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KINEMATICAL ANALYSIS OF SHOULDER JOINT DURING ELEVATION MEASURED BY ULTRASOUND-BASED MEASURING SYSTEM

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Abstract

In order to analyse shoulder joint movements, the author uses a ZEBRIS CMS-HS ultrasound-based movement sensor and a related measurement program developed by the researchers in Biomechanical Laboratory in TUB. In essence, the measurement involves the determination of the spatial position of the 16 anatomical points specified on the basis of the coordinates of ultrasound-based triplets positioned on the upper limb, the scapula, and the thorax, measured in the course of motion. Kinematic characteristics of 74 shoulder joints of 50 healthy persons were identified during elevation. A specially developed processing program was used for the calculation and analysis of humerus elevation, scapulothoracal, and glenohumeral angles, defined as angles of spatial vectors; the glenohumeral, scapulothorocal and capuloglenoid ratio to be determined therefrom; and of scapulothoracal and glenohumeral rhythm during motion. Motion of the humerus and the scapula relative to each other was characterized by the rotation center of the two bones and rigid bodies as well as their absolute and relative displacement relative to each other. The biomechanical model of the shoulder joint during elevation can be described by analysing the results of the measurements performed.

Keywords: shoulder joint, shoulder joint kinematics, rotation centres, range of angle.

1. Introduction

The glenohumeral joint, which is the most freely moving joint in the human body, makes it possible to execute flexion, extension, hyperextension, abduction and adduction, horizontal abduction and adduction, as well as the medial and lateral rotation of the humerus by the combination of three motion types: turning, sliding, and rolling. Turning means rotation of the humerus head on the glenoidal surface. Sliding means a simple translation motion of the humerus head relative to the glenoidal surface. Rolling is produced as a combination of the two motions above [24]. The scapula can move both in the saggital and the frontal plane within the scapulothoracal 'joint' as it slides along the wall of the thorax and it performs rotation and tilting along its own longitudinal and transversal axes. In the sternoclavicular joint, the clavicle and the scapula rotate primarily in the frontal and transversal planes; in the sagittal plane, they only perform a tilting motion. In the acromioclavicular joint, rotation can be produced around all three axes. According to INMAN et al

[9], rotation in both joints may even reach 40 degrees. On the basis of tests using electrodes placed in the acromion and the clavicle ROCKWOOD and GREEN [21] demonstrated that the clavicle rotated less than 10 degrees in the course of an entire abduction.

Up to a 30-degree abduction of the arm, the glenohumeral ratio is between 4:1 and 7:1; over 30 degrees, the motion range of the two joints is nearly identical [5, 6, 15, 16, 20]. According to DODDY et al. [5], in abduction of 90 to 150 degrees, the motion ranges of the scapulothoracal and glenohumeral joints are nearly identical; POPPEN and WALKER [18] specified scapuloglenoid ratio of 5:4.

POPPEN and WALKER [18] measured glenohumeral translation on X-ray images of healthy shoulder joints. Based on their measurements, the proximal translation is 3 mm in the first phase of abduction – between 0 and 30 degrees –; as abduction is increased, an 1 to 2 mm distal translation – rather than proximal translation – can be observed. HOWELL et al. [7] also applied radiological methods to measure posterior translation of approx. 4 mm in maximum extension and outward rotation. SIDLES et al. [22] studied normal shoulder joint translation by physical examination and instability tests: it may reach as much as 11 mm.

MESKERS et al [13] used an electro-magnetic motion analysis system ('Flock of Birds') to examine shoulder joint motion during symmetric elevation between 0 and 150 degrees. Their measurement essentially means that the triplet transmitters placed on the sternum and the upper arm can be used for the on-going recording of the position of these bones. The spatial position of the scapula was determined by a locator after stopping the motion. The system is quasi-dynamic: the motion must be stopped to perform the measurement, meaning that motion dynamics could not be recorded. Based on the characteristics measured it was established that in case of elevation performed symmetrically by two arms, the thorax is rotated backwards to a small degree and as a consequence of symmetrical motion, there is a minimum torsion and lateral rotation of the thorax. The clavicle is elevated to a 100-degree abduction in the course of abduction by the humerus, then the degree of elevation is decreased; rotation gradually increases from 0 degrees to reach a maximum of approx. 60 degrees. Based on their investigations, the scapulothoracal ratio is 2:1. Scapular pronation changes only to a small degree.

