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Analysis of the scapulohumeral rhythm and electromyography of the shoulder muscles during elevation and lowering: Comparison of dominant and nondominant shoulders

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Hypothesis: Assessment of whether elevation and lowering of the dominant and nondominant arms occur in a similar manner in healthy individuals is clinically important in terms of shoulder disorders.
Materials and methods: We examined the scapulohumeral rhythm (SHR) and performed electromyography (EMG) for the middle deltoid, upper trapezius, lower trapezius, and lower part of the serratus anterior muscles of both shoulders in 18 healthy volunteers (14 men, 4 women) with a mean age of 24 years (range, 19-30 years). The participants randomly elevated and lowered either the right or left arm in the scapular plane, and the motion was measured using a 3-dimensional motion analyzer.
Results: The average angles of maximum arm elevation and scapular upward rotation were $130.3° \pm 7.9°$ and $32.2° \pm 5.6°$, respectively, for dominant arms, and $130.8° \pm 6.4°$ and $31.8° \pm 5.8°$, respectively, for nondominant arms. The SHR in each 10° increment did not differ significantly between the dominant and nondominant arms in each participant during elevation ($P = .337$) and lowering ($P = .1$). A significant difference was found in the percentage integrated EMG (%IEMG) of the lower trapezius between the 2 shoulders ($P < .049$).
Discussion: If the kinematic difference is identified between both shoulders, we can predict the dysfunction or disorder in shoulder complex. Moreover, we should evaluate how shoulder muscles are used and whether the muscle becomes weak.
Conclusions: Healthy individuals elevate and lower the dominant and nondominant shoulders in a similar kinematical pattern despite 3 of 4 muscles indicating different EMG activities between both shoulders.
Level of evidence: Basic science study.

Keywords: Shoulder joint; dominance; scapulohumeral rhythm; electromyography

Approval of the study was obtained from the internal review board of the Koriyama Institute of Health Sciences (No. 07-002).

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Arm dominance, the tendency to prefer a particular arm in performing selected tasks, is a prominent but poorly understood aspect of human motor performance. Recent findings have suggested that a major factor distinguishing

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the dominant from the nondominant arm is the manner in which the effects of intersegmental dynamics are controlled by the central nerve system.[2,19,35] In addition, movement with small differences in hand−path kinematics show substantial differences in torque patterns and corresponding electromyography (EMG) profiles, which implies a greater torque-efficiency strategy for the dominant arm and suggests that EMG is a useful tool to differentiate the properties of the dominant and nondominant arms.[2]

A few comparisons of dominant and nondominant shoulders have been reported, including those on radiologic shoulder balance,[1] range of motion of the shoulder,[4,13] rotational strength in elite athletes,[12] and proprioception.[40] To our knowledge, however, dynamic and kinematic analyses of the dominant and nondominant shoulders have not been documented yet.

Activities of daily life require combined and coordinated motions of the scapulothoracic (ST) and glenohumeral (GH) joints. Because the humerus links the scapula to the trunk, ST motion is necessary to achieve full humerus-to-trunk scapular plane elevation. Cathcart[5] first described the contribution of the ST to normal shoulder complex kinematics. The kinematic interaction between the scapula and the humerus was termed the ‘‘scapulohumeral rhythm’’ (SHR) by Codman,[6] and subsequently, this has been shown to be valid for analysis of dynamic motion of the shoulder complex, with the classic 2:1 ratio first described by Inman et al.[17] Numerous studies have investigated the 2- or 3-dimensional (3D) motion of the GH joint and scapula using the SHR.[8,10,17,26,31,34,37] Hence, the SHR has been established as the kinematic hallmark indicating motion of the shoulder joint.

Alteration of the SHR in shoulder disorders has also been documented widely.[21,24,27,28,32,33,39,41] Alterations in the resting scapular position and dynamic scapular motion occur frequently in association with many types of shoulder disorders, including impingement, instability, rotator cuff tears, and frozen shoulder.[21] Scapular upward rotation is significantly increased in patients with full-thickness rotator cuff tears compared with controls in both forward and scapular plane elevation,[28] and the supraspinatus and serratus anterior muscles exhibit significantly less activity during abduction and forward elevation with anterior instability compared with normal shoulders.[11] Compared with healthy young adults, patients with impingement have a significantly lower posterior tilting angle of the scapula in the sagittal plane and a higher superior-inferior scapula position with maximal arm elevation.[24] An increased scapular component is generally thought to contribute to the SHR in frozen or stiff shoulder.[32,33,39] Thus, shoulder disorders manifest as abnormal motion of the ST or GH joint and consequently alter the SHR. Comparison of the SHR between both shoulders would be clinically beneficial to evaluate shoulder disorders.

