Muscle activity pattern of the shoulder external rotators differs in adduction and abduction: an analysis using positron emission tomography

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Background: The muscle activity pattern during shoulder external rotation has not been fully clarified. This study aimed to determine the activities involved in external rotation in the adducted and abducted positions using positron emission tomography (PET).

Methods: Seven healthy volunteers underwent PET examinations after performing external rotation using an elastic band at both 0° and 90° of shoulder abduction in the frontal plane. External rotation exercise was performed before and after injection of fluorine 18 fluorodeoxyglucose, which was followed by PET examination. The protocols for external rotation exercise were identical between the 2 shoulder positions. To obtain control data, PET examination was also performed under resting conditions. The order of these 3 PET examinations was randomized, and they were performed at intervals of 1 week or greater. Each PET image was fused to the corresponding magnetic resonance image to identify each shoulder muscle. After this, the standardized uptake value was calculated in each muscle and was compared between the 2 shoulder positions.

Results: The infraspinatus showed the greatest muscle activity during external rotation at 0° of abduction, whereas the teres minor showed the greatest activity at 90° of abduction. The teres minor–infraspinatus ratio at 90° of abduction (mean ± SD, 1.21 ± 0.23) was significantly higher than that at 0° of abduction (0.84 ± 0.15) (P < .01).

Conclusion: The infraspinatus and teres minor are the main shoulder external rotators. The teres minor is more important as an external rotator in abduction than in adduction.

Level of evidence: Basic Science, Physiology, Imaging.
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Keywords: Shoulder external rotation; positron emission tomography; shoulder rehabilitation; rubber tube training; teres minor; infraspinatus

The experimental protocol of this study was approved by the Ethics Committee of Tohoku University School of Medicine (2010-145), and a signed consent form was obtained from each subject before fluorine 18 fluorodeoxyglucose positron emission tomography examination.

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During physical examination of the shoulder, external rotation strength is usually measured with the arm against the torso (adducted position). However, it is necessary to externally rotate the shoulder in the abducted position for various activities of daily living, such as eating, shaking hands, and combing. The infraspinatus and teres minor are known to be the main external rotators of the shoulder. Although several authors have investigated the difference in shoulder external rotation between the abducted and adducted positions, the contribution of individual muscles has not been fully clarified to date. On the basis of the previous studies, approximately 90% of shoulder external rotation torque is produced by the rotator cuff muscles (infraspinatus and teres minor). This is quite unique when compared with abduction (30% by the cuff muscles and 70% by the deltoid) and internal rotation (50% by the cuff muscles and 50% by other muscles)\(^9,13,14,26,27\). Regarding the various results, they concluded that the teres minor plays an important role during external rotation in abduction.

Shoulder position affects external rotator activity\(^6,5,11,15\) and technical disadvantages for application to the shoulder muscles.\(^20\) Several studies have shown the efficacy of positron emission tomography (PET) with fluorine 18 (18F) fluorodeoxyglucose (FDG) in evaluating the function of the skeletal muscles.\(^5,7,18-20,22-25\) FDG PET is a nuclear medicine tool for non–mechanically invasive quantification of regional blood flow and tissue glucose metabolism in vivo. PET, therefore, reflects a sum of muscle activities during motion. Fujimoto et al\(^6\) showed that both FDG uptake and EMG data are reliable and comparable parameters for the assessment of muscle activity as long as the exercise is aerobic. Compared with electromyography, PET examination has 3 major advantages for assessing muscle activities. First, the insertion of needle electrodes is not required. Even with fine-wire electrodes, the insertion of needles into the muscle is invasive. Pain sometimes occurs during motion in EMG studies, which may affect muscle activity. Second, the FDG uptake pattern in the entire body of the muscle can be visualized. In contrast, needle electrodes can monitor only a limited area of the entire muscle in EMG studies. Third, injected FDG is taken up by the muscle cells and remains as FDG-6-phosphate in these cells after phosphorylation. Different from EMG studies, PET can assess muscle activities during a certain period. All these advantages enable us to quantify the activity of each skeletal muscle by FDG accumulation and to visualize the activity pattern in the whole muscle during any type of exercise by coregistering the PET scan with magnetic resonance imaging (MRI).

In 2003, Shinozaki et al\(^23\) first applied FDG PET to the shoulder muscles. They showed that FDG PET could be a useful tool for the objective evaluation of rotator cuff muscle activities. On the basis of these reports, Omi et al\(^20\) and Shinozaki et al\(^22\) investigated shoulder muscle activities during scaption exercises using this method. To date, however, no studies have focused on external rotation.

