Scapular Kinematics and Muscle Activities during Pushing Tasks

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Abstract: Scapular Kinematics and Muscle Activities during Pushing Tasks: Chun-Kai HUANG, et al. Division of Physical Therapy Education, School of Allied Health Professions, University of Nebraska Medical Center, USA—Objectives: Pushing tasks are functional activities of daily living. However, shoulder complaints exist among workers exposed to regular pushing conditions. It is crucial to investigate the control of shoulder girdles during pushing tasks. The objective of the study was to demonstrate scapular muscle activities and motions on the dominant side during pushing tasks and the relationship between scapular kinematics and muscle activities in different pushing conditions. Methods: Thirty healthy adults were recruited to push a four-wheel cart in six pushing conditions. The electromyographic signals of the upper trapezius (UT) and serratus anterior (SA) muscles were recorded. A video-based system was used for measuring the movement of the shoulder girdle and scapular kinematics. Differences in scapular kinematics and muscle activities due to the effects of handle heights and weights of the cart were analyzed using two-way ANOVA with repeated measures. The relationships between scapular kinematics and muscle activities were examined by Pearson’s correlation coefficients. Results: The changes in upper trapezius and serratus anterior muscle activities increased significantly with increased pushing weights in the one-step pushing phase. The UT/SA ratio on the dominant side decreases significantly with increased handle heights in the one-step pushing phase. The changes in upward rotation, lateral slide and elevation of the scapula decreased with increased pushing loads in the trunk-forward pushing phase. Conclusions: This study indicated that increased pushing loads result in decreased motions of upward rotation, lateral slide and elevation of the scapula; decreased handle heights result in relatively increased activities of the serratus anterior muscles during pushing tasks.

Keywords: Electromyography, Shoulder girdle, Upper extremity

Pushing tasks are functional activities of daily living. According to previous studies, pushing tasks are one of the risk factors that result in discomfort in upper extremities, and 25–41% of workers who exposed to regular pushing conditions have shoulder complaints. In the upper quarter, the scapula acts as a foundation of the shoulder girdle for multiple directions and movements of the upper extremities. Alternatively, poor positions and abnormal movements of the scapula may change the length-tension relationship of the muscles attached to on it and affect the normal functions of the shoulder girdle. Ultimately, they may also lead to shoulder-related dysfunctions.

There are some latent risks, such as overexertion of the musculoskeletal system, environmental factors, collisions and unstable loadings, in pushing tasks that may lead to injuries. Previous reports pointed out that truck drivers who needed to transport goods by pushing had shoulder complaints twice as often compared with the control group. Another study also found that workers exposed to pushing conditions for a long time had more chances to experience shoulder-related dysfunctions than general workers (by 2.09–6.37 times). The results of a pushing experiment among healthy subjects concluded that the peak torque value of the shoulder joint increased biomechanically with pushing weight. This finding may indicate why people had shoulder complaints while pushing for a long time or pushing with heavy weights.

