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Kinematic and muscle activity characteristics of multidirectional shoulder joint instability during elevation

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Abstract Alterations of shoulder motion have been suggested to be associated with shoulder disorders. The objective of this study was to perform a 3D motion analysis (kinematic and electromyographical) of skeletal elements and muscles of shoulder joint in patients with multidirectional instability. Fifteen patients with multidirectional instability and 15 normal controls were investigated during continuous elevation in the scapular plane. The spatial coordinates of 16 anatomical points of the shoulder to determine kinematical parameters were quantified by an ultrasound-based motion analyzer. The activities of 12 muscles were measured by surface electromyography. Kinematic characteristics of motion were identified by scapulothoracic, glenohumeral, and humeral elevation angles; range of angles; scapulothoracic and glenohumeral rhythm; scapulothoracis, glenohumeral, and scapuloglenoid ratios; and the relative displacement between the rotation centers of the humerus and the scapula. The electromyographical characteristics of motion were modeled by the on–off pattern of muscle activity. Significant alterations in kinematical parameters were observed between patients and asymptomatic volunteers. The anterior, posterior, and inferior dislocations of shoulders with multidirectional instability could be properly modeled by the relative displacement between the rotation centers of the scapula and humerus. The shorter activity by m. pectoralis maior and all three parts of m. deltoideus and longer activity by m. supraspinatus, m. biceps brachii, and m. infraspinatus assure the centralization of the glenuhumeral head of a shoulder with multidirectional instability.

Keywords Shoulder joint · 3D kinematics · Electromyography Movement pattern · MDI

Introduction

Multidirectional instability of the shoulder is a complex condition that can be difficult to diagnose and treat [1, 2, 24, 25]. Neer and Foster [29] first recognized multidirectional instability as a unique and separate condition from unidirectional instability and developed the inferior capsular shift as a specific surgical procedure for its treatment. Multidirectional instability can occur in males and females, in different age groups and in most segments of the population, from sedentary individuals to elite athletes, and is considered to be a serious and more prevalent condition than previously realized [1]. It is characterized by a symptomatic global laxity of the glenohumeral joint [5], and may be present either traumatically, atraumatically, unilaterally, bilaterally, or with or without generalized joint laxity [7, 12, 24]. Individuals having multidirectional instability subluxate or dislocate anteriorly, posteriorly or inferiorly with current reproduction of symptoms in at least two directions [16, 32, 34]. Symptoms typically are associated with midrange positions of glenohumeral motion and often occur during activities of daily life [5]. The glenohumeral joint's relatively poor osseous and capsoligamentous stability necessitates a reliance on stabilization more than any other joint in the human body [30].

Earlier studies established that abducting muscle activity causes reductions of the subacromial joint pace and centering of the humeral head relative to the glenoid [4, 16]. Using a 3D MRI technique, an increased tilt of the scapula (2–4°) and a decreased scapulohumeral rhythm (2.2–2.5) in symptomatic shoulders of persons with a multidirectional diagnosis have been demonstrated [14] during humeral elevation in the scapular plane.

Baeyens et al. [3] identified the helical axis and the rotation center of the glenohumeral joint. They described that the humerus head of shoulder joints with inferior glenohumeral ligament disorder rotated outward from the glenoidal surface during the abduction with outward rotation while healthy shoulder joints did not tend to rotate. During the abduction, the rotation center of the injured glenohumeral joint tended toward the humerus head while the rotation center of the healthy joint did not.

To produce the complex kinematics at the shoulder during humeral elevation complemetary action of scapulothoracic and glenohumeral muscles are necessary. Electromyographic studies verified that patients with multidirectional instability have different electromyographical activity of m. deltoideus [27], of m. trapesius [33] and of rotator cuff [33] in the course of various kinds of arm movement. The different movement patterns and the imbalance of muscle strength of patients with multidirectional instability support that in-coordinated operation, the insufficient operation of dynamic stabilizers may play an important role in the development of shoulder joint with multidirectional instability [4, 16, 27, 33].

The results of previous investigation indicate that the assessment of 3D kinematical parameters including angular parameters; scapulothoracic, glenohumeral rhythm; displacement of rotation centers; and of electromyographical parameters is necessary to understand the motion of shoulders with multidirectional instability. A more complete understanding of shoulder motion (scapular and humeral) and muscle activity during continuous elevation in the scapular plane is needed in order to provide a basis for further understanding of shoulder dysfunction in individuals with multidirectional instability. The purposes of this paper are (1) to describe and compare kinematical parameters of stable and unstable shoulders; (2) to describe and compare muscle activities of m deltoideus, m. pectoralis maior, m. infraspinatus, m. supraspinatus with m. trapesius, m. biceps brachii, m. triceps brachii, the inferior part of m. trapesius, m. serratus anterior, m. latissimus dorsi and m. sternocleidomastoideus.

Materials and methods

Subjects

Fifteen subjects with multidirectional instability and 15 control subjects with normal, healthy shoulders participated in the study. Both shoulders were tested in all subjects. Subjects in the multidirectional instability group were tested after the original clinical diagnosis and did not receive any treatment or intervention before the test session. Pagnani and Warren [31] and Brown et al. [7] classify multidirectional instability according to three subsets that include (1) acute trauma, repetitive trauma or no trauma; (2) generalized joint laxity or isolated shoulder laxity; and (3) unilateral or bilateral symptoms. The 15 subjects with multidirectional instability tested in the current study were representative of all three subset categories. Of the 30 shoulders tested in the multidirectional instability group, 18 were symptomatic and 12 were asymptomatic (nine subjects were symptomatic bilaterally and six unilaterally). Given that bilateral symptoms occur relatively frequently in multidirectional instability, it was not possible to test homogeneous samples of unilateral subjects. Four of six subjects with unilateral instability had symptoms in the dominant limb, whereas two had symptoms in the nondominant limb. Patients were diagnosed and selected for inclusion in the multidirectional instability group based on the following criteria: (1) functionally significant inability to keep the humeral head centered in the