This study aimed to determine the muscle activities during external rotation with the arm at 0° and 90° of abduction using FDG PET.

### Materials and methods

#### Subjects

Seven healthy volunteers, who were recruited in our department, were examined by PET. Inclusion criteria consisted of the following: (1) age between 20 and 50 years, (2) willingness to...
participate in this study, and (3) no history of shoulder pain. Exclusion criteria were as follows: (1) previous diagnosis of shoulder disorders, including rotator cuff tear; (2) surgery around the shoulder; and (3) metabolic diseases, such as diabetes mellitus. All the subjects were men, and the dominant side was the right side. The mean age was 33 years (range, 27-42 years). MRI examination was performed in all the subjects to confirm that there were no pathologic conditions around the shoulder, such as rotator cuff tears. The teres minor was not shown to be absent on magnetic resonance (MR) images in any of the subjects. All the subjects refrained from eating and drinking, except for water, for at least 8 hours before the examination. They also refrained from strenuous exercise for 3 days before the examination.

**Experimental protocol**

The subjects underwent 3 PET examinations to obtain data on external rotation at 0° of abduction, at 90° of abduction, and under resting conditions. The order of these conditions was randomized, and the minimum interval between each examination was set at 1 week (mean, 2 weeks). For external rotation at 0° of abduction, the exercise protocol consisted of repetitive shoulder external rotations in the supine position with the arm at 0° of abduction in the frontal plane. The supine position was chosen because we aimed to keep the body position identical, except for the arm position, for consistency. During each exercise, only the dominant shoulder was rotated from 30° of internal rotation to 30° of external rotation with resistance by use of an elastic band (yellow Thera-Band; The Hygenic Corporation, Akron, OH, USA) (Fig. 1, A). A 60-cm-long elastic band was wrapped around the wrist and was stretched to 150% of its original length when the exercise was started. The subjects were asked to exercise before and after FDG injection. The number of repetitions for the exercise before FDG injection was 100 (Fig. 2). In each exercise set, the subjects were asked to rotate the shoulder externally over a 1-second period and then to relax to allow passive internal rotation caused by the tension of the elastic band. Each subject took a 20-second rest after every 40-second exercise (20 repetitions of shoulder external rotation) to avoid excessive muscle fatigue. FDG was dissolved in approximately 2 mL of saline solution, which was then intravenously injected through the median cubital vein. The mean dose of injected FDG and standard deviation were 75.7 MBq and 3.1 MBq, respectively. After the injection, the subjects were asked to rotate the shoulder externally an additional 200 times. PET images were obtained 50 minutes after the injection by use of a whole-body positron camera (SET-2400W; Shimadzu, Kyoto, Japan) (Fig. 2). Before each PET scan was started, the subject’s blood sugar level was measured. The mean blood sugar level and standard deviation were 94.5 mg/dL and 8.1 mg/dL, respectively.

To evaluate external rotation at 90° of abduction, we asked the subjects to perform the exercise on a separate day. They rotated the shoulder externally in the supine position with the arm at 90° of abduction in the frontal plane. The rest of the experimental protocol was the same as that for external rotation at 0° of abduction (Fig. 1, B).

**PET examination**

By use of a PET scanner with an intrinsic spatial resolution of 3.9 mm full width at half maximum, a set of emission scans in the 3-dimensional data acquisition mode, ranging from the base of the neck to the middle of the upper arm, was obtained 50 minutes after FDG injection. The axial field of view of the scanner was 200 mm, and images were obtained by performing 2 incremental scans, each of which took 8 minutes. A germanium 68/gallium 68 (68Ge/68Ga) external rotating line source was then used to obtain transmission scans (lasting 5 minutes each) after the emission scans (post-injection transmission) to correct tissue attenuation. All the data were corrected for dead time, decay, and measured photon attenuation. They were reconstructed into a 128 × 128 × 63 matrix for a set of 3-dimensional volume images by Fourier rebinning and the ordered-subset expectation maximization algorithm with the aid of an SX-9 (NEC Corporation, Tokyo, Japan) at the Cyberscience Center, Tohoku University, Sendai, Japan.

**Magnetic resonance imaging**

To quantify the muscle activity in each muscle, it was necessary to determine the exact location of each muscle on PET images. For this purpose, MR images of the dominant shoulder were obtained for image fusion in each subject (Signa Horizon LX 1.5T, version 9.1; GE Healthcare, Milwaukee, WI, USA). The measurement conditions were as follows: repetition time/echo time: 3,000 milliseconds/85 milliseconds; number of excitations: 1; field of view: 46 cm; number of matrices: 512 × 512; slice thickness: 3 mm; and slice gap: 1.5 mm.