EMG studies have greatly increased the understanding of the relative muscular contributions to the shoulder kinematics.[18,38] Computerized 3D analysis, which is established as a noninvasive method for recording dynamic shoulder motion, combined with EMG profiles of shoulder muscles, provides the essence of the shoulder kinematics.[30] Previous studies have shown that the upper and middle trapezius, lower trapezius, serratus anterior, and deltoid contract dynamically throughout the motion of abduction of the shoulder.[3,15,22] The deltoid mainly moves the GH joint, whereas the upper trapezius and serratus anterior rotate the scapula upward. The deltoid and trapezius also work as antagonists to scapular upward rotation, especially in the initial phase of elevation. Thus, complementary actions of the ST and GH muscles are required to produce the complex kinematics in the shoulder during arm elevation and lowering.

The SHR, scapular motion, and relative EMG contribution have not been compared in dominant and nondominant arms. An investigation of whether healthy individuals elevate and lower the dominant and nondominant arms in the same kinematical manner may have relevance to evaluation and treatment of patients with shoulder disorders.

In the current study, our first hypothesis is that the SHR of the dominant arm does not differ significantly from that of the nondominant side, validating side-to-side comparisons. A recent study indicated that the biceps and pectoralis major amplitude were significantly smaller for the dominant compared with the nondominant arm during the performance of reaching movements.[2]

Our second hypothesis is that the EMG of each shoulder muscle shows a different pattern between the bilateral shoulders. Therefore, the purposes of the study are (1) to compare the SHR of dominant and nondominant arms during elevation and lowering and (2) to compare the EMG of the middle deltoid, upper trapezius, lower trapezius, and lower part of the serratus anterior muscles of both shoulders.

Materials and methods

Participants

The study included 18 healthy college students (14 men, 4 women), with a mean age of 24 years (range, 19-30 years), who did not often participate in sports activities. Their mean (± standard deviation) height was 1.68 ± 0.84 m and weight was 61.0 ± 7.8 kg,, and their self-reported dominant arms were right in 14 and left in 4. None of the volunteers had shoulder pain or a medical history of shoulder disorders. They did not have instability, restriction of range of motion, scoliosis, or asymmetry of the thoracic cage. Approval of the study was obtained from the Internal Review Board of the Koriyama Institute of Health Sciences. Each participant was informed of the details of the study and provided signed consent before participation.

Experimental protocol

Error analysis of the computerized 3D motion analysis system was conducted to assess the system performance in terms of repeatability and accuracy. Potential experimental error due to skin slippage was estimated by measuring the distances between bony landmarks and marker locations, using skin palpation and radiographs taken at the starting position, 30°, 60°, 90°, and at maximum elevation.

Assuming that the scapula lies at 30° to the coronal plane, each participant stood in front of a wall that was 30° to the coronal plane. Before measurements were taken, the participants were given several practice trials to ensure that they understood the proper movement pattern and timing. They attempted to raise their arm in 6 seconds, maintain maximum elevation for 3 seconds, and then lower their arm in 6 seconds in the scapular plane. The participants stood with their thoracic spine, both arms, pelvis, and knee exposed. Reflecting markers were placed bilaterally on the skin of the coracoid process, acromial angle, the root of the scapular spine, medial and lateral epicondyles of the humerus, spinous processes of the second and seventh thoracic vertebrae (T2 and T7) and fifth lumbar vertebra (L5), lateral condyle of the knee, and lateral malleolus of the ankle.[23] Palpation of bony landmarks and sticking skin markers were confirmed by a senior author (H. J.).

A computerized 3D motion analyzer (MAC 3D System, Motion Analysis Corp, Santa Rosa, CA) was used for collection of kinematics data. This system allowed for 50-Hz data capture with 6 synchronized infrared cameras placed circumferentially around the participant. For measurements, all participants randomly elevated and lowered their dominant and nondominant arms in the scapular plane 3 times for each arm. Data were analyzed using KineAnalyzer system software (Kissei Comtec Co, Nagano, Japan).