The electromagnetic 'Flock of Birds' motion analysis system and the corresponding measurement control and processing softwares made it possible to determine the helical axis and rotation center, of the glenohumeral joint on a cadaver shoulder joint [4, 23, 24] for characterizing the dynamics of motion. Movement of the joint can be characterized by displacement along a special axis named helical axis and turning around this axis. The rotation center, is a special point of the helical axis which is located the closest to a selected point of the joint. The helical axis of the glenohumeral joint was calculated from the angular velocity of joint, which is determined from change of glenohumeral angle [14, 23, 24], while rotation center, was calculated by mathematical regression [4, 23]. Both methods provided evidence that the rotation center, constantly changes and moves in the course of motion in the case of both abduction / adduction and elevation.

PASCOAL et al. [17] examined the scapulothoracal angle in the function of the humerus elevation in the case of various motions and loads, which is termed as scapulothoracal rhythm. They stated that scapulothoracal rhythm significantly changes to the impact of load.

The triplet [8] developed for the ZEBRIS ultrasound-based motion test system and to be fastened onto the acromion, the measurement control program pertaining to the system, and the 16-point biomechanical model used for shoulder joint motion analysis made it possible to define angles used in orthopaedy (humerus elevation, scapulothoracal, and glenohumeral angle) as angles of spatial vectors. The accuracy of the measurement method and the processing program [8] enables us to calculate, with proper accuracy, the velocity and acceleration of the designated anatomical points from the position vectors of such points, as well as to determine the angular velocity and the position vector of the rotation centers of the bones constituting the shoulder joint as rigid bodies using the closed formula deduced by KOCSIS and BÉDA [11]. The relative position and displacement of the rotation centers, of the bones constituting the shoulder joint are assumed to be suitable for the dynamic analysis of shoulder joint motion.

The research is aimed to jointly produce a test method and corresponding biomechanical parameters suitable for modelling shoulder joint motion. A further objective is to identify the physiological background of the new parameters on healthy subjects and generate a databank for performing further investigations.

2. Materials and Methods

Subjects

In the course of the examination, the kinematic characteristics during elevation of 74 shoulder joints of 50 healthy subjects were analysed. Before starting motion tests, a specialist of orthopedic physically examined each of the subjects, on the basis of which the Constant score was taken [2, 3]. Those reporting any pain or disorder in the upper limb in the course of the previous year were excluded from the study. There were 32 males (average age 28.1± 5.1 years, average height 175.9± 14.9 cm, average weight 77.1± 8.4 kg, Constant score 100/100) and 18 females (average age 24.6± 6.12 years, average height 168.9± 22.3 cm, average weight 66.1± 5.5 kg, Constant score 100/100) involved in the tests.

The tests were authorized by the Regional Science and Research Ethics Committee of Semmelweis University under no. 114/2004. Each voluntary subject provided an informed written consent to performing the tests in advance.

Measurement Method, Biomechanical Model

Displacements of the shoulder joint can be recorded without stopping the movement using the ZEBRIS CMS-HS (ZEBRIS, Medizintechnik GmbH, Germany) computer-controlled ultrasound-based movement analysis system located at the Biomechanical Laboratory of the Department of Applied Mechanics of Budapest University of Technology and Economics. The movements of scapula can be recorded by self-developed triplets that can be fastened by vacuum to the acromion. In order to record shoulder joint motion, further triplets were placed onto the sternum, the upper arm and the lower arm; furthermore, three individual sensors were fastened to the clavicle. The measurement control software enables us to determine the spatial co-ordinates of specific anatomical points of the sensors and the segments examined (thorax, clavicle, upper arm, lower arm, scapula) from the dispersion time of the ultrasound recorded by the measurement system using the triangulation method. This requires that the position vectors of the anatomical points to be examined should be determined by an ultrasound-based pointer in the local system of co-ordinates defined by the measurement triplets before starting the measurement. [8, 10]. Using the 16-point biomechanical model developed, involving the following anatomical points into the examination: incisura jugularis, processus xyphoideus, processus spinosus of spondyle Th1, processus spinosus of spondyle Th6, 3 points of the clavicle, angulus acromialis scapulae, trigonum spina scapulae, angulus inferior scapulae, insertion point of m. deltoideus at the humerus, epicondylus ulnaris humeri, epicondylus radialis humeri, olecranon ulnae, processus styloideus radii, and processus styloideus ulnaea – shoulder joint motion can be described in a reproducible manner [8].