The shoulder girdle consists of the glenohumeral joint, acromioclavicular joint, sternoclavicular joint...
and scapulothoracic articulation\textsuperscript{12-15}. The interactive movements of the glenohumeral and scapulothoracic joints affect the mobility of the shoulder girdle\textsuperscript{6}. Interactive movement of the glenohumeral joint and scapulothoracic joint occurs when the arm is lifted and is well known as the scapulohumeral rhythm (SHR)\textsuperscript{7-9}. Innan et al. determined that a ratio of 2:1 existed between abduction of the arm and upward rotation of the scapula when lifting the arm\textsuperscript{14}. Furthermore, the scapula was rotated upward, tilted posteriorly and rotated externally; thus the subacromion space of the shoulder joint was increased, and this prevented impingement of the shoulder joint\textsuperscript{5-7,17-23}. Without the proper mechanism of movement of the scapula, an uncoordinated movement would lead to injuries, for example, increased stress in the shoulder joint\textsuperscript{5,24,25}. Scapular motions consist of gliding and rotation\textsuperscript{7,17,23}. Scapular gliding includes up/down glides and medial/lateral slides; scapular rotation includes upward/downward rotation, anterior/posterior tipping and internal/external rotation\textsuperscript{15,18}. The diversity of scapular movements is controlled by muscles attached to the scapula such as the serratus anterior, trapezius, rhomboids, levator scapula and pectoralis minor. Theses scapular muscles play different roles as stabilizers or rotators in the shoulder girdle\textsuperscript{6,9,15,20}. The serratus anterior (SA) pulls the scapula out laterally, tips it posteriorly and rotates it upward and externally\textsuperscript{6,8,20,24}. The upper trapezius (UT) elevates the scapula, glides it medially and rotates it upward; the lower trapezius stabilizes the scapula against the rib cage\textsuperscript{20,26}. Hence, sufficiently strong scapular muscles can maintain an adequate scapular position in the shoulder girdle\textsuperscript{22}. In addition, a force couple made up of the SA and UT activates the scapula upwardly and affects the function of the upper extremity\textsuperscript{6,9,13,18,24-28}, and this has been widely discussed in terms of coordination and the importance of the force couple and scapular muscle strengthening\textsuperscript{6,13,26,27,29}. It has previously been reported that insufficient strength of the scapular muscles led to scapular deviations in the shoulder girdle when performing open kinetic chain exercises. The scapula tended to tip forward and rotate downward and internally after repetitive exercises of shoulder internal and external rotation\textsuperscript{30}. It has been shown that deviation of the scapular upward rotation after a fatigue protocol resulted in an altered SHR\textsuperscript{31}. In research on subjects with shoulder-related dysfunctions, it was indicated that disorganization of scapular muscles caused scapular dyskinesia\textsuperscript{30}. Subjects with shoulder impingement were found to have significantly lower protractor muscle strength than healthy subjects. The scapula elevated and rotated upward excessively in subjects with shoulder adhesive capsulitis, while the UT was found to be abnormally activated\textsuperscript{30}. An abnormal muscle activation pattern of the upper and lower trapezius was also found in subjects with shoulder-related dysfunctions while abducting their arms, which compensated for the lower activation of the SA muscle\textsuperscript{19,20}. The UT/SA ratio (the ratio of the UT and SA muscle activations) increased in patients with shoulder-related dysfunction, who had increased UT activations and decreased SA activation, which caused excessive scapular elevation\textsuperscript{12,20}. Occurrence of scapular substitution patterns, for example, excessive scapular tipping, elevation or upward rotation, may narrow the subacromion space or may induce tendinitis of the rotator cuff\textsuperscript{8,12,16,17,20,21,26,31}.

Previous reports in closed kinetic chain exercises revealed that the SA muscles were significantly activated in healthy subjects performing the push-up exercise\textsuperscript{13,15}; on the contrary, the UT/SA ratio rose as a result of abnormal higher activities in the upper trapezius among subjects with shoulder disabilities\textsuperscript{40}. The pushing task belongs to a type of closed kinetic chain movements, which correspond to the following description: “the distal part of the extremity was fixed while the proximal part of the extremity moved\textsuperscript{15}.” Some related factors during pushing tasks have previously been discussed. The exerted hand force increases with the pushing weight\textsuperscript{41}, the proper handle heights for maximum exerted pushing force is from one meter to shoulder height, and people can easily perform pushing tasks with their hands at a height of 50-60% of their shoulder height\textsuperscript{42}. Other factors that affected the hand forces, such as the direction and coefficient of the floor during pushing, were also mentioned previously\textsuperscript{1-10}. However, there is still a lack of discussions concerning how theses related factors, for instance, the weight and height of pushing, affect scapular motion and scapular muscular control in the shoulder girdle. The purpose of this study was to investigate scapular control as well as the relationships between scapular kinematics and muscle activities among different pushing tasks.

**Subjects and Methods**

The subjects were thirty healthy young adults (15 females; weight, 61.2 ± 10.48 kg; height, 1.67 ± 0.08 m; shoulder height, 90.27 ± 5.98 cm; pelvic height, 63.58 ± 4.49 cm) who were informed about the process of the experiments and signed a consent form approved by the Institutional Review Board of Chang Gung University. Subjects did not report any history of shoulder-related dysfunctions during the past of 12 months. The exclusion criteria were histories of shoulder fractures, dislocations, subluxations, impingements, and adhesive capsulitis or surgeries in the
shoulder girdles.

Instrumentation

A 26-kg-cart (63 cm × 72 cm × 144 cm) with four wheels was loaded with different weights (0, 50 and 100 kg) on a fixed track. A video-based system was set up with three digital cameras (GR-DVL9800, JVC Corporation, Japan), and the sampling rate was set at 60 Hz. The Ariel Performance Analysis System (APAS) software (Ariel Dynamics Inc., Trabuco Canyon, CA, USA) was used for calculating the kinematic data. The electromyographic (EMG) signals were collected using an MP150 System (BIOPAC Systems, Inc., Goleta, CA, USA) at 1,000 Hz with and TSD 150B bipolar surface electrodes (BIOPAC Systems, Inc., Goleta, CA, USA) with a 20-mm inter electrode distance and 11.4 mm diameter.