Table 1 Summary of subject data

	Control group		MDI patients	
	Female	Male	Female	Male
Number (*N*)	5	10	5	10
Age (year)	24.6 ± 6.12	28.1 ± 5.1	24.5 ± 4.6	19.2 ± 3.1
Height (cm)	168.9 ± 22.3	175.9 ± 14.9	166.9 ± 13.1	178.3 ± 12.1
Weight (kg)	66.1 ± 5.5	77.1 ± 8.4	60.3 ± 3.1	71.1 ± 4.1
Constant score	100/100	100/100	92/93	91/93

glenoid fossa, especially in positions not at the extremes of motion; (2) the absence of an injury mechanism likely to tear the glenohumeral ligaments; (3) spontaneous reductions of translations; (4) glenohumeral translations that duplicated the symptoms of concern to the patients; (5) a diminished resistance to translation in multiple directions as compared with a normal glenohumeral joint; and (6) an absence of traumatic lesions [26].

Exclusion criteria for subjects with multidirectional instability were mental incompetency, psychiatric or emotional difficulties related to voluntary instability and any musculoskeletal, neurological or genetic abnormality other than shoulder instability. Control subjects had no history of shoulder injuries, complaints or surgery. Before participating in the study, subjects were required to indicate limb dominance and to provide informed consent. Before starting movement tests, a specialist of orthopedics physically examined each of the subjects, on the basis of which the Constant score was taken [9, 10]. Table 1 summarizes the data of the subjects examined. The current study was administered according to ethical guidelines and procedures outlined by the Regional, Science and Research Ethics Committee of Semmelweis University under no. 114/2004.

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 motion analysis system located at the Biomechanical Laboratory of the Department of Applied Mechanics at the Budapest University of Technology and Economics.

The measurement head with three transmitters, emitting ultrasound signals at specific intervals, which are recorded by the active markers (the measurement frequency being 100 Hz) is located in front of the person (Fig. 1). Through a knowledge of the speed of the ultrasound, the distance between each marker and the measurement head, the location of transmitters can be calculated from the time delay of the transmission. Through a knowledge of the distance between the active markers and each of the three transmitters of the measurement head and the spatial coordinates of the transmitters, the spatial coordinates of the markers can be calculated using the method of triangulation at each moment of time during the measurement [21].

A fundamental assumption of biomechanical models is that the segments of the upper limb (the upper and lower arms), the scapula and the clavicle can be modeled as rigid bodies and all motion is generated in the joints [21]. The position and the orientation of a segment of the human body are determined by the position of three points per segment, named fundamental points. The position of an anatomical point of the same segment could be determined by its position in relation to the fundamental points. This means that before the measurement, the position of investigated anatomical points should be determined in relation to the fundamental points. The position of the anatomical points of a segment in relation to the fundamental points (in this case, the three markers) was specified by an ultrasound-based pointer during the calibration phase before measurement [21]. During motion, the position of fundamental points of each segment of the human body has to be measured by the ultrasound device. A computer code calculates online the position of investigated points from the position of fundamental points using the position vector of investigated anatomical points in a local

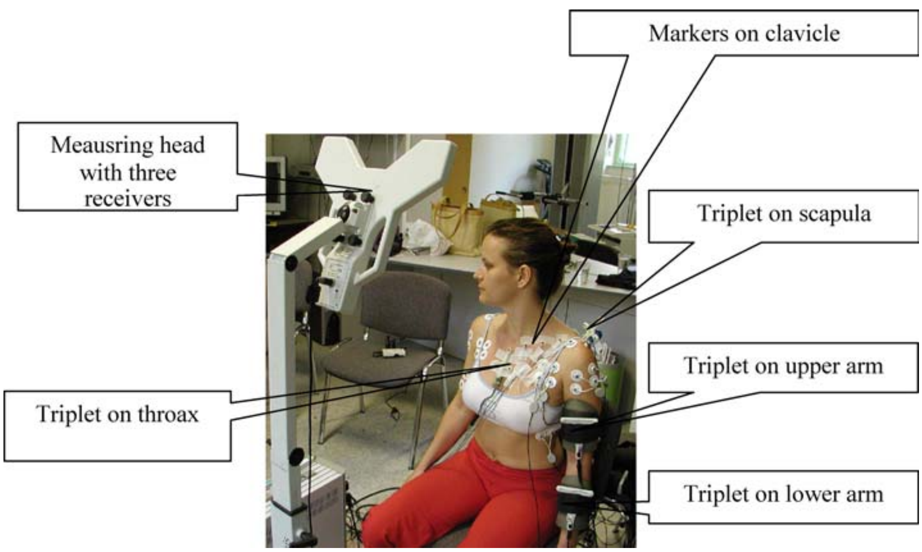

Fig. 1 Measurement arrangement

coordinate system defined by markers. The spatial coordinates of any number of anatomical points can be specified using the method described above. During measurement, the ArmModel software connected to the system promptly calculates, continuously records, numerically stores, and displays the spatial position of anatomical points [21].

The three fundamental points of a segment are the three markers, which are attached to the segment. The rigid plate with the three active markers, which are mounted at predefined distances from each other on rigid plates, is named a triplet. The triplets are attached to the lower and upper arm segments by a belt with a polyester shell (Fig. 1). The special polyester shell developed by us and a safe fixation by belt ensure no relative motion of the marker system on the segment and resist muscle motion. The three individual markers are fixed to different points of the clavicle by bilateral adhesive pads (Fig. 1). Movements of the scapula can be recorded by triplets of own development that can be fastened by vacuum to the acromion (Fig. 1); connection by vacuum ensures no relative motion of triplets on the acromion. The anatomical points are fixed to the local coordinate system by a pointer during the calibration phase, the relative position vectors are constant, which means that when the skin is moving on the hypothetical anatomical point; the calculation does not take this into consideration. The triplets and the fixation together reduce skin motion. It is important to check whether the triplet is stable. During the measurement, the software calculates the distances between the epicondylus ulnaris humeri and epicondylus radialis humeri, between the processus styloideus ulnae and radii and between the angulus acromialis and angulus inferior scapulae. If those distances are constant during the motion, the triplets are stable; if those distances are not constant, the triplets are repositioned during the measurement, and the whole procedure has to be repeated.