Procedure

Tests are performed with males stripped to the waist and with females in bra, so that the anatomical points around the shoulder and on the upper limb are easy to access. Each of the points involved in the investigation represent manually properly touchable anatomical and anthropometrical points for the person performing the examination. The 40 to 50 minute test includes the following major steps:

- Using polystyrene belts, the triplets containing three active sensors are fastened on the lower arm, the upper arm, and the sternum; three individual sensors are fixed on specific points of the clavicle by bilateral adhesive pads; and the self-developed triplet fastened to the scapula; and they are connected to the measurement system by the cables and the data collection unit according to the respective channel distribution (*Fig.1*).
- In the calibration phase, the person performing the examination uses an ultrasound-based pointer to assign anatomical points and records their position vector in the system of co-ordinates specified by the measuring triplets.
- The person examined abduces (elevates) his/her arm from a neutral position to a position of about 100 to 120 degrees in the plane of the scapula, which is a 20-degree anteflexion position of the arm. During the entire period of motion, the elbow is in a maximally extended position, and the lower arm remains pronated. In the course of six to eight motion cycles, the spatial

co-ordinates of the designated anatomical points are detected and recorded by the measurement control program.

Assessment Parameters

Stable and unstable shoulder joint kinematics can be properly described primarily by angles used in orthopaedic practice for characterizing shoulder motion. In biomechanical practice, the angles included by segments are projected to various planes and the size of the angles may change considerably. Errors caused by projection can be eliminated by applying angles included by spatial vectors. The following angles were included in our investigation:

1. The angle included by the thorax and the humerus (humerus elevation angle, HE): The angle included by the spatial vectors defined by the two points specified at the proximal and distal points of the sternum, the insertion point of musculus deltoideus, and the epicondylus radialis humeri anatomical points.
2. The angle included by the thorax and the scapula (scapulothoracal angle, ST): The angle included by the spatial vectors defined by the two points specified at the proximal and distal points of the sternum, and the angulus acromialis and trigonum spinae anatomical points.
3. The angle included by the humerus and the scapula (glenohumeral angle, GH): The angle included by the spatial vectors defined by the insertion point of musculus deltoideus and the epicondylus radialis humeri, angulus acromialis, and trigonum spinae anatomical points.

The range of different shoulder motions is described by the humeral angle range (range of the humeral angle formed by differences of the humeral angle at the initial and final positions); the scapulothoracic angle range (range of the scapulothoracic angle formed by differences of the scapulothoracic angle at the initial and final positions); and the glenohumeral angle range (range of the glenohumeral angle formed by differences of the glenohumeral angle at the initial and final positions. An advantage of applying the range of angles is that discrepancies arising from initial angular values due to different anthropometrical features of people can be eliminated, meaning that angle changes between the initial and final states of motion can be specified and analysed. We determined the glenohumeral ratio by dividing the humeral elevation angle range by the glenohumeral angle range; the scapulothoracic ratio by dividing the humeral elevation angle range by the scapulothoracic angle range; and the scapuloglenoid ratio by dividing the scapulothoracic angle range by the glenohumeral angle range. The advantage of the analysis of angular kinematics is that angular kinematics is used in orthopaedic practice to model the physical state of shoulder. A disadvantage is that angular kinematics cannot be used for characterizing dynamic motion accurately.

The theorem of CHASLES [1] states that the movement of a rigid body can be characterized by displacement along a special axis named helical axis and turning

