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Feedforward coactivation of trunk muscles during rapid shoulder movements

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Background: Shoulder movements that involve unilateral and bilateral flexion, extension, abduction, and asymmetrical flexion-extension cause the activity of trunk muscles. There has not been a fixed consensus on the onset of deep trunk muscle activities including the psoas major (PM), quadratus lumborum (QL), transversus abdominis (TrA), and lumbar multifidus (MF) during shoulder movements. The purpose of this study was to measure the onset of electromyographic activity of the deep trunk muscles during rapid shoulder movements and clarify the coordinated activity pattern of the deep trunk muscles during 11 shoulder movements.

Methods: Thirteen men participated in this study. The onset of activity of the right deep trunk muscles (PM, QL, TrA, and MF) were measured using fine-wire electrodes, and those of the right and left deltoid (anterior, middle, and posterior) and right superficial trunk muscles (rectus abdominis, external oblique [EO], and internal oblique [IO]) were measured using surface electrodes as participants performed 6 types of unilateral, 3 types of bilateral, and 2 types of asymmetrical rapid shoulder movements. We defined feedforward activation as the onset of activity of trunk muscle before or within +50 ms onset of the deltoid muscle and feedback activation as that after +50 ms. A 1-way analysis of variance was performed to compare the onset of activity of each muscle during each shoulder movement.

Results: The mean onset of activity of the PM (26.0 ms), QL (13.1 ms), TrA (−19.7 ms), and MF (20.4 ms) muscles demonstrated feedforward activation during left shoulder flexion. The onset of activity of the TrA (1.6-48.7 ms), rectus abdominis (−1.7 to 17.3 ms), and EO (5.6–40.8 ms) muscles demonstrated feedforward activation during left, right, and bilateral shoulder extension. The onset of activity of the PM (22.9 ms), QL (23.0 ms), TrA (18.9 ms), and EO (15.4 ms) demonstrated feedforward activation during left shoulder abduction, while that of the IO (4.4–10.9 ms) only demonstrated feedforward activation during right and bilateral shoulder abduction. The onset of activity of the TrA (−27.6 ms) and IO (−23.9 ms) demonstrated feedforward activation during left shoulder flexion-right shoulder extension, and that of the MF (33.4 ms) and EO (−17.2 ms), during left shoulder extension-right shoulder flexion.

Conclusion: Rapid shoulder movements occur with coordinated muscle activation of the deep trunk muscles depending on the direction of shoulder movements. Feedforward activation of single or combined deep trunk muscles may facilitate rapid shoulder movements.

During activities of daily living, jobs, or sports, the unilateral or bilateral shoulder moves for flexion-extension, adduction-abduction, and internal-external rotation. These movements involve the activity of trunk muscles in addition to the shoulder muscles.[4–7,11,13–15,20,21,27–29,34] Previous studies reported that trunk muscles (transversus abdominis [TrA], lumbar multifidus [MF], rectus abdominis [RA], external oblique [EO], and internal oblique muscles [IO]) were activated prior to shoulder flexion and

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extension movement,[1,2,8,11,13–15,22–24] and this activation also contributes to shoulder and scapular movement.[17,31,33]

The TrA increases intra-abdominal pressure by transmitting force through the thoracolumbar fascia, thereby stabilizing the trunk,[5,11] and has the role of trunk flexion and ipsilateral rotation.[34] The MF has the role of fixing the lumbar spine,[4] trunk extension, and trunk lateral flexion.[6,21] The psoas major (PM) and quadratus lumborum (QL) muscles also exert compressive forces on the lumbar spine[7,20,28,29]; these muscles act for trunk extension, ipsilateral trunk lateral flexion, and trunk rotation.[20,27] These deep trunk muscles (TrA, MF, PM, and QL) are considered to be involved in trunk stability not only in the sagittal plane but also in the frontal and horizontal planes. Although many studies have demonstrated the activity of the deep trunk muscles during shoulder flexion and extension,[2,13–15,24–26] very few studies have measured those during shoulder abduction movements which caused trunk lateral flexion,[14,24] and even fewer studies have measured those during shoulder asymmetrical movements which caused trunk rotation (eg, left shoulder flexion and the right shoulder extension during running or throwing motion). Only activity of the TrA has been measured during asymmetrical shoulder movements,[22,25,35] and the activities of other deep trunk muscles have not been measured. In addition, no studies have simultaneously measured the activity of all deep trunk muscles during unilateral and bilateral shoulder movements; therefore, coordinated activity of all deep trunk muscles has not been presented. Clarifying the deep trunk muscles' activities required for shoulder movements (abduction, asymmetric movements) in which trunk movements occur in the frontal and horizontal planes would provide a better understanding of the relationship between shoulder movements and the activity of the deep trunk muscles for improving shoulder movements and performance.