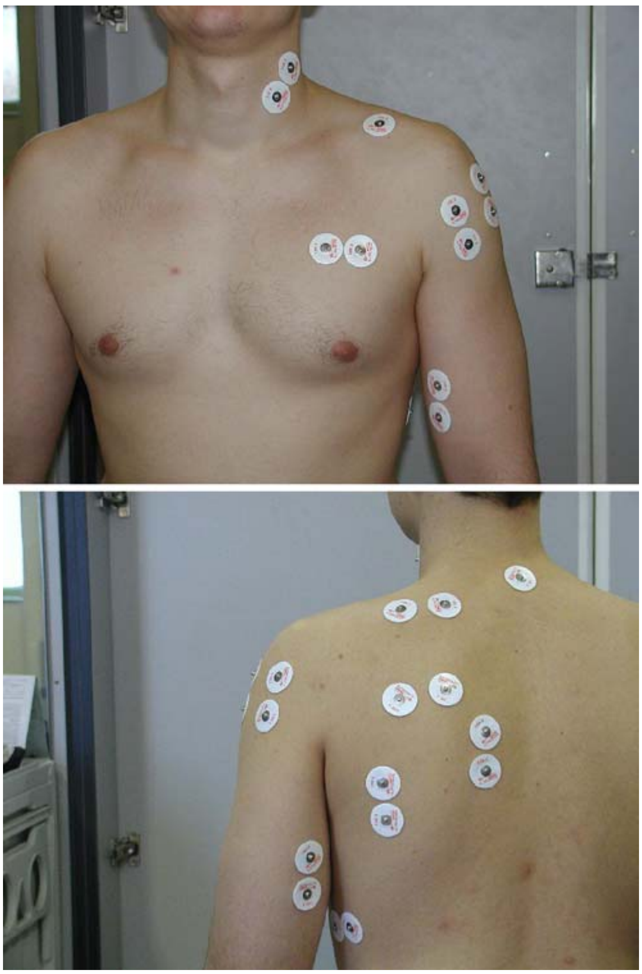

Fig. 2 Electromyography measurement arrangement during the complex measurement of the shoulder joint

Using the 16-point biomechanical model developed, involving the following anatomical points in 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, adhesion point of m. deltoideus at the humerus, epicondylus ulnaris humeri, epicondylus radialis humeri, olecranon ulnae, processus styloideus radii, and processus styloideus ulnae—shoulder joint movements can be described in a reproducible manner [17]. The verification and description of measuring method are written in detail [17].

The structure of the ZEBRIS CMS-HS movement analysis system and the measurement control software enables us to measure changes of electric potential generated in muscles in the course of movement simultaneously recording the kinematic characteristics of movements, without any subsequent synchronization, by surface electromyography. Changes in the electric potential of muscles were detected by monopolar electrodes of 18 mm diameter made from Ag–AgCl (blue sensor P-00-S, Germany) Two monopolar surface electrodes are stuck on the washed depilated skin surface degreased by alcohol (skin resistance may not exceed 5,000 Ω) in the area of the belly of the muscle; the distance between the active parts is 30 mm. As for the positioning of surface electrodes, proposals by SENIAM were taken into consideration [11]; the ANVOLCOM model [15] was used for filtering out interference between muscles. SENIAM [11, 15] recommends usage of a double-side tape for the fixation of the electrodes and cables to the skin in such a way that the electrodes are properly fixed to the skin, movements are not hindered by a cable or the electrodes are not pulled.

The following muscle groups were included in the investigation: (1) m. pectoralis maior, (2) m. infraspinatus, (3–5) anterior, middle, and posterior parts of m. deltoideus, (6) m. supraspinatus with m. trapesius, (7) m. biceps brachii, (8) m. triceps brachii, (9) inferior part of m. trapesius, (10) m. serratus anterior, (11) m. latissimus dorsi, (12) m. sternocleidomastoideus. Figure 2 shows the measurement arrangement.

The surface EMG signal is quasi-stochastic (random), of Gauss distribution, the amplitude value of which varies between −2,000 and +2,000 mV, its frequency spectrum value is 10–500 Hz. Accordingly, the CMRR value of the amplifier integrated in the ZEBRIS CMS-HS movement sensor system is higher than 80 and its noise limit is below 2 μV. The reception frequency is 1,000 Hz. The EMG signals transmitted through the amplifier are recorded by the measurement control system.

Procedure

Each of the points involved in the investigation represent manually properly touchable anatomical and anthropometrical points for the person performing the examination.

After gently preparing the skin with abrasive paste (Epicont, Germany) and shaving off hair, the monopolar electrodes attached strictly along fiber direction taking into account the international accepted recommendations for electrode locations [11]. Using polyester belts, the triplets containing three active sensors are fastened onto the lower arm, the upper arm, and the sternum; three individual sensors to specific points of the clavicle by bilateral adhesive pads; and the triplet of individual development to the scapula. 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 coordinates specified by the measuring triplets. Electrode, triplet placement and calibration for all subjects were carried out by the same experienced investigator.

The person examined abducts (elevates) his/her arm from a neutral position to a position of about 100 to 120° in the plane of the scapula, which is a 20° 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. The spatial coordinates of the designated anatomical points are detected and recorded by the measurement control program. The movement was standardized by asking the subjects to put their index fingers on circular pipes mounted alongside the sitting subjects.