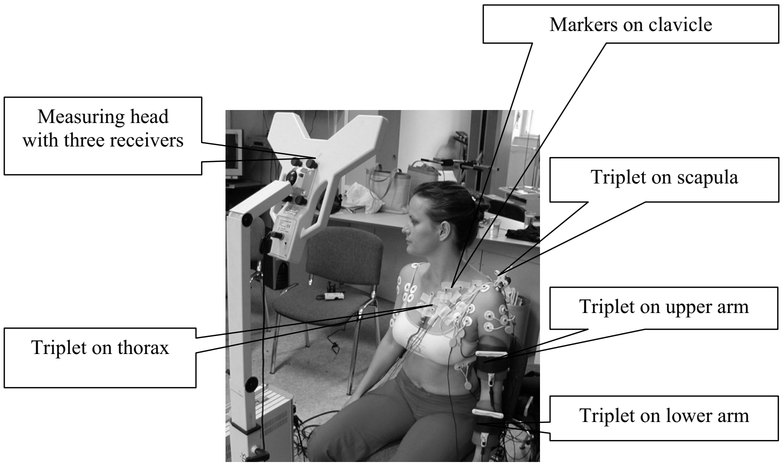

Fig. 1. Measurement arrangement

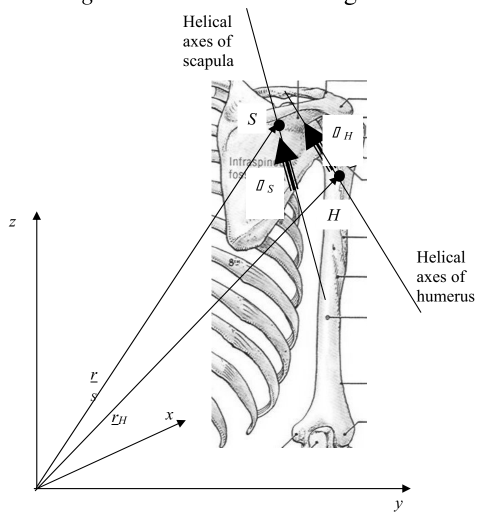

Fig. 2. Determination of the positions of rotation centers

around this axis. During motion, the helical axis itself is also moved, shifted, and rotated. In order to describe the state of motion of a body, two characteristics are required: (1) angular velocity calculated from the velocity of three points of the body; (2) position vector of the rotation center – a point on the helical axis which is the closest to a selected point of the rigid body.

The biomechanical processing program commercially available determines angular velocity inaccurately from the changes of angles projected to a plane. Instead, we use the velocities of investigated anatomical points for determining the angular velocity and position vector of rotation center of the rigid body. The accurate calculation procedure was deduced by KOCSIS and BÉDA [11], details of which are available in the literature [11, 12].

In order to analyse shoulder joint motion, (1) the rotation center of the shoulder joint or (2) the relative positions of the rotation centers of the bones constituting the shoulder joint can be used. The rotation center of the shoulder joint can be specified by the difference of the angular velocities of two bones constituting the shoulder joint [11, 12]. A disadvantage is that the motion of any two bones constituting the shoulder joint cannot be analysed in comparison to each other. In our investigations, the positions of the rotation centers of the humerus and the scapula are analysed, which can be used for characterizing both the own and the relative motion of the two bones examined (*Fig. 2*).

During the analysis of stable and unstable shoulder joint motion, the position vectors of the rotation centers of the humerus and the scapula were determined in each moment of the motion by an MS Excel-based processing program [10]. In case of the humerus, the point selected is the insertion point of m. deltoideus and while for the scapula it is angulus acromialis. The relative positions of the rotation centers of the humerus and the scapula are characterized by the absolute displacement of two points relative to each other (absolute displacement of rotation centers). The steps of determining the parameter are as follows:

- To determine the rotation centers of the humerus and the scapula when the two rotation centers are the closest to ($r_{H\,\min}$ and $r_{S\,\min}$), and the farthest from each other ($r_{H\,\max}$ és $r_{S\,\max}$).
- The maximum distance ($d_{SH,max}$) between the rotation centers of the scapula and the humerus:

$$d_{SH,\max} = \|r_{H,\max}, r_{S,\max}\|$$

where

$d_{SH,\max}$ is the maximum distance between the rotation centers of the scapula and the humerus;

$r_{H,\max}$ is the position vector of the rotation center of the humerus when the two rotation centers are the farthest from each other;

$r_{S,\max}$ is the position vector of the rotation center of the scapula when the two rotation centers are the farthest from each other;

and to determine the minimum distance ($d_{SH,\min}$)

$$d_{SH,\min} = \|r_{H,\min}, r_{S,\min}\|$$

where

$d_{SH,\min}$ is the minimum distance between the rotation centers of the scapula and the humerus;

$r_{H,\min}$ is the position vector of the rotation center of the humerus when the two rotation centers are the closest to each other;

$r_{S,\min}$ is the position vector of the rotation center of the scapula when the two rotation centers are the closest to each other;

- To determine the absolute displacement of rotation centers:

$$\Delta_{SH} = d_{SH,\max} - d_{SH,\min}$$

where

Δ_{SH} is the absolute displacement of the rotation centers of the scapula and the humerus;

$d_{SH,\max}$ is the maximum distance between the rotation centers of the scapula and the humerus;

$d_{SH,\min}$ is the minimum distance between the rotation centers of the scapula and the humerus.