**Data analysis**

Each PET image was fused to the corresponding MR image at the identical level using Dr. View/Linux software (AJS, Tokyo, Japan) according to the methods of Omi et al; this enabled the delineation of the contour of each shoulder muscle (Fig. 3). A T2-weighted transverse MR image was used to determine the contour of the deltoid muscle on PET images, and a T2-weighted oblique sagittal MR image was used to determine the contour of the supraspinatus, subscapularis, infraspinatus, and teres minor. The deltoid muscle was divided into 3 portions (anterior, middle, and posterior). Each portion of the deltoid muscle was divided by lines drawn from the center of the humerus to the 12-o’clock and 9-o’clock directions according to the methods of Omi et al. Subsequently, the volume of interest was placed on the MR image of each shoulder muscle. After this, the standardized uptake values (SUVs) of each segment of the deltoid muscle and SUVs of the rotator cuff muscles were calculated to quantify their activities by use of the following equation:

\[
\text{SUV} = \left[ \frac{\text{Mean VOI count (cps/g)} \times \text{Body weight (g)}}{\text{Injected dose (MBq)} \times \text{Calibration factor (cps/MBq)}} \right]
\]

The SUV expresses the ratio of the amount of FDG accumulated in a certain volume of interest (VOI) compared with the amount of FDG that is equally distributed over the entire body. For further comparisons, the exercise-rest ratio was established in each muscle to minimize the individual variation in SUVs.

We performed the following 3 comparisons: First, the SUV in each muscle at both 0° and 90° of abduction was compared with that in the corresponding muscle at rest to identify the FDG uptake due to external rotation exercises. Second, the exercise-rest ratio of the SUV was compared among 5 muscles for both 0° and 90° of abduction to clarify which muscle was the most activated during
Third, the teres minor–infraspinatus (TMi/ISP) ratio of the SUV was established to determine the relative contribution of these 2 muscles to external rotation exercise. Finally, this ratio was compared at 0° and 90° of abduction.

**Statistical analysis**

Statistical analysis was performed with JMP software, version 10 (SAS Institute, Cary, NC, USA). The Dunnett test was used to compare the SUV of each muscle after exercise with that of the corresponding muscle at rest. The Tukey honestly significant difference test was used to compare the exercise-rest ratio among 5 muscles. Furthermore, the paired t test was used to compare muscle activities between 0° and 90° of abduction. Differences with $P < .05$ were considered statistically significant.

**Results**

There were no abnormal accumulations, suggesting the presence of a tumor, on the PET images at rest. High FDG uptake was observed in all 4 rotator cuff muscles after external rotation exercise was performed at both 0° and 90° of abduction in the frontal plane (Table I). After external rotation exercise was performed at 0° of abduction, the SUV of the infraspinatus was the highest among all the shoulder muscles (Fig. 4, A). Interestingly, after external rotation exercise at 90° of abduction, the teres minor showed the highest SUVs in 6 of 7 subjects (Fig. 4, B). In the remaining case, the SUV of the teres minor was almost equal to that of the infraspinatus.

The exercise-rest ratio of both the infraspinatus and teres minor was significantly higher than that of the other muscles at 0° of abduction (Fig. 5, A). These 2 muscles also showed a significantly higher exercise-rest ratio than the other muscles at 90° of abduction (Fig. 5, B).

The mean TMi/ISP ratio was 0.84 (SD, 0.15) at 0° of abduction, whereas it was 1.21 (SD, 0.23) at 90° of abduction. The TMi/ISP ratio at 90° of abduction was significantly higher than that at 0° of abduction ($P < .01$) (Fig. 6).

**Discussion**

The results of this study show that the activities of both the infraspinatus and teres minor muscles are significantly higher than those of other shoulder muscles during external rotation exercises. Moreover, we found that the muscle activity patterns of these 2 muscles differ in adduction and abduction. In adduction, the infraspinatus is more activated than the teres minor. In contrast, the teres minor is more activated than the infraspinatus in abduction. These results support previous clinical observations by Walch et al.28

Many studies have examined the function of the external rotators in different arm positions; some of these have used cadavers, whereas some have used patients or volunteers.8,12,14,16,26,28,30 However, none of these studies clearly showed the difference observed in our study. This was probably because of the heterogeneity of the previous studies. This study, for the first time, clearly shows that the infraspinatus and teres minor have different functions in different arm positions in healthy volunteers. This is the primary strength of our study.