Assessment parameters

Stable and unstable shoulder joint kinematics can be properly described primarily by different angles used in orthopedic practice for characterizing shoulder motion. The humeral angle (the angle formed by spatial vectors between the proximal and distal points of the sternum and between the insertion points of musculus deltoideus and the epicondylus radialis humeri), the glenohumeral angle (the angle formed by spatial vectors between the insertion points of musculus deltoideus and the epicondylus radialis humeri and the angulus acromialis, and trigonum spina), and the scapulothoracic angle (the angle formed by spatial vectors between the proximal and distal points of the sternum and the angulus acromialis and trigonum spinae) were calculated [18, revised manuscript]. The analysis of scapulothoracic (ST) and glenohumeral (GH) angles in the function of the humeral elevation (HE) angle describes the rhythm of the two angles [18].

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 [18, revised manuscript]. An advantage in 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 analyzed. 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 statement of shoulder. A disadvantage is that angular kinematics cannot be used for characterizing dynamic motion accurately.

The theorem of Chasles [8] states that the movement of a rigid body can be characterized by displacement along a special axis named helical axis and turning around this axis. During motion, the helical axis itself is also moved, shifted, and rotated [8]. 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 commercial biomechanical processing program determines angular velocity inaccurately from the changes of angles projected to a plane. Instead, we use the velocity of investigated anatomical points for determining the angular velocity and position vector of the rotation center of the rigid body. The accurate calculation procedure is deducted by Kocsis and Béda [22], details of which are available in the literature [22]. In our investigations, the position of the rotation centers of the humerus and the scapula is analyzed, which can be used for characterizing both the own and the relative motion of the two bones examined (Fig. 3).

At 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 [20]. In case of the humerus, the point selected is the insertion point of m. deltoideus and for the scapula, it is angulus acromialis. The relative position of the rotation centers of the humerus and the scapula is characterized by the absolute displacement of two points relative to each other (absolute displacement of rotation centers). The steps in determining the parameter are as follows: (1) to determine the rotation centers of the humerus and the scapula when the two rotation centers are the closest to (r_{Hmin} and r_{Smin}), and the farthest from each other (r_{Hmax} and r_{Smax}); (2) to determine the maximum distance ($d_{\mathrm{SH,\ max}}$) and minimum distance between the rotation centers of the scapula and the humerus; (3) to determine the absolute displacement of rotation centers (Δ_{SH}), which is the difference between the maximum and the minimum distance.

The motion of the two bones constituting the shoulder joint can be characterized in relation to each other

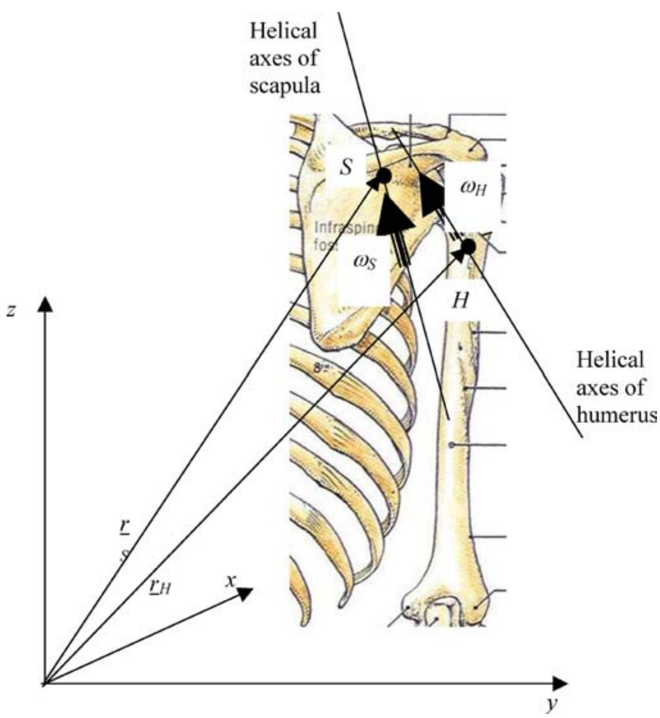

Fig. 3 Determination of the position of rotation centers

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 for 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 ($d_{\mathrm{SH,\ min}}$); the relative displacement between the rotation centers of humerus and scapula ($\varepsilon_{\mathrm{SH}}$). This means that the relative displacement between the rotation centers of the humerus and the scapula is the displacement of the rotation centers projected to a unit of length.

Changes in electrical potential measured by surface electromyography are called muscle contractions [6]. The so-called raw curves yielded by measurements cannot be utilized directly: they need to be further processed, consisting of the operations of rectification, filtering, smoothing, and averaging by time or frequency, and normalization. In the case of kinesiological electromyographic analysis, time-based processing should be applied and the purpose is to generate a linear cover curve in order to be able to determine the motion pattern of each muscle group in the course of movement.

The most widespread processing method is the root-mean-square method. A condition for using this method is that the EMG reception frequency—1,000 Hz in our case—should be many times but at least twice as much as motion reception frequency—100 Hz in our case. In the course of rectification, the absolute value of EMG signal values should be taken (negative values should be mirrored to the positive side); filtering is performed at 7 Hz. The values of the EMG cover can be calculated using a formula in the frequency of motion uptake [20].

In order to more precisely clarify the role of dynamic stabilizers, the motion patterns of shoulder muscles were analyzed for both the control group and all the patients with multidirectional instability in cases of elementary motion and overhead throwing as well [19]. There was a minimum amount of time passing between electromyographic tests linked with kinematic tests and those performed during elementary and throwing movements: the surface electrodes used for recording changes in electric potential were not removed between the two tests. For this reason, modified maximum reference muscle contraction [19] specified for the analysis of isometric movements and throwing movements, can be used for normalizing the linear cover curve generated from the raw curves recorded at this test.