The motion of the two bones constituting the shoulder joint can be characterized in relation to each other by the absolute displacement of rotation centers (Δ_{SH}). A disadvantage of applying this parameter is that displacements depend on the relative anthropometrical position of the bones constituting the shoulder joint. Results of various subjects cannot be compared with proper accuracy. In order to eliminate the error, this parameter was normalized by the minimum distance between the two rotation centers ($d_{SH,\min}$); the relative displacement of the rotation points thus arrived at is the displacement of the rotation points projected to a unit of length:

$$\varepsilon_{SH} = \frac{\Delta_{SH}}{d_{SH,\min}} = \frac{d_{SH,\max} - d_{SH,\min}}{d_{SH,\min}},$$

where

ε_{SH} is the relative displacement of the rotation centers of the scapula and the humerus;

Δ_{SH} is the absolute displacement of the rotation center of the scapula and the humerus;

$d_{SH,max}$ is the maximum distance between the rotation centers of the scapula and the humerus;

$d_{SH,min}$ is the minimum distance between the rotation centers of the scapula and the humerus.

Statistical Analysis

Data processing and statistical analyses were performed using MS Excel-based software of own development. In case of each subject examined, we calculated the average and the standard deviation of the kinematic characteristics calculated from the measurement results of the motion cycles recorded, and these data were further processed.

The biomechanical properties of individuals pertaining to a given group were statistically analysed using the MS Excel Analysis Tool Pak software. The average and standard deviation of the biomechanical properties of individuals pertaining to a given group were calculated. The uniformity of standard deviations was checked by an F-test; significance levels of the difference between the average values of identical parameters were determined by a t-test applying a symmetrical critical range in terms of shoulder joints on the dominant and opposite sides of both males and females.

3. Results

The spatial co-ordinates of the anatomical points specified in the course of shoulder joint motion analysis were used for determining humerus elevation (HE), scapulothoracal (ST), and glenohumeral (GH) angle values and their evolution through time, as well as the range of angle to be calculated from angle values. The absolute and relative displacement of the rotation centers of the scapula and the humerus were examined as new parameters. The average and standard deviation of the parameters were calculated. The F-test demonstrated the uniformity of standard deviations; significance levels of the difference between expected values can be determined by a two-sample t-test applying a symmetrical critical range. Results can be summarized as follows:

1. Changes through time of humerus elevation (HE), scapulothoracal (ST), and glenohumeral (GH) angle values do not add substantial extra information to motion analysis. The angle values to be determined at the initial and final states of motion (*Table 1*) greatly depend on the anthropometric data of the subject.
2. The analysis of scapulothoracal (ST) and glenohumeral (GH) angles in the function of the humerus elevation (HE) angle (*Fig. 3*) describes the rhythm of the two angles. The following statements can be made:
   - For the group of healthy subjects, scapulothoracal and glenohumeral rhythm are bilinear (*Fig. 3*), their regression lines are

$$y_1 = 75.08 + 0.303 \cdot x$$
$$y_2 = 59.95 + 0.557 \cdot x$$

The point of intersection of the two regression lines is at 59.57 degrees. The steepness of the regression lines shows that the steepness of scapulothoracal rhythm significantly (p=0.00113) increases over 60 degrees of elevation.

Regression lines of glenohumeral rhythm:

$$y_1 = 86.861 + 0.673 \cdot x$$
$$y_2 = 94.491 + 0.547 \cdot x$$

The point of intersection of the two regression lines is at 60.13 degrees. The steepness of the regression lines shows that the glenohumeral rhythm is significantly decreased over 60 degrees (p=0.121).

3. The following statements can be made by analysing the range scapulothoracal, glenohumeral and scapuloglenoid ratio (*Table 1*):

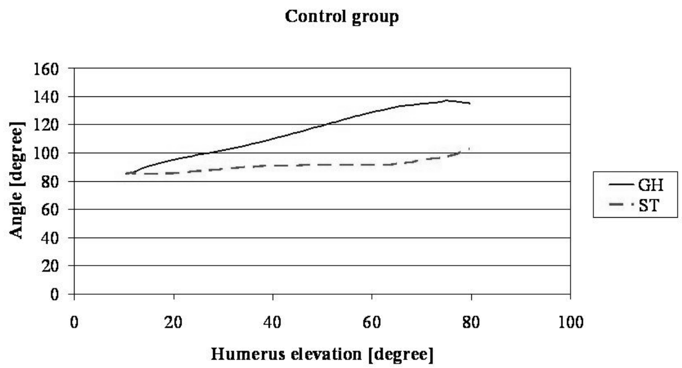

Fig. 3. Scapulothoracal and glenohumeral rhythm for healthy subjects

Table 1. Humerus elevatio (HE), scapulothoracal (ST), and glenohumeral (GH) angles in the initial and final position of motion; ranges