Experimental procedures

Subjects were required to fill out an informed consent form that had been approved by Chang Gung University and then understand well the context of the experiments. The subjects’ skin was prepared by shaving the hair off the electrode placement area if necessary, cleansing the skin with 70% alcohol and application of conductive gel to the skin surface. Two EMG surface electrodes were applied to both UTs parallel to the muscle fibers midway between the seventh spinous process of the cervical vertebra and acromion process. The other two electrodes were applied to both SAs parallel to the muscle fibers midway between the pectoralis major and latissimus dorsi below the axilla area. The reference electrode was applied to the left ankle on the medial malleolus. To perform maximal voluntary contractions (MVC) of a subject’s UT (MVC\text{\text{\textit{UT}}}), the subject sat without a back support, and the neck side-bent to the same side, rotated to the opposite side and extended as resistance is applied at the occipital and shoulder. The MVC of the SA (MVC\text{\text{\textit{SA}}}) was performed with the subject in the same seating position and with the shoulder flexed to 125 degrees as resistance was applied above the elbow while the scapula was fixed.

Seven reflective markers (4-cm in diameter) were placed on bony landmarks in accordance with the International Society of Biomechanics recommendation: the seventh spinous process of the cervical vertebra (C7), right acromion (AC), trigonum spineae (TS, root of scapular spine) and angulus inferior (AI, inferior angle of scapula), eighth spinous process of the thoracic vertebra (T8), right greater trochanter (GT) and lateral epicondyce (LE)\text{\textsuperscript{11, 29}}. The kinematic data of the shoulder girdle from these markers included the angles of shoulder flexion and scapular upward rotation and the distances of scapular elevation and lateral slide of the scapular inferior angle (protraction).

There were three sub-phases in the pushing task in this study. In the initial phase, subjects stood with their hands placed on the pushing bar and waited for the “Go” verbal signal (Fig. 1-a). When the subjects heard the first “Go” signal, they pushed the cart immediately one step forward and with their elbows extended (one-step pushing phase, Fig. 1-b). After the second “Go” signal, the subjects pushed with their trunk leaning forward and kept their feet fixed (trunk-forward pushing phase, Fig. 1-c). Subjects performed six pushing tasks with three different weights (0, 50 and 100 kg) and two different heights (shoulder and pelvic) randomly. The shoulder and pelvic heights were defined as 80% and 60% of the acromion height respectively\text{\textsuperscript{3}}. Data processing

In the glenohumeral joint, the angle of shoulder flexion was defined as the angle composed of the AC, LE and GT. In the scapulohumeral articulation, scapula motion was assumed to rotate and glide purely in the coronal plane. Scapular upward rotation was defined as the angle composed of the spinal column (C7-T8) and medial side of the scapula (TS-AI), which can be calculated by subtracting angle C7-AI-TS from angle T8-C7-AI (Fig. 2-a). In addition, Fig. 2-b shows that using a trigonometric method and the angle consisting of T8, C7 and AI (θ), scapular horizontal and vertical slides can be defined (the sine and cosine values of the distance between C7 and AI under the angle θ).

EMG data were processed using the AcqKnowledge software (BIOPAC Systems, Inc., Goleta, CA, USA), a band-pass filter with a frequency of 20–500 Hz and a full-wave rectifier followed by processing with a root-mean-square (RMS) algorithm with a 50-ms moving window. To normalize the RMS-EMG data, the differences between pushing phases and the initial phase were divided by the MVC\text{\textsubscript{UT}} or MVC\text{\textsubscript{SA}} and multiplied by 100 (presented in percentage). Both scapular kinematics and muscle activations were synchronized post-experimentally.

Statistical analysis

Statistical analysis was completed using SPSS for Windows 10.0 (SPSS Inc, Chicago, IL, USA). Descriptive statistics were used to analyze the subjects’ demographic data. Differences in scapular kinematics and scapular muscle activations were calculated between the initial phase and one-step pushing phase as well as between the one-step pushing phase to trunk-forward pushing phase. These differences were examined by two within-factors (height × weight).
ANOVA with repeated measures ($\alpha=0.05$). If the interaction between height and weight was not significant, two-way ANOVA was used for testing the main effect; if the interaction was significant, the multiple comparisons were examined by Bonferroni adjustment. The relationships between scapular kinematics and scapular muscle activations were examined by Pearson’s correlation coefficients ($\alpha=0.05$).