Maximum muscle contraction was specified by taking the highest muscle contraction achieved in the course of various forms of motion (pulling, pushing, elevation against elastic resistance, overhead throwing) as a reference level, that is, 100%. Muscle contraction measured in the course of motion was normalized with this reference muscle contraction [19]. For specifying the

Table 2 Humeral elevation (HE), scapulothoracic and glenohumeral angles in the initial and final position of motion, as well as their range of angles for the control group and patients with multidirectional instability

	Control group						MDI patients					
	Dominant side			Opposite side			Unaffected side			Affected side		
	Initial position	Final position	Range of angle	Initial position	Final position	Range of angle	Initial position	Final position	Range of angle	Initial positionq	Final position	Range of angle
HE	7.18	97.74	90.59	7.97[a]	97.79[a]	89.89[a]	6.97 [b]	92.11 [b]	85.14[b]	17.87[a, b]	90.67[a, b]	72.79[a, b]
GH	91.75	142.05	50.3	85.24	140.84	44.41	95.12	141.23	46.11	85.24	140.84	55.60
ST	83.98	106.84	22.85	85.91[a]	110.69[a]	24.78[a]	88.45[b]	108.23[b]	19.78[b]	74.72[a, b]	88.50[a, b]	13.78[a, b]

[a] Significant differences between the opposite side of healthy persons and the affected side of patients with multidirectional instability
[b] Significant differences between the affected and unaffected side of patients with multidirectional instability

on–off pattern of various muscles' activity, a muscle can be considered as active if its normalized value is higher than 0.2 (20%) [35].

Statistical analysis

Measurement data are primarily processed, improved, smoothed, and transformed using the MS Excel-based RehaRob software package, developed by the Biomechanical Laboratory of BUTE Department of Applied Mechanics [20]. Data processing and statistical analyses were performed using MS Excel-based software of own development [20]. In the case of each subject examined, we calculated the average and the standard deviation of the kinematic characteristics and muscle activity periods 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 and those of various groups were statistically analyzed 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. A two-sample *t* test was applied when comparing the results for stable and unstable shoulder joints. It is assumed that the biomechanical parameters of stable and unstable shoulder joints should be different, and results present statistically significant differences if $P<0.05$.

Results

Angular kinematics

The angle values to be determined at the initial and final state of motion (Table 2) greatly depend on the anthropometric data of the subject [18]. The humeral elevation angle ($P=0.009$) and scapulothoracic angle ($P=0.0062$); the range of humeral elevation angle ($P=0.000087$), and scapulothoracic angle ($P=0.000098$); the scapulothoracic ratio ($P=0.009$) as well as the scapuloglenoid ratio ($P=0.000034$) displayed significant differences between the control group and the affected shoulder of patients, and between the unaffected and the affected shoulder of the patients (Tables 2, 3).

The scapulothoracic rhythm of healthy shoulders is bilinear (Fig. 4a). The steepness of the regression line until 60° of humeral elevation is 0.303; over 60° of humeral elevation it is 0.557. The difference is significant ($P=0.00113$). The glenohumeral rhythm of healthy shoulders until 60° of humeral elevation is 0.673; over 60° of humeral elevation it is 0.547. The difference is significant ($P=0.00121$). Both the scapulothoracic and

Table 3 Glenohumeral ratio, scapulothoracic ratio and scapuloglenoid ratio for the control group and patients with multidirectional instability

	Control group		MDI patients	
	Dominant side	Opposite side	Unaffected side	Affected side
Glenohumeral ratio	1.80	2.08	1.78	1.31
Scapulothoracic ratio	3.97	4.26[a]	3.84[b]	5.28[a, b]
Scapuloglenoid ratio	2.20	2.08[a]	2.27[b]	4.03[a, b]

[a] Significant differences between the opposite side of healthy persons and the affected side of patients with multidirectional instability
[b] Significant differences between the affected and unaffected side of patients with multidirectional instability