	Dominant side			**Opposite side**		
	Initial position	*Final position*	*Range*	*Initial position*	*Final position*	*Range*
HE	7.18	97.74	90.59	4.97	97.79	92.79
GH	91.75	142.05	50.3	85.24	140.84	44.41
ST	83.98	106.84	22.85	88.91	110.69	21.78

- There is no significant difference between the average values of ranges for the dominant and the opposite side.
- The glenohumeral ratio are 1.80 and 2.08, respectively in terms of the dominant and the opposite side; the scapulothoracal ratio are 3.97 and 4.26, respectively; and the scapuloglenoid ratio are 2.20 and 2.08. There is no significant difference between the average values of range of angle for the dominant and the opposite side.

For the dynamic analysis of motion, the positions of the scapula and the humerus relative to each other were analysed in terms of the maximum and minimum distance between the rotation center of the scapula and the humerus, the absolute and relative displacement of rotation centers:

1. The parameters of maximum ($d_{SH,max}$) and minimum ($d_{SH,\min}$) distances between rotation points and of the absolute displacement of rotation centers (Δ_{SH}) can be considerably affected by subjects' anthropometrical data,

therefore data evaluation is not objective (*Table 2*).

2. The relative displacement parameter (ε_{SH}) introduced in order to eliminate anthropometrical differences is independent from the anthropometrical data of subjects (*Table 2*).
3. Components to all three spatial directions of the relative displacements of rotation centers were calculated (*Table 2*).
4. There is no significant difference between the average values of any parameters in terms of the dominant and the opposite side (*Table 2*).

Table 2. The minimum ($d_{SH,\min}$) and maximum ($d_{SH,max}$) distance between the rotation centers of the scapula and the humerus, absolute (Δ_{SH}),relative (ε_{SH}) displacement and components of the relative displacement (ε_{SH}) of the rotation centers of the scapula and the humerus during motion

	Dominant side	**Opposite side**
$d_{SH,,\min}$(mm)	214.78	213.3
$d_{SH,,max}$(mm)	228.8	230.2
Δ_{SH}(mm)	14.12	16.92
ε_{SH}	0.065	0.079
$\varepsilon_{SH,x}$	0.039	0.042
$\varepsilon_{SH,y}$	0.021	0.019
$\varepsilon_{SH,z}$	0.047	0.064

4. Discussion

Shoulder joint motion kinematics can be described in the simplest manner by the parameters most frequently used, that is, angles describing shoulder joint motion, namely humerus elevation, scapulothoracal, and glenohumeral angle values. Definitions for the calculation of the angles used for the analysis of shoulder joint motion were altered as compared to angle calculations known in the literature. Due to the differences in the calculation method, the values found in the literature and the angle values specified by us are not comparable. The difference between the two calculation methods is most salient in the humerus elevation angle value at the neutral position of the humerus. If the humerus is in a neutral position, then its projection to the sagittal plane is zero, this means that the earlier definition of humerus elevation neglects the fact that the spatial vectors defined by the two points designated at the proximal and distal points of the sternum, the insertion point of musculus deltoideus, and epicondylus ulnaris humeri anatomical points are not parallel (*Fig. 4*). If the humerus elevation angle is defined as an angle of spatial vectors, then the angle value will not be zero in the neutral position, either. By analysing angle values, it can be established that the initial values depend on the anthropometrical characteristics of the subjects, therefore they cannot be used in themselves. Instead, range of angle as well as scapulothoracal and glenohumeral rhythm were examined. It is known from the literature [5, 6, 15, 16, 18] that in

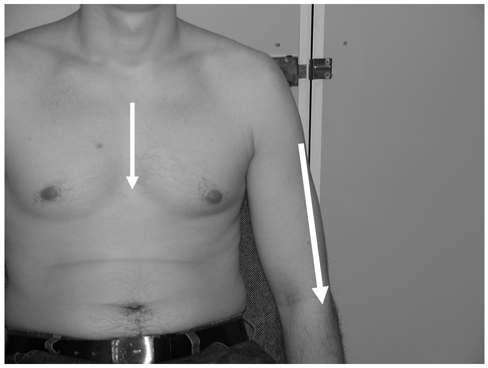

Fig. 4. Position of spatial vectors – defined by two points specified on the proximal and distal points of the sternum, the insertion point of musculus deltoideus, and the epicondylus ulnaris humeri anatomical points – relative to each other in a neutral position of the upper arm

