veeger, 2007).

The human upper extremity range-of-motion covers almost 65% of a sphere while the humerus can be axially rotated at almost any orientation within this sphere. In addition to the truly three-dimensional mobility of the shoulder complex, the system is capable of exerting forces in almost any direction. This versatility is enabled by a wide variety of mono-, bi- and tri-articular muscles. Each muscle will not only generate joint moments to meet external forces, but will also generate considerable undesired joint moment components, which must be compensated by other muscles. This effect is highly depended on the shoulder posture at hand. The large range of motion of the shoulder and the large moment arms imply large shortening ranges for scapulohumeral muscles. This is reflected in their fascicle lengths. The optimal muscle fascicle length for the scapulohumeral muscles varies between approximately 70 mm (m. supraspinatus) to 180 mm (Veeger, 2007). The lengths in the scapulothoracic muscles 111.4 mm are significantly longer than the glenohumeral muscles 91.5 mm (Altobelli, 2005). The long fascicle lengths for shoulder muscles guarantee a long active force trajectory, which covers the full movement range of shoulder. The long fascicle lengths will make muscles relatively insensitive for length changes in most of their working range (Veeger, 2007).

Joint moments are determined by the muscle force and muscle moment arms. The scapula provides large moment arms for the scapulothoracic muscles. The serratus anterior is the main torque-generating muscle during elevation of the arm, whereas the trapezius directs the clavicle and scapula towards the plane of elevation, and elevates the clavicle to allow the rotations of the scapula. The m. serratus anterior provides a latero-rotating moment. Adduction moments at the humerus are mainly generated by the tri-articular muscles like the m. pectoralis major (dependent on elevation angle) and m. latissimus dorsi. These muscles directly transfer force to the thorax, providing simultaneous adduction moments around the GH, AC and SC joint. This adducting moment presses the laterally rotated scapula against the thorax. During forward flexion of the humerus, the gravitational forces will lift the scapula from the thorax. The serratus anterior and the rhomboidei will press the scapula on the thorax, and provide a stable base for the humeral motions. This process is what is visible as the scapula humeral rhythm (Veeger, 2007). This rhythm is that scapula upward rotates relative to humeral elevation. This rhythm shows to deviate from normal in subjects with impingement syndrome (Ebaugh, 2005). For three-dimensional structures such as the shoulder, it is difficult to describe the muscle function needed to obtain the desired joint moments. A description by the potential moment vector (pmv) combines the effect of moment arm (r) and force direction, unit vector (f):

$$\mathbf{pmv} = \mathbf{r} \times \mathbf{f}$$

$$r = p_{insertion} - p_{joint}$$

$$f = (p_{origin} - p_{insertion}) \,/\, //p_{origin} - p_{insertion}//$$

The pmv has the direction of the moment vector caused by the muscle. Multiplication with the actual muscle force will result in the muscles moment. The magnitude of the pmv is equal to the magnitude of the moment arm r (Veeger, 2007).

CONCLUSION

The scapula is important part of the shoulder complex and it helps us to determine the shape and motion of the shoulder. Altered scapular position in static posture or during the movement of the upper extremity can highlight to shoulder pathology. [Johnson, 1997] That's why it is necessary in clinical praxis to know the biomechanical relations among shape and mobility of shoulder complex.

ACKNOWLEDGEMENTS

This work was supported by the grant SVV-2011-263601 and by the GAČR P 407/10/1624 grant.

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VZTAH TVARU A POHYBLIVOSTI PLETENCE RAMENNÍHO Z POHLEDU BIOMECHANIKY

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SOUHRN

Cílem práce je popsat biomechaniku pletence ramenního. Rameno je nejsložitějším kloubem lidského těla. Biomechanické modely ramene poukazují na fakt, že právě lopatka je nejdůležitější částí ramene, která determinuje nastavení ostatních kloubů celého pletence. Tato práce popisuje tvar a pohyblivost pletence ramenního (a to především lopatky) u zdravých i nemocných jedinců. V případě patologie ramene mění lopatka nejen svou polohu ale i pohyblivost. Pletenec ramenní zajišťuje značnou pohyblivost při současné stabilitě kloubu. Článek se také věnuje problematice stability a instability ramene.

Klíčová slova: model kloubu, scapulothorakální kinematika, odstávající lopatka, scapulohumerální rytmus

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