The axis of the humerus was designated as the line connecting the midpoint of the coracoid process and acromial angle with the midpoint of the lateral and medial epicondyles. The line drawn between the root of the scapular spine and the acromial angle was defined as the line of the scapular spine. The starting angles of both arms and the scapular spine were set at 0°. During recording of the angle of humeral elevation, the angle of scapular upward rotation was determined simultaneously in each 10° increment. In addition, each measured angle was automatically corrected from the numeric value of the 3D leaning of the thoracic spine because thoracic spine motion has an influence on shoulder kinematics.[20] The angle of the humerus (H) and that of scapular upward rotation (S) were recorded for each participant during elevation and lowering. The SHR was calculated from the formula (H−S)/S, and the coefficient of variation [CV = (standard deviation/mean) × 100%] of the SHR was determined.

EMG analysis during motion

EMG was recorded in synchronizing 3D motion computerized analysis of arm elevation and lowering for 4 muscles: the middle deltoid, the upper and lower trapezius, and lower part of the serratus anterior. Before placement of the surface electrodes, which had an interelectrode distance of 20 mm, the skin was abraded and defatted to achieve a skin impedance of less than 5 kΩ. The location of each surface electrode was based on a textbook description of the muscle positions.[9] EMG signals were transmitted with telemetry to multichannel receivers (MQ 8, Marq-Medical of Denmark, Farum, Denmark) and analyzed with Bimutas 2 software (Kissei Comtec Co, Nagano, Japan). The signals were band-pass filtered at 15 to 350 Hz, sampled at 1000 Hz, and stored for further analysis. EMG data for each 10° increment were resampled at 5 Hz, and the integrated EMG (IEMG) of the 4 muscles from 120° to maximum elevation was obtained by summation. The %IEMG in each 10° increment was calculated based on a %IEMG of 100% for each muscle from 120° to maximum elevation. The %IEMG for each muscle in each 10° increment was compared for dominant and nondominant shoulders.

Repeatability test and data analysis

Five healthy participants (4 men and 1 woman; age, 22-30 years) participated in a repeatability test. Measurement of both extremities were made with random elevation and lowering of both extremities 5 times in 1 day (the first day), with repetition of the measurements 1 week later (the second day). 3D angular displacements were measured for 5 repeated elevation and lowering trials for each participant, and the values were used to calculate intraclass correlation coefficients (ICC [1,5]) for the angle of the scapular upward rotation and the SHR.

Statistical analysis was performed using SPSS 15.0J software (SPSS Japan Inc, Tokyo, Japan), with a level of significance of $P < .5$. Repeated-measures analysis of variance (ANOVA) was performed to compare the angles of the scapular spine and the SHR between dominant and nondominant arms in each 10° increment and to compare the %IEMG of each muscle between the 2 shoulders.

Results

The system was accurate for length measurements within 0.07 mm at rest and within 0.42 mm during motion, and for angular orientations within 0.13° at rest and 0.62° during motion. The error due to skin slippage of the markers was 1.2 ± 1.0 cm for the root of the scapular spine, 0.7 ± 0.6 cm for the acromial angle, 0.8 ± 1.0 cm for the coracoid process measured by radiograph, and the marker of both epicondyles ranged within 0.5 cm with surface palpation. The repeatability for scapular motion was very high (ICC, 0.97-0.99) on the first day, second day, and both days, and the repeatability of the SHR was also high (ICC, 0.71-0.98).

The average maximum angle of arm elevation and the average angle of scapular upward rotation were 130.3° ± 7.9° and 32.2° ± 5.6°, respectively, for dominant arms and 130.8° ± 6.4° and 31.8° ± 5.8°, respectively, for nondominant arms. Measured angles of leaning of the thoracic spine at maximum elevation were 11.3° ± 6.7° for axial rotation, 3.0° ± 1.3° in the coronal plane, and 3.0° ± 1.3° in the sagittal plane. The average SHR was 3.4 (range, 3.0-4.0) for dominant arms and 3.1 (range, 3.0-4.3) for nondominant arms. The angle of scapular upward rotation was almost linear throughout the range of motion (Figure 1), with no significant difference in the angle of upward rotation between dominant and nondominant arms ($P = .767$).