healthy individuals, the scapuloglenoid ratio are between 4:1 and 7:1 in terms of the entire range of elevation. Based on our measurements, the respective scapulothoracal ratio, the glenohumeral ratio, and the scapuloglenoid ratio can be specified. The scapuloglenoid ratio is 2.20:1. This discrepancy may be attributed to the fact that in the literature, these values were specified by projected angle values determined by less accurate radiological tests and static postures to model motion, whereas we calculated the range of angle from spatial angles measured during motion. MESKERS et al. [14] stated that scapulothoracal rhythm was 2:1. No data were found for the trends of scapulothoracal and glenohumeral rhythms during the entire period of motion. On the basis of our measurements, it can be stated that for healthy subjects, the regression lines characterizing scapulothoracal and glenohumeral rhythm are bilinear (*Fig. 3*). The rhythm below 60 degrees is 3.3:1 and while it amounts to 1.79:1 over 60 degrees, meaning that following 60 degrees of elevation, the role of the scapula considerably increases in the execution of the motion. This discrepancy may be attributed to the fact that MESKERS et al. [14] calculated the rhythm from the angle values determined at the initial and final states of motion.

Based on the results yielded by specifying rotation centers, it can be established that during elevation, the location of rotation centers constantly changes. Correlations between the maximum ($d_{SH,max}$) and minimum ($d_{SH,\min}$) distance of rotation centers (*Table 2*), the absolute displacement (Δ_{SH}) between the rotation centers of the scapula and the humerus as calculated therefrom and the anthropometrical characteristics of subjects are not known, therefore these characteristics cannot be used as yet for characterizing the relative displacement of the humerus and the scapula.

The rotation centers relative displacement parameter (ε_{SH}) enables modelling of the relative position of the scapula and the humerus dynamically, taking motion into consideration, because it is independent from the anthropometric differences between subjects due to normalization. Components were calculated, to all three spatial directions of the relative displacements of rotation centers. Our tests show that the size of the parameter is independent from lateral dominance (*Table 2*). The size of this parameter depends on the movement of the scapula and the humerus relative to each other and the condition of ligaments and muscles. Motion of the scapula and the humerus relative to each other can also be modelled by the humerus elevation and the scapulothoracal angle values, range of angle, as well as the average of the two ranges of angle. On the basis of our tests, it was established that there was no significant difference between the average values of these parameters either, what also proves the independence of the rotation centers relative displacement parameter from lateral dominance.

The measurement method and the corresponding biomechanical parameters enable the modelling of shoulder joint motion. By using the 16-point model, humerus elevation, scapulothoracal, and glenohumeral angles can be defined as angles of spatial vectors. An advantage of this calculation method is that there are no errors arising from projection – which represents mapping not retaining angles. In order to eliminate the anthropometrical characteristics of subjects, the range of angle was introduced, representing the difference between the actual angle value and the angle value to be specified in the initial position. In our tests, rotation centers of the scapula and the humerus were analysed during motion. The measurement method introduced made it possible to determine the relative displacement of the two rotation centers. Following displacement normalization, parameter values will not depend on the anthropometrical characteristics of subjects. This parameter enabled the numerical display of the relative motion of the scapula and the humerus, which can be used for a more accurate modeling of shoulder joint motion. It is probably suitable for the analysis of injured shoulders and the numerical display of the kinematic effect of injuries or deformations.