Walch et al28 reported that hypertrophy of the teres minor muscle was observed in 7 of 12 patients with infraspinatus tears, together with its severe fatty degeneration.
Because the hornblower’s sign was not positive in any of the patients, Walch et al concluded that the teres minor can contribute enough power to external rotation to prevent the hornblower’s sign. On the basis of their study, we assume that it may be possible to avoid the appearance of the hornblower’s sign even with a chronic infraspinatus tendon tear if strengthening exercises of the teres minor are successfully performed. Our study also provides important information regarding strengthening exercises for the teres minor muscle. We found that the teres minor showed higher

### Table I  Mean SUV for each shoulder girdle muscle

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Rest</th>
<th>External rotation at 0° of abduction</th>
<th>External rotation at 90° of abduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deltoid</td>
<td>0.72 ± 0.10</td>
<td>0.74 ± 0.08</td>
<td>0.76 ± 0.04</td>
</tr>
<tr>
<td>Anterior</td>
<td>0.69 ± 0.10</td>
<td>0.72 ± 0.06</td>
<td>0.68 ± 0.11</td>
</tr>
<tr>
<td>Middle</td>
<td>0.65 ± 0.12</td>
<td>0.67 ± 0.08</td>
<td>0.68 ± 0.09</td>
</tr>
<tr>
<td>Posterior</td>
<td>0.75 ± 0.09</td>
<td>0.76 ± 0.10</td>
<td>0.82 ± 0.03</td>
</tr>
<tr>
<td>Subscapularis</td>
<td>1.29 ± 0.05</td>
<td>1.43 ± 0.12 *</td>
<td>1.48 ± 0.10 *</td>
</tr>
<tr>
<td>Supraspinatus</td>
<td>1.19 ± 0.10</td>
<td>1.35 ± 0.10 †</td>
<td>1.34 ± 0.08 *</td>
</tr>
<tr>
<td>Infraspinatus</td>
<td>1.13 ± 0.07</td>
<td>2.50 ± 0.81 ‡</td>
<td>2.12 ± 0.55 ‡</td>
</tr>
<tr>
<td>Teres minor</td>
<td>1.15 ± 0.10</td>
<td>2.11 ± 0.64 †</td>
<td>2.54 ± 0.43 ‡</td>
</tr>
</tbody>
</table>

Data are given as mean ± standard deviation.

* Statistically significant increase compared with value at rest: P < .05.
† Statistically significant increase compared with value at rest: P < .01.
‡ Statistically significant increase compared with value at rest: P < .001.
FDG uptake in the abducted position. Therefore, we recommend that external rotation exercises be performed with the arm in abduction to strengthen the remaining teres minor in patients with decreased teres minor strength.

Further clinical relevance of this study involves injury prevention in throwing athletes. A rubber resistance exercise in external rotation is used as one element of an injury prevention program for throwing athletes. In professional pitchers, reduced external rotation strength in the preseason period can reportedly be a risk factor for throwing injuries. During the deceleration phase of the pitching motion, the shoulder abduction angle is approximately 90°. DiGiovine et al reported that the teres minor shows the highest level of activity among all the glenohumeral muscles during the deceleration phase of the pitching motion. From the results of our study, we assume that external rotation exercises in the abducted position may also be useful for overhead athletes to increase the muscle strength of the teres minor and prevent throwing injuries. Further clinical studies will be required to prove our assumption.

There were several limitations to this study. First, FDG uptake on PET scans reflects the sum of muscle activities during motion but does not reflect a real-time contraction of each muscle. In other words, we were unable to identify the exact phase with the highest activity in each muscle from the pattern of FDG uptake. Second, the shoulder position of each subject was not exactly the same between MR images and PET scans. The minimum resolution of PET images was relatively low (4-5 mm), which made it difficult to identify the border of each muscle. Because we had no PET/MRI unit, it was impossible to examine both the PET scan and MRI study simultaneously. Another limitation was the variation in shoulder position. We chose only 2 positions to limit the exposure to radiation. If various positions could have been investigated, more detailed results may have been obtained. Finally, the number of subjects was small. This was because the research facilities for PET scanning in our institution are limited. Despite the small number of subjects, we were able to successfully show the difference in muscle activity patterns between the 2 arm positions.

**Conclusion**

The infraspinatus and teres minor, known as the main shoulder external rotators, have different functions in different arm positions. The teres minor assumes more importance as an external rotator in the abducted position than in the position with the arm against the torso. On the other hand, the contribution of the infraspinatus is greater in the position with the arm against the torso than in the abducted position. These results may provide useful information when one is considering external rotation function during activities of daily living.

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