The purpose of this study was to measure the electromyography (EMG) activity of the deep trunk muscles during rapid shoulder movements and clarify the coordinated activity pattern of the deep trunk muscles during 11 shoulder movements. We hypothesized that the pattern of activity of the deep trunk muscles depended on the direction of shoulder movements and that the activity of deep trunk muscles would have an earlier onset than that of the deltoid muscles.

Materials and methods

Participants

The number of participants was calculated using G*power 3.1.9.2 and was estimated to be 13, assuming alpha = 0.05, power = 0.80, and effect size (ES) = 0.40. Thus, 13 healthy male volunteers were recruited for this study: age (mean ± standard deviation [SD]), 22.5 ± 3.2 years; height, 175.1 ± 5.8 cm; weight, 69.9 ± 6.8 kg; and body mass index, 22.8 ± 2.1 kg/m^2. All the participants were right-handed. We judged the dominant hand as the side used for both writing and throwing. Participants were recruited through announcements made on posters that were exhibited on a student bulletin board. Participants were excluded if they had a history of any disease in the upper limb, lower limb, or lumbar region and had current pain or neurological deficits and scapula dyskinesis. Before the study began, written informed consent was obtained from all the participants, and the scapular dyskinesis test reported by Kiblar et al[19] was performed by an orthopedic surgeon and 2 registered physical therapists. The study was approved by the ethical committee of the university (approval number: 19R107103). All procedures performed in this study conformed with the regulations set forth by the 1964 Declaration of Helsinki and its later amendments.

Electromyography

Bipolar intramuscular fine-wire electrodes (stainless steel, urethane coated, 50-μm diameter, 250-mm length, 1 mm of urethane removed from the tips; Unique Medical Co., Tokyo, Japan) were threaded into a hypodermic needle (diameter: 0.72 mm, length: 100 mm, bent back to form a 5-mm hook) and inserted into the right PM, QL, TrA, and MF of each participant. Based on previous reports,[24,26,27] an experienced orthopedic doctor inserted the electrodes into each muscle under ultrasonographic guidance using the convex and linear probes of an Aplio 300 ultrasound system (Canon Medical Systems, Tokyo, Japan). The PM electrodes were inserted into the skin 7 cm lateral to the spinous process between the L3 and L4 transverse processes.[27] The QL electrodes were inserted into the skin 9 cm lateral to the spinous process between the L3 and L4 transverse processes.[27] The tip of the wire was placed in the center of these muscles (Fig. 1). The TrA electrodes were inserted midway between the anterior superior iliac spine and the lower border of the rib cage.[14] The MF electrodes were inserted 2 cm lateral to the spinous processes at the L4-L5 level.[14] Surface electrodes (cordless active electrode: width, 1 mm; length, 10 mm; interelectrode distance, 10 mm; Nihon Kohden Corp., Tokyo, Japan) were placed on the anterior, middle, and posterior deltoid muscles on both sides. The EMG of the right RA, EO, and IO was measured using line-connected electrodes (wired active electrode: width, 1 mm; length, 10 mm; interelectrode distance, 10 mm; Nihon Kohden Corp., Tokyo, Japan). Based on recommendations from the Surface Electromyography for the Non-Invasive Assessment of Muscles project (http://www.seniam.org/), the surface and line-connected electrodes were placed on each muscle belly parallel to the orientation of the muscle fibers.[10] The grounding electrodes were placed on the head of the right fibular and right lateral malleoli. The skin was scrubbed and wiped with 70% alcohol before inserting the wire or placing the electrodes.

Electrode recordings were acquired using an RMT-1000 polygraph system (Nihon Kohden Corp