The CV of the SHR of all participants in each 10° increment is shown in Figure 2. This value varied from the

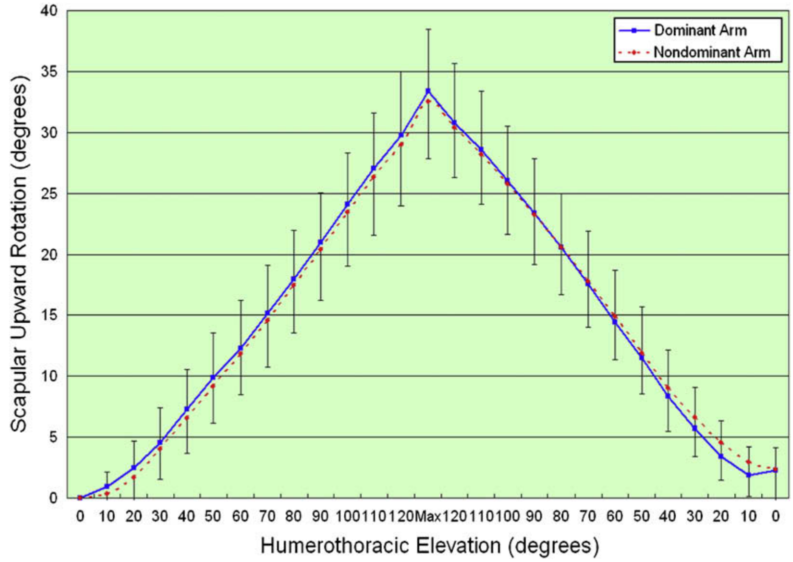

Figure 1 Motion of the scapular spine during elevation and lowering of the arm. The error bar show the standard deviation. The average maximum angle of arm elevation and the average angle of scapular upward rotation were 130.3° ± 7.9° and 32.2° ± 5.6°, respectively, for dominant arms and 130.8° ± 6.4° and 31.8° ± 5.8°, respectively, for nondominant arms. There was no significant difference in the angle of upward rotation of the scapula between dominant and nondominant arms (P = .767).

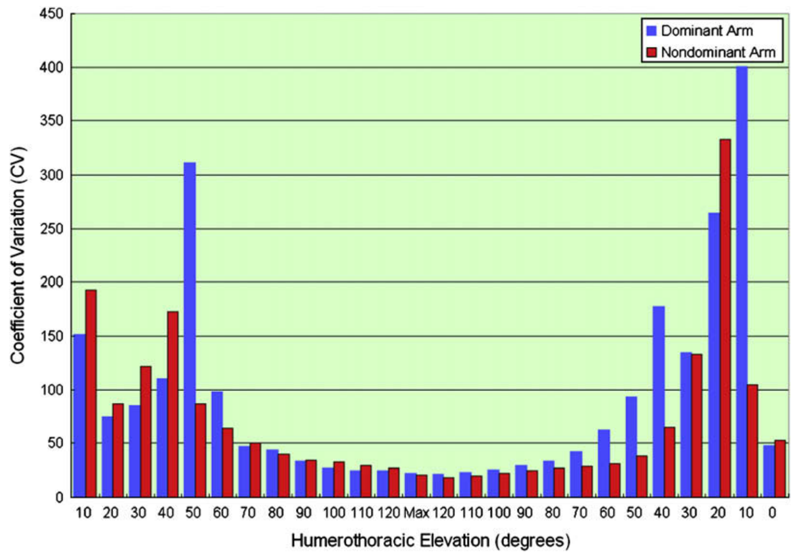

Figure 2 Coefficient of variance (CV) of the scapulohumeral rhythm (SHR) is shown in dominant vs nondominant arms. The CV of the SHR varied from the starting point to 60° of elevation, converged to a constant ratio, and increased again from 60° of lowering to the end point. The SHR in each 10° increment did not differ significantly between dominant and nondominant arms in each individual during elevation (P = .337) and lowering (P = .1).

starting point to 60° of elevation, inversely converged to a constant ratio, and then increased again from 60° of lowering to the end point. The SHR in each 10° increment did not differ significantly between dominant and nondominant arms in each individual during elevation (P = .337) and lowering (P = .1).