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References

[1] CHOLNOKY, T., Mechanics (in Hungarian). Budapest: Tankönyvkiadó, 1968.
[2] CONSTANT, C. R. – MURLEY, A. H. G., A Clinical Method of Functional Assessment of the Shoulder. *Clin. Orthop* **214**, 1987, pp. 160–164.
[3] CONSTANT, CR., Assessment of the Shoulder Function. In: Gazielly, D.F., Gleyze, P., Thomas, P., editors. The cuff. Paris: Elsevier. 1979: pp. 39–44.
[4] DE GROOT, J.H. – BRAND, R., A three-dimensional regression model of the shoulder rhythm. *Clin. Biomech*, **16**, 2001, pp. 735–743.
[5] DODDY, S.G. – FREEDMAN, L. – WATERLAND, J., Shoulder Movements during Abduction in the Scapular Plane. *Arch. Phys. Med. Rehabil,* **51**, 1970, pp. 595–604.
[6] FREEDMAN, L. – MONROE, R.L., Abduction of the Arm in Scapular Plane: Scapular and Glenohumeral Movements. *J. Bone Joint Surg.,* **48A**, 1966, pp. 1503–1510.
[7] HOWELL, S. M. – GALINAT, B. J. – RENZI, A. J., Normal and Abnormal Mechanics of the Glenohumeral Joint in the Horizontal Plane. *J. Bone Joint Surg* **70A**, 1988, pp. 227–232.
[8] ILLYÉS Á – KISS, R. M. Method for Determining the Spatial Position of the Shoulder with Ultrasound-based Motion Analyzer. *Journal of Electromyography and Kinesiology*, **16(1)**, 2006, pp. 79–88.
[9] INMAN, V.T. – SAUNDERS, D.M.– ABBOTT, L.C., Observations on the Function of the Shoulder. *J. Bone Joint Surg* **26**, 1944, pp. 1–30.
[10] JURÁK, M. – KOCSIS, L., New Package for Calculation of Gait Parameters using Instrumented Treadmill. *In Proceedings of the third conference on mechanical engineering*, Budapest. 2002, pp. 500–504.
[11] KOCSIS, L. – BÉDA, G., Closed Formulae to Determine the Angular Velocity of a Body Segment Based on 3D Measurements. *Acta Physiologica Hungarica,* **88**, 2001, pp. 1–13.
[12] KOCSIS, L. – KISS, R. M. – JURÁK, M., Determination and Representation of the Helical Axis to Investigate Arbitary Arm Movements. *FACTA UNIVERSITATIS Series Physical Education,* 1, 2000, pp. 31–37.
[13] MESKERS, C.G.M. – VAN DER HELM, F.C.T. – ROZENDAAL, L.A. – ROZING, P.M., In Vivo Estimation of the Glenohumeral Joint Rotation Center from Scapular Bony Landmark by Linear Regression. *J. Biomech*, **31**, 1988, pp. 93–96.
[14] MESKERS, C.G.M. – VERMEULEN, H. M. – DE GROOT, J. H. – VAN DER HELM, F.C.T. – ROZING, P.M., 3D Shoulder Position Measurements Using a Six-degree of-freedom Electromagnetic Tracking Device. *Clin. Biomech*, **13**, 1998, pp. 280–292.
[15] MOOREY, B. – AN, K. N., Biomechanics of the Shoulder. In:. Rockwood Jr, C.A., Matsen III., F.A., editors. The shoulder. Philadelphia: WB Saunders. 1990, pp. 208–245.
[16] NOBUHARA, K., The Shoulder: Its Function and Clinical Aspects. Tokyo: Igaku-Shoin, 1987.
[17] PASCOAL, A.G. – VAN DER HELM, F.C.T. – CORREIA, P.P. – CARITA, I., Effects of Different Arm External Loads on the Scapulo-humeral Rhythm. *Clin. Biomech* S1, 1999, S21-S24.
[18] POPPEN, N.K. – WALKER, P.S., Normal and Abnormal Motion at the Shoulder. *J. Bone Joint Surg* **58A**, 1976, pp. 195–201.
[19] PROCTER, P. – PAUL, J., Ankle Joint Biomechanics. *J. Biomech,* **15**, 1982, pp. 627–634.
[20] RHOAD, R.C. – KLIMKIEWICZ, J.J. – WILLIAMS, G.R. – KESMODEL, S.B. – UDUPA, J.K. – KNEELAND, J.B. – IANOTTI, J. P., A New In-vivo Technique for Three-dimensional Shoulder Kinematics Analysis. *Skeletal Radiologie,* **27**, 1998, pp. 92–97.
[21] ROCKWOOD, C.A. JR. – GREEN, D.P., Fractures in Adults. Philadelphia: J.P. Lippincott, 1984.
[22] SIDLES, J. A. – HARRYMAN, D. T. II. – HARRIS, S. L., In Vivo Quantification of Glenohumeral Stability. *Trans. Orthop. Res. Soc* **16**, 1991, p. 646.
[23] VEEGER, H. E. J. – YU, B. – AN, K. N. – ROZENDAL, R. H., Parameters for Modeling the upper Extremity. *J. Biomech* **30**, 1997, pp. 647–652.
[24] VEEGER, H.E.J., The Position of the Rotation Center of the Glenohumeral Joint. *J. Biomech* **33**, 2000, pp. 1711–1715.
[25] WOO, S. L. Y. – MCMAHON, P. J. – DEBSKI, R. E. – FU, F.H. – BLOMSTROM, G. L., Factors limiting and defining shoulder motion: what keeps it from going farther? In: Matsen, F.A., Fu, F.H., Hawkins, R.J., editors. The Shoulder: A balance of mobility and stability. Philadelphia: WB Saunders. 1990, pp. 343–398.