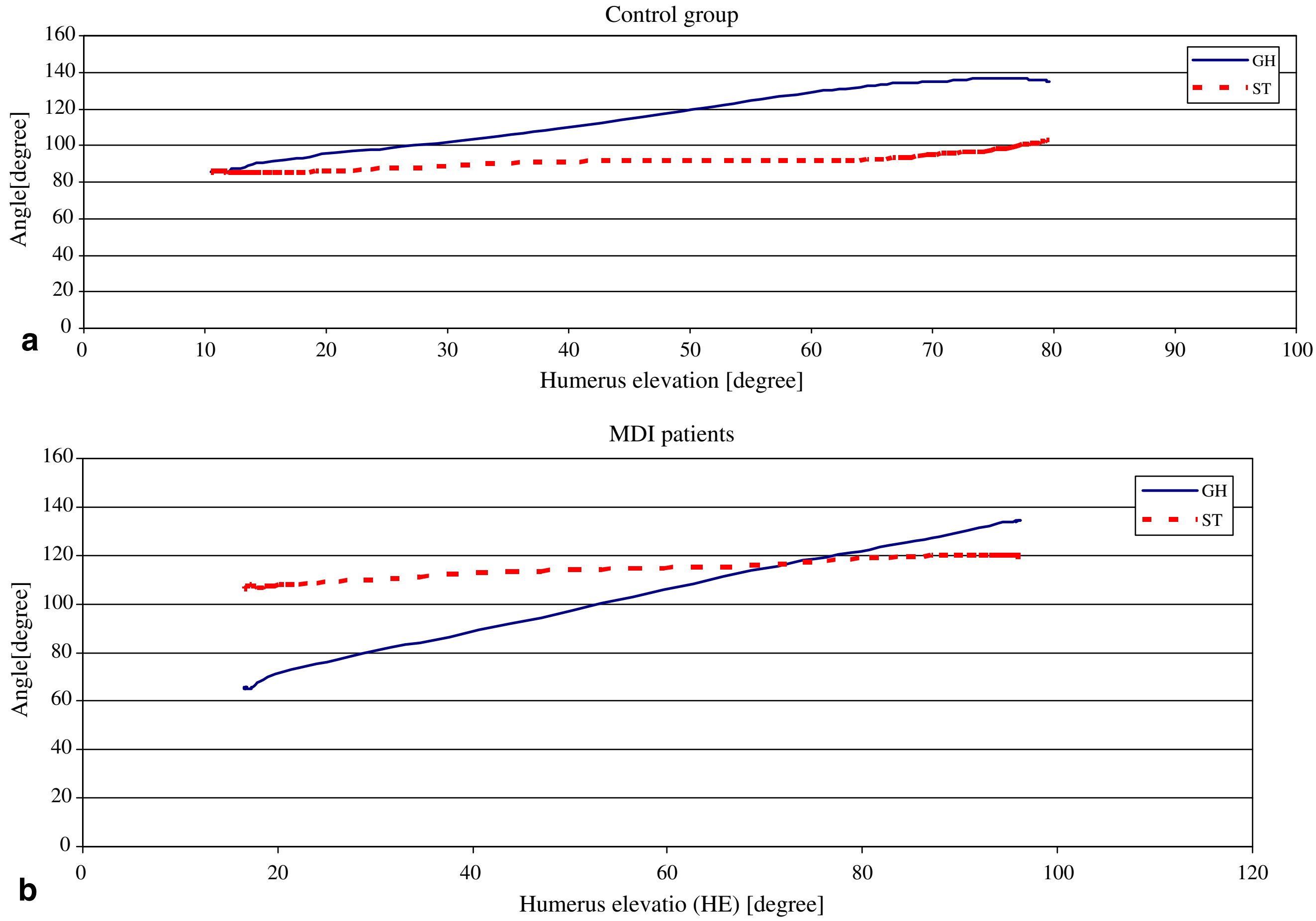

Fig. 4 Scapulothoracic and glenohumeral rhythm for **a** the control group **b** patients with multidirectional instability

glenohumeral rhythm of the affected shoulders are linear (Fig. 4b). The steepness of the regression line of the scapulothoracic rhythm is 0.248, that of glenohumeral rhythm is 0.759.

Displacement between rotation centers of the scapula and the humerus

For the dynamic analysis of motion, the position of the scapula and the humerus relative to each other was analyzed in terms of the maximum and minimum distance between the rotation centers of the scapula and the humerus; of the absolute and relative displacement of rotation centers.

The difference of the average values of maximum ($d_{SH,\ max}$) and minimum ($d_{SH,\ min}$) distances is significant ($P = 0.04$) between the control group and the affected shoulder of patients, and between the unaffected and the affected shoulder of the patients. The anthropometrical data of the subjects may have a considerable impact on the results received, therefore, data evaluation is not objective (Table 4) [18].

There is a significant difference ($P = 0.0034$) in the average values of the absolute displacement (Δ_{SH}) of rotation centers between the control group and the affected shoulder of patients, and between the unaffected and the affected shoulder of the patients. The results received may be influenced by subjects' anthropometrical data (Table 5) [18]. There is also a significant difference ($P = 0.00045$) in the average values of relative displacement between the rotation centers of scapula and humerus (ε_{SH}), between the control group and the affected shoulder of patients, and between the unaffected and the affected shoulder of the patients, introduced to eliminate anthropometrical differences (Table 5).

In the event of shoulder joint with multidirectional instability, it is an important question whether instability is identical in three spatial directions. Components to three spatial directions of the relative displacements of rotation centers were calculated (Table 6). Differences in the average values of the component to direction y (transversal to the sagittal plane) were not significant ($P_y = 0.654$), while differences between the other two directions are significant ($P_x = 0.0034$, $P_z = 0.00069$) between the control group and the affected shoulder of

Table 4 The smallest ($d_{SH,\ min}$) and longest ($d_{SH,\ max}$) distance (mm) between the rotation centers of the scapula and the humerus during elevation in scapular plane

	Dominant/unaffected side		Opposite/affected side	
	$d_{SH,\ min}$	$d_{SH,\ max}$	$d_{SH,\ min}$	$d_{SH,\ max}$
Control group	214.78	228.8[a]	213.3[b]	230.2[b]
MDI patients	207.3[a]	231.1[a]	171.8[a, b]	211.3[a, b]

[a] Significant differences between the opposite side of healthy persons and the affected side of patients with multidirectional instability
[b] Significant differences between the affected and unaffected side of patients with multidirectional instability

patients, and between the unaffected and the affected shoulder of the patients.

There is no significant difference between the average values of any parameters in terms of the dominant and the opposite side of the healthy control group (Tables 4, 5, 6) and of the dominant side of healthy subjects and the unaffected side of patients.

Muscle activity

An important issue of the biomechanical analysis of the shoulder joint is represented by the analysis of the motion pattern of muscles. Based on an analysis of raw EMG data, we can establish that the functioning of m. sternocleidomastoideus was impossible to be evaluated because of the substantial audibility of carotis.

For some people in the control group, m. triceps brachii ($n = 11$), m. biceps brachii ($n = 5$), and m. pectoralis maior ($n = 15$) are inactive during the entire period of motion; for others, these muscles showed some activity in some cycles of motion. In the case of 11 affected shoulders, m. pectoralis maior is inactive during the entire period of motion. The length of the activity period of m. pectoralis maior ($P = 0.0013$), the anterior part ($P = 0.0006$), the middle part ($P = 0.00062$), and the posterior part of m. deltoideus ($P = 0.0087$) of shoulder joint with multidirectional instability decreased significantly; the length of the activity period of m. supraspinatus ($P = 0.0000087$), m. infraspinatus ($P = 0.00001$), m. biceps brachii ($P = 0.00008$), and m. triceps brachii ($P = 0.00011$) increased significantly.

Discussion

In this study, we have performed a 3D analysis of the shoulder motion including the humerus, the clavicle, the scapula and the thorax in a control group and in patients with multidirectional instability. Since the investigated motion (elevation in the scapular plane) is continuous (the motion is not stopped for recording of the position of different anatomical points), we were able to determine potential changes in the motion pattern of skeletal elements and changes in muscle activity. The diseased and the healthy shoulder were compared with each other to assess whether the potential changes in the motion pattern were restricted to the affected shoulder or were also present in the asymptomatic contralateral side.