The respective %IEMG for the 4 muscles in each 10° increment for dominant and nondominant shoulders are shown in Figures 3 and 4, respectively. The EMG activities of the 4 shoulder muscles increased consistently, peaked at 120° to 130° elevation, and then gradually declined. The middle deltoid showed the highest activity, and the lower trapezius had the least activity during motion. EMG activities of the 4 muscles during elevation were always greater than the respective activities on lowering. No significant difference was noted in %IEMG of the upper trapezius throughout the range of motion between dominant and nondominant shoulders (P > .163; Figure 5, *A*); however, the %IEMG of the lower trapezius was significantly

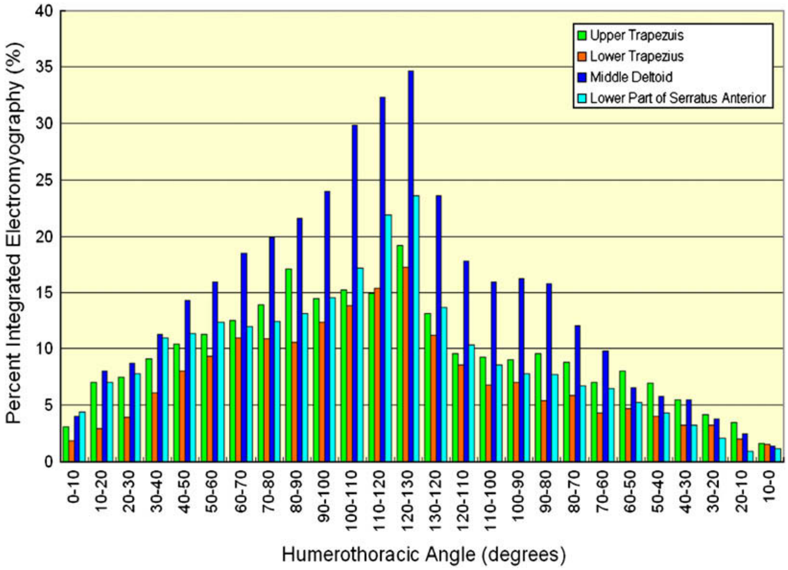

Figure 3 Electromyography (EMG) of shoulder muscles is shown in each 10° increment for the dominant arm. The respective EMG activities of the 4 shoulder muscles increased consistently with elevation, reached a peak between 120° to 130°, and then gradually declined. The highest and lowest activities during motion were observed for the middle deltoid and the lower trapezius, respectively.

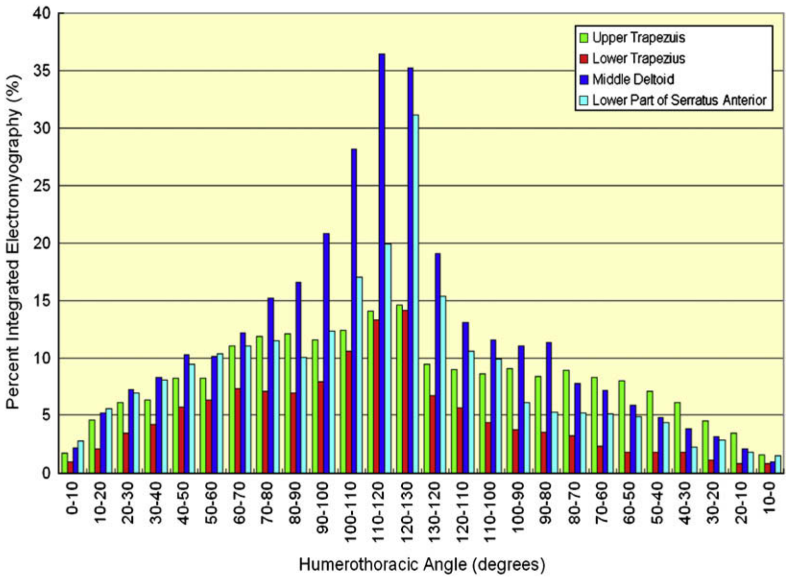

Figure 4 Electromyography (EMG) of shoulder muscles is shown for the nondominant arm. The trend of EMG activity in each muscle was the same as that for the dominant shoulder.

different ($P < .049$; Figure 5, *B*). A statistically significant difference was found only in the initial phase of elevation for the middle deltoid ($P = .007$) and serratus anterior ($P = .03$) muscles (Figure 5, *C*, *D*).