**Results**

*From the initial phase to the one-step pushing phase*

Regarding the scapular muscle activation, although no main effect of pushing weight or handle height on SA activation was found, the significant interaction between pushing weight and handle height showed that SA activation at the pelvic handle height was significantly higher than that at the shoulder handle height while pushing a 100-kg cart ($F_{(2,58)}=3.42$, $p<0.05$; Table 1). In addition, handle height revealed a significant main effect on UT/SA ratio under different pushing conditions, and a higher UT/SA ratio at the shoulder height was found when compared with that at the pelvic height ($p<0.01$; Table 2).

Regarding the scapular kinematics, Table 3 demonstrates a significant main effect of handle height on
changes in scapular horizontal displacement in which the scapula slid more when pushed at the pelvic height when compared with that at the shoulder height ($p<0.01$). In addition, there was a significant interaction between pushing weight and handle height on scapular vertical displacement, and the displacement was increased significantly more at the pelvic handle height ($F_{2,5}=16.73$, $p<0.01$) than that at the shoulder handle height while pushing an empty cart.

A significant moderate correlation between SA activation and shoulder flexion was revealed while pushing a 100-kg cart at the shoulder handle height ($r=0.42$, $p<0.05$).

From the one-step pushing phase to the trunk-forward pushing phase

Regarding the scapular muscle activation, there was no main effect of pushing weight or handle height on UT activation, but the significant interaction between the two factors showed a significant increase in UT activation at the pelvic handle height compared with that at the shoulder handle height while pushing a 100-kg cart ($F_{2,5}=3.86$, $p<0.05$; Table 1). In addition, handle height and pushing weight revealed main effects on changes in SA activation ($p<0.01$). This indicated that SA activation increased more at the pelvic height than at the shoulder height regardless of the pushing weight. It also revealed significant differences in SA activation among the three pushing weight conditions regardless of the handle height (Table 1).

Regarding the scapular kinematics, pushing weight showed a main effect on the changes in scapular upward rotation, scapular horizontal displacement, and vertical displacement ($p<0.01$; Table 3). In multiple comparisons, pushing a 100-kg cart resulted in more scapular horizontal slide than pushing an empty cart ($p<0.01$); it also showed significant differences in scapular elevation among the three different pushing weight conditions ($p<0.01$).

A significant moderate correlation was revealed between SA activation and scapular horizontal displacement while pushing an empty cart at the shoulder height ($r=0.37$, $p<0.05$). While pushing a 100-kg cart at the pelvic height, there were moderate correlations of SA activation and scapular horizontal displacement ($r=0.56$, $p<0.05$) as well as SA activation and scapular vertical displacement ($r=0.43$, $p<0.05$).

**Discussion**

The purpose of this study was to investigate the changes in scapular kinematics and muscle activities under different pushing conditions. All the data analyzed and presented were from the subjects’ dominant side. From the initial phase to the one-step pushing phase, handle height was an important factor that affected the UT/SA ratios in the pushing task. The significantly lower UT/SA ratio at the pelvic height than that at the shoulder height was due to the higher activations of the SA while pushing a 100-kg cart at the pelvic height compared with at the shoulder height (MVC 6.24% higher) (Table 1). Handle height also affected the scapular horizontal displacements significantly: the higher the handle position was, the lower the deviations of scapular horizontal displacement revealed. This was because the starting position of the scapular was set at a higher angle of upward rotation, which meant a larger horizontal displacement at shoulder handle height than at pelvic handle height. Therefore, the changes in scapular horizontal displacement would not be greater at the shoulder handle height than at the pelvic handle height. The lower deviations in scapular horizontal displacement explained the more stable condition of the scapula while pushing at the shoulder handle height.

### Table 1. Changes in scapular muscles activations among different pushing conditions (N=30)

<table>
<thead>
<tr>
<th>Pushing weight</th>
<th>Handle height</th>
<th>Changes in the UT (%MVC)</th>
<th>Changes in the SA (%MVC)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>One-step pushing</td>
<td>Trunk-forward pushing†</td>
</tr>
<tr>
<td>0 kg</td>
<td>Shoulder</td>
<td>2.62 ± 2.72</td>
<td>2.54 ± 3.48</td>
</tr>
<tr>
<td></td>
<td>Pelvic</td>
<td>2.54 ± 3.34</td>
<td>5.10 ± 7.67</td>
</tr>
<tr>
<td>50 kg</td>
<td>Shoulder</td>
<td>10.93 ± 11.60</td>
<td>8.95 ± 10.39</td>
</tr>
<tr>
<td></td>
<td>Pelvic</td>
<td>8.11 ± 8.91</td>
<td>7.96 ± 7.79</td>
</tr>
<tr>
<td>100 kg</td>
<td>Shoulder</td>
<td>19.25 ± 15.23</td>
<td>10.99 ± 9.77</td>
</tr>
<tr>
<td></td>
<td>Pelvic</td>
<td>16.93 ± 11.35</td>
<td>15.58 ± 11.56*</td>
</tr>
</tbody>
</table>