We found that, generally, patients with multidirectional stability displayed significant alterations in shoulder motion in comparison with healthy control subjects or in comparison with the unaffected contralateral side under the given conditions of this examination. By applying a 3D ultrasound-based system, the kinematical parameters were determined in the function of time during a continuous elevation in the scapular plane.

In the current study, the regression of the scapulothoracic and glenohumeral rhythm of affected shoulders is demonstrated to be linear (Fig. 4b), which is in agreement with a previous radiographic study [14]. However, the steepness of scapulothoracic (0.248) and glenohumeral rhythm (0.759) is different compared to data in literature (0.32 and 0.5, respectively) [14]. This discrepancy is likely to be due to the fact that Graichen

Table 5 Absolute (Δ_{SH}) and relative (ε_{SH}) displacement between the rotation center of the scapula and the humerus

	Dominant/unaffected side		Opposite/affected side	
	Δ_{SH} (mm)	ε_{SH}	Δ_{SH} (mm)	ε_{SH}
Control group	14.12	0.065	16.92[a, b]	0.079[b]
MDI patients	13.8[a]	0.073[a]	39.49[b]	0.23[a, b]

[a] Significant differences between the opposite side of healthy persons and the affected side of patients with multidirectional instability
[b] Significant differences between the affected and unaffected side of patients with multidirectional instability

Table 6 Components in directions x, y, and z of the relative (ε_{SH}) displacement between the rotation center of the scapula and the humerus

	Dominant/unaffected side			Opposite/affected side		
	$\varepsilon_{SH,\,x}$	$\varepsilon_{SH,\,y}$	$\varepsilon_{SH,\,z}$	$\varepsilon_{SH,\,x}$	$\varepsilon_{SH,\,y}$	$\varepsilon_{SH,\,z}$
Control group	0.039	0.021	0.047	0.042[b]	0.019	0.064[b]
MDI patients	0.043[a]	0.018	0.044[a]	0.116[a, b]	0.017	0.195[a, b]

[a] Significant differences between the opposite side of healthy persons and the affected side of patients with multidirectional instability
[b] Significant differences between the affected and unaffected side of patients with multidirectional instability

et al. [14] calculated rhythm from the angle values possible to be determined from MRI images recorded in static conditions modeling motion, while we measured it in the course of motion. The difference compared to a stable shoulder joint may be caused by the development of neuromuscular protection—sparing the shoulder joint. This is supported by the significant difference between the average values of range of the scapulothoracic angle. As a consequence of the decreased role of the scapula, the range of humeral elevation angle also significantly decreases at shoulder with multidirectional instability (Table 2). Differences in the rhythm are explained by a significant difference in the scapulothoracic and scapuloglenoid ratios between the healthy and the affected shoulder.

On the basis of our results, it can be established that the location of rotation centers continuously changes in the course of elevation. There is a significant difference between the average values of the maximum ($d_{SH,\ max}$) and minimum ($d_{SH,\ min}$) distance of rotation centers (Table 4), and of the absolute displacement (Δ_{SH}) between the rotation centers of the scapula and the humerus (Table 5). Our standpoint is that the correlation between the distance of rotation centers and the anthropometric characteristics of subjects is not known; therefore, these characteristics cannot be used as yet for describing the displacement of the humerus and the scapula relative to each other.

The motion of shoulder joint can be characterized by a relative displacement between the rotation centers of scapula and humerus (ε_{SH}), because it is modeled such that the position of the scapula and the humerus are relative to each other dynamically, and it is independent from the anthropometric differences of the subjects due to normalization. It can be assumed from the experiences of our tests that the size of the parameter is independent of lateral dominance (Table 5). 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. It could be supported by significant differences in the humeral elevation and the scapulothoracic angle values, range of humeral and scapulothoracic angle as well as the scapulothoracic ratio between the affected and unaffected shoulder.

Our investigations show that the relative displacement between the rotation centres (ε_{SH}) of shoulders with multidirectional instability significantly increases compared to healthy shoulders (Table 5). Ligaments regulate the motion, relative to each other, of the bones constituting the shoulder joint. If any of the ligaments is stretched, displacements must considerably increase as elongated ligament(s) do not prevent excessive movements. The greater relative displacement of the rotation centers of the scapula and the humerus may also represent a prearthritis factor. The differences indicate that in the event of insufficient passive stabilizers, active stabilizers cannot properly stabilize the joint. This raises further issues, namely that the insufficiency of dynamic stabilizers develops in a primary or secondary manner; it may also be the fact that muscle operation is normal, it is just insufficient for eliminating such instability. Individuals having multidirectional instability subluxate or dislocate anteriorly, posteriorly or inferiorly [16, 32, 34], which is supported by significantly increased relative displacement between the rotation centers of scapula and humerus into these two directions (Table 6). It would be interesting to see prospectively how the relative displacement of rotation centers changes after a surgery or after therapeutical gymnastics.

At extreme positions of the motion, ligaments and muscles would prevent shoulder joint luxation. Following the development of multidirectional instability, changes in the activity of the neuromuscular system—brought about by learning or reflexes—hinder the development of luxation or subluxation [1, 2, 5, 30]. Altered kinematic characteristics should be associated with an altered motion pattern and modified muscle activity.

Alterations in the operation of dynamic stabilizers were analyzed by electromyographic tests. On the basis of literature data, it can be assumed that in case of shoulder joints with multidirectional instability, the movement patterns of the superior part of m. deltoideus and m. trapesius are different [23, 27, 33], and no discrepancies are shown by m. supraspinatus, m. infraspinatus, and m. subscapularis [27, 33]. Others revealed discrepancies in the movement patterns of m. supraspinatus, m. subscapularis, and m. biceps brachii [13, 28].