Discussion

The results support our first hypothesis that there is no difference between the SHR for both shoulders in the simple task of elevating and lowering the arm in the scapular plane without any external load. No significant difference was found in %IEMG for the upper trapezius throughout the range of motion. The %IEMG for the middle deltoid and serratus anterior showed a difference in the initial phase of elevation. In contrast, %IEMG for the lower trapezius showed a significant difference between the dominant and nondominant shoulders. Therefore, the EMG activities of the muscles, except for the upper trapezius, are consistent with the second hypothesis that the EMG of each

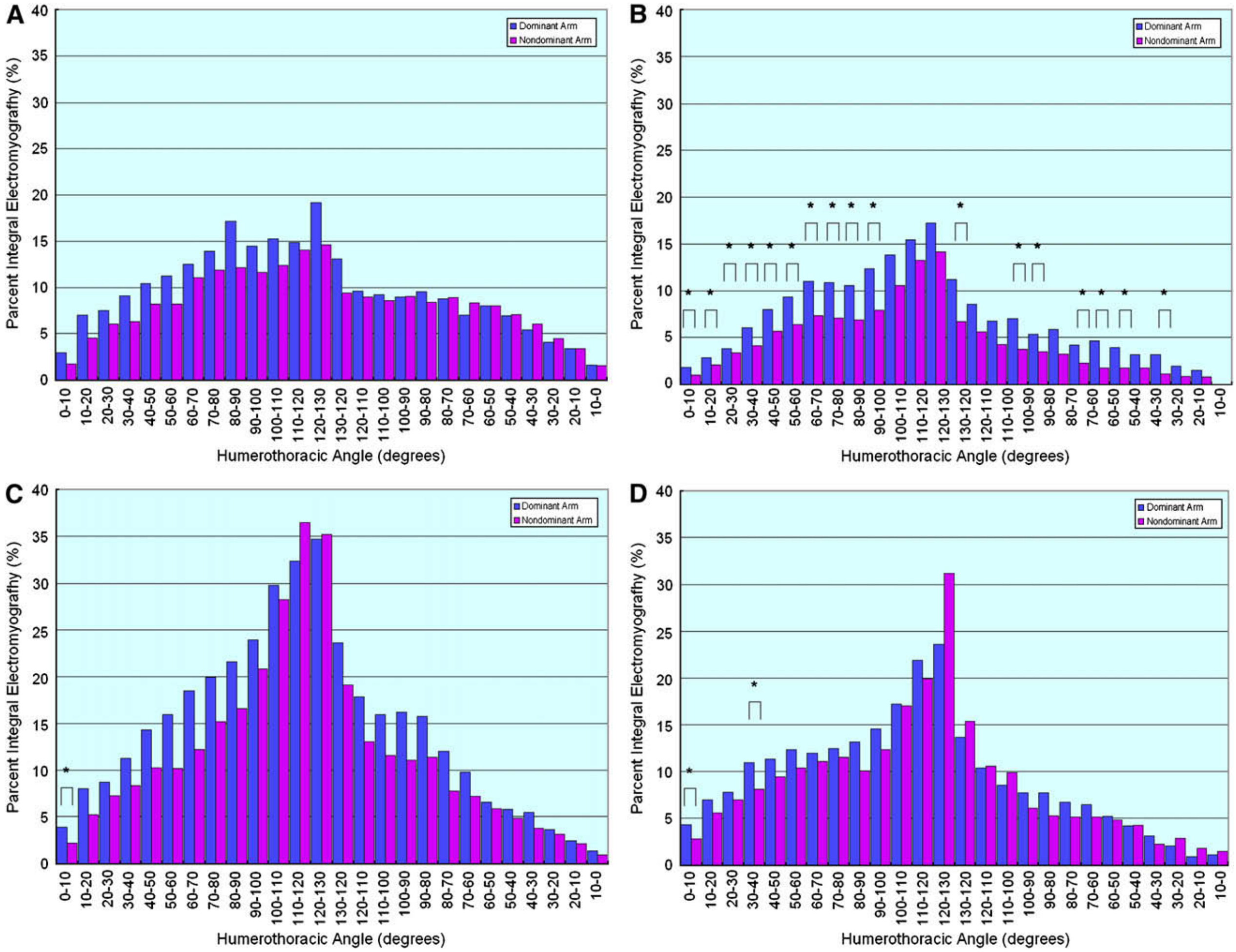

Figure 5 Electromyography (EMG) of each shoulder muscle in the dominant vs nondominant arm in each 10° increment. (**A**) Upper trapezius; (**B**) lower trapezius; (**C**) middle deltoid; and (**D**) lower part of the serratus anterior. *IEMG*, integrated electromyography.

shoulder muscle has a different pattern between both shoulders.