*Pushing weight shows the main effect ($p<0.05$). †Handle height shows the main effect ($p<0.01$). *There was significant interaction between weight and height in this phase using ANOVA with repeated measures. ‡The muscle activations were significantly higher at the pelvic handle height than at the shoulder level while pushing a 100-kg cart ($p<0.05$). UT: upper trapezius. SA: serratus anterior. MVC: maximal voluntary contractions.
changes in scapular vertical displacement were greater at the pelvic handle height than at the shoulder handle height, which was supported not only by the lower starting position of the scapular setting but also by the significant activations of the SA while pushing at the pelvic handle height.

From the one-step pushing phase to the trunk-forward pushing phase, handle height affected significantly the SA activation, with SA decreasing as the handle height increased. This contrasts with the proposed proportioned relation between SA activation and shoulder flexion in research performed on subjects doing wall-slide exercises. The increased SA activations with pelvic handle height (lesser angle of pelvic handle height) may imply the cause of injuries as a result of overexertion. Pushing weight was the other factor affecting the activations of the SA: the pushing weight increased, the activations of the SA increased. This corresponded to the results of a previous study of push-up exercises in which the more difficult the push-up exercises were, the more scapular muscle activations appeared. If workers are exposed to heavy pushing weights conditions for a long time, the scapular muscles are also exposed to the risk of injury.

The angles of shoulder flexion and scapular upward rotation increased proportionally in this phase, and this corresponded to the notion of interactive scapulo-humeral rhythm. Pushing weight significantly affected the changes in angles of shoulder flexion and scapular upward rotation and horizontal and vertical displacement, with increased pushing weights resulting in decreased changes in angle and displacement (Table 3). This indicated that the SA which attached scapula against the chest wall worked as a scapular stabilizer rather than a scapular rotator in closed kinetic chained tasks with difficulty.

The UT and SA are the prime movers for scapular upward rotation. However, we did not find any significant correlations between the activations of the UT, SA, and changes in angles of shoulder flexion and scapular upward rotation. According to the relationship between shoulder flexion and SA activities, the activations of the SA revealed apparently 120 to 150 degrees of shoulder flexion, but the mean value of shoulder flexion during pushing tasks was merely 85.49 degrees. The reason for the insufficient SA activation may be due to the insufficient angle
of shoulder flexion, which may cause a poor length-tension relationship.

In the interaction between handle height and pushing weight, the changes in SA activations while pushing a 100-kg cart at pelvic handle height were significantly greater than those at shoulder handle height. This finding may be the reason for related injuries in this pushing condition. The changes in UT activations were lesser than those in the SA across the pushing phases because the SA served as a scapular stabilizer during upper limb activities.

In summary, we demonstrated that pushing weight was the first factor that affects the scapular kinematics and muscle activities during pushing tasks. Increased pushing weight not only increased significantly the changes in scapular muscle activations, scapular upward rotation and lateral slide, but also decreased the changes in scapular upward rotation on the dominant side of the subject. Handle height was the second factor, with increased handle height resulting in decreased changes in horizontal displacement and decreased activations of the UT and SA in pushing tasks.

Limitations

The pushing task in this study was limited to represent a real situation when pushing a cart weighing less than 100 kg. However, injuries or discomfort in the shoulder occur in situations such as when pushing a cart weighing more than this. Therefore, in order to elicit the maximal exertion force of pushing as well as to standardize the method adopted in this study, we instructed subjects to perform trunk-forward pushing with their feet fixed. The pushing task was also limited due to the space constraints of our facility, so the subjects could not perform the task continuously which is similar to actual conditions. Future study focusing on sequential and dynamic pushing rather than phase-by-phase pushing will benefit the understanding of scapular control during a pushing task. In addition, this study only gathered data from the subjects’ dominant side. Therefore, we were not able to examine the changes on the non-dominant side and compare the scapular kinematics between the two sides of the body. Last but not the least, there are many other scapular muscles that control the scapular kinematics and that may need to be investigated in the future.

Occupational health relevance

Even if the unusual pushing task that subjects adopted may cause changes in their shoulder region, we suggest that workers should use a proper shoulder height for pushing, which could decrease the activations of the SA under prolonged pushing or sudden exertion conditions. In addition, further investigation of the impact of scapular muscle strengthening on pushing workers is expected to alleviate shoulder complaints and prevent repeatedly-caused injuries in the shoulder girdle.

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