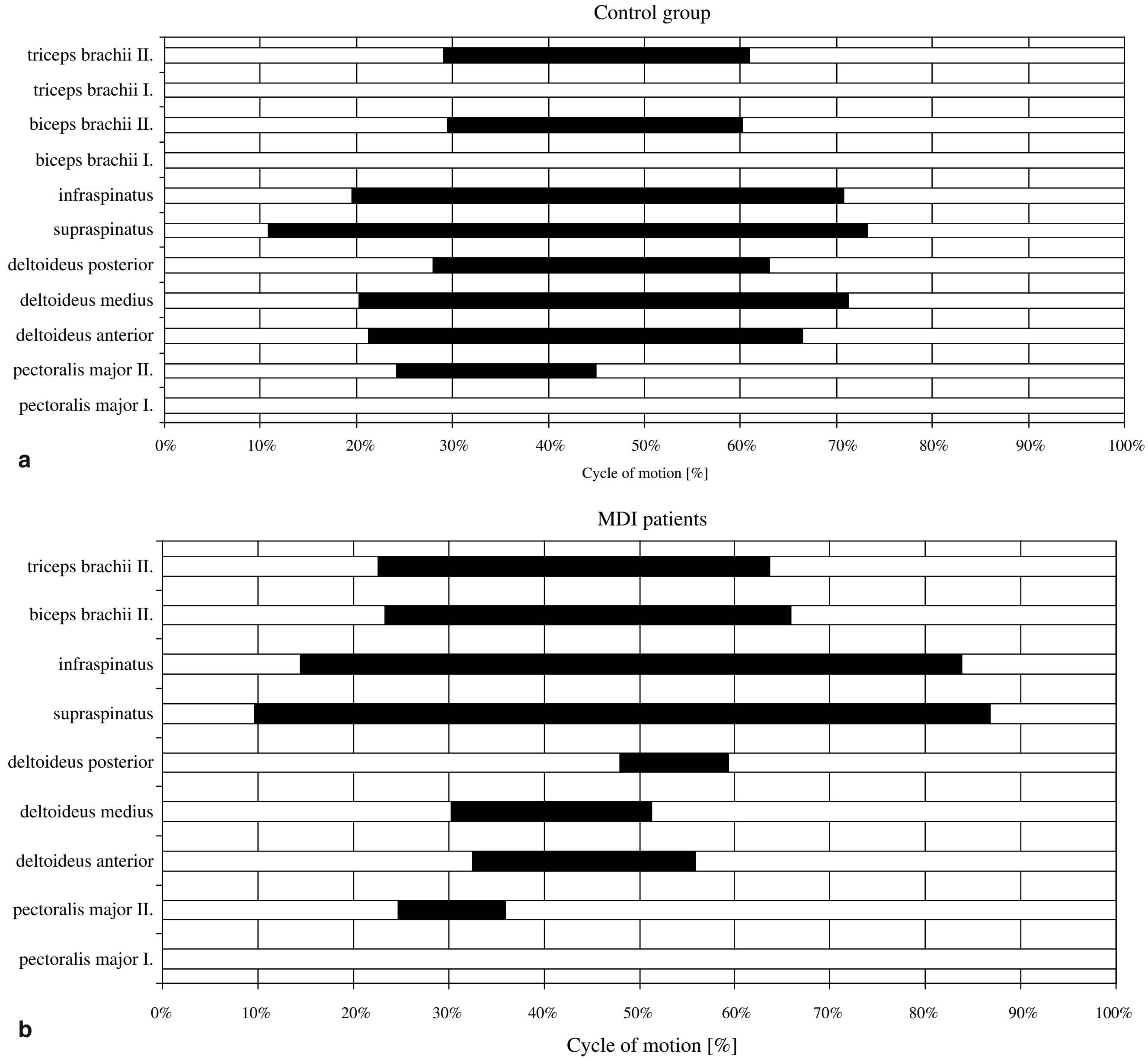

Fig. 5 On–off pattern of muscle activity generated by normalization with modified muscle contraction in the course of elevation for **a** the control group **b** patients with multidirectional instability. For some people in the control group, m. triceps brachii ($n=11$), m. biceps brachii ($n=5$), and m. pectoralis maior ($n=15$) are inactive during the entire period of motion (noted by I); for others, these muscles showed some activity in some cycles of motion (Noted by II). In case of 11 affected shoulders m. pectoralis maior is inactive during the entire period of motion (Noted by I)

Reduction—or elimination for some people (Fig. 5)—of the activity period of m. pectoralis maior and all three parts of m. deltoideus is also reflected in the changed humeral elevation and the scapulothoracic angle of affected shoulders compared to healthy shoulders. Reduced muscular functions may result in the linear scapulathoracic and glenohumeral rhythm. Reduced muscle functions may be interrelated with an increase in the scope of motion to compensate the elongation of reflex or passive structures.

The increased role of m. supraspinatus, m. infraspinatus, m. biceps brachii, and m. triceps brachii (Fig. 5) compensates the reduced functions of m. pectoralis maior and all three parts of m. deltoideus. The reduced scope of scapulothoracic motion is compensated by the increased glenohumeral motion, which is supported by the linear glenohumeral rhythm of affected shoulders. In our assumption, the altered motion pattern is caused by the fact that the organism strives for a proper centralization of the glenohumeral joint, which, in case of shoulder joints with multidirectional instability, requires shorter activity by m. pectoralis maior and all three parts of m. deltoideus and longer activity by m. supraspinatus, m. biceps brachii, and m. infraspinatus.

Changes in muscle activity are independent of lateral dominance, which again supports the independence of kinematic characteristics from lateral dominance.

In conclusion, we have observed that patients with multidirectional instability generally displayed significant alterations in shoulder kinematics in comparison with the contralateral unaffected shoulder and with normal volunteers. The anterior, posterior, and inferior dislocations of shoulders with multidirectional instability could be properly modeled by the relative displacement between the rotation centers of the scapula and the humerus. The shorter activity by m. pectoralis maior and all three parts of m. deltoideus and longer activity by m. supraspinatus, m. biceps brachii, and m. infraspinatus assure the centralization of the glenohumeral head of shoulders with multidirectional instability.

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