The current study shows that the kinematic joints motion is the same between the dominant and nondominant shoulders despite 3 of 4 shoulder muscles working differently. Previous studies[2,35] have shown that the flexor and extensor muscle torque impulses are both substantially lower at the dominant shoulder joint, and nondominant shoulder muscle torque must counter the effects of elbow muscle torque to accelerate the upper arm. These systematic differences in torque were observable in EMG recordings of the elbow and shoulder muscles (biceps brachii, triceps brachii, pectoralis major, and posterior deltoid), and flexor activity remained substantially lower for the dominant arm after movement onset.[2]

The difference in EMG activities of shoulder muscles in our work compared with those in the previous study[18,35,38] may be due to the different motion planes and task. The previous study[35] was performed in the sagittal plane, in contrast to our observations in the oblique-coronal plane, and reaching vs elevation and lowering in regard to the task. The disparity between the previous[35] and current studies may also be due to assessment of EMG activities of different muscles: the scapula rotator muscles and middle deltoid in our study and the flexor and extensor of the shoulder and elbow joints in the previous study.[35]

Early kinematic investigations of the shoulder complex suggested decoupling of the GH and ST joints, and the angle of upward rotation has a direct influence upon the SHR. The angle of scapular upward rotation in previous studies has ranged from 29° to 49°, whereas our study indicates 32°.[7,11] Collectively, the reported ratios of the SHR have ranged from 1.35:1 to 7.9:1.[8,10,11,17,25,26,29,31,36,37] The current data show that the average SHR was 3.4 for dominant arms and 3.1 for nondominant arms, which are not completely consistent with previous findings. This may be due to many factors, including differences in instrumentation, planes of analysis, determination of angular values about the starting position, static vs dynamic motion, measuring range, trunk position, and characteristics of participants.

The shoulder has little inherent stability, and proper function largely depends on optimal muscle function. The prime muscles that abduct the GH joint are the middle deltoid and supraspinatus muscles, and coordinated action of both muscles is essential for smooth, efficient motion of the GH joint.[16] The upper and lower trapezius and the lower part of the serratus anterior muscle form a force couple that upwardly rotates the scapula.[3] Relative EMG contributions of the 4 muscles show a consistent increase in activity according to arm elevation, and the current EMG results are consistent with those of previous investigations.[15,17,22] The middle deltoid showed the largest EMG activity, followed in order by the serratus anterior, the upper trapezius, and the lower trapezius.

Electrographic descriptions of trapezius and serratus anterior activities during humeral elevation have commonly been related to 2D kinematic patterns of scapular upward rotation. The lower part of the serratus anterior is the prime muscle for upward rotation of the scapula, and therefore EMG activity in the serratus anterior is greater than that in the upper or lower trapezius.[14] The lower trapezius is particularly active during the later phase of shoulder abduction,[3] and our results are consistent with these observations. The lower trapezius is important in maintaining upward scapula rotation in throwing.[30] The lower trapezius showed a significant difference in EMG activity for the dominant and nondominant shoulders during motion. We suggest that differences in EMG activity of each muscle between the dominant and nondominant shoulders would occur in more complicated tasks or with the addition of an external load on the arms.

The current study shows that healthy participants elevate and lower both arms in the same kinematic pattern. These findings can be used in clinical evaluation and treatment of shoulder disorders, including instability,[11,41] stiff shoulder,[32,33,39] impingement syndrome,[24,41] rotator cuff tears,[28,31,37] and scapular dysfunction.[21] Clinically, motion of the GH joint or scapula, or both, is hard to visualize, but careful observation of the scapular motion would allow comparison of the affected shoulder with the nonaffected side. If the kinematic difference is identified between both shoulders, we can predict the dysfunction or disorder in the shoulder complex. Because the variability of the muscles activities are observed in both shoulders, we should evaluate how shoulder muscles are used during elevation and lowering and whether the muscles become weak. We suggest that patients with shoulder disorders should be treated toward the same condition as that of the nonaffected side.

Even though repeatability was high, we used skin markers in a static position and performed dynamic measurements. Skin surface palpation has been validated as an accurate indicator of the location of thoracic and scapular landmarks.[23] However, the accuracy of the relationship between the location of bony landmarks and the position of skin markers was not completely clear, and this limitation in the measurement requires correction in a future study.

Our study was performed in healthy young participants, and caution is required in extrapolating these findings to other populations. Also, the participants did not elevate and lower their extremities at speed or flex their elbow joints similarly to motions in daily life, in which the speed of motion is generally faster and the arm is elevated below a flexed elbow joint. In future studies, we plan to make measurements under conditions more consistent with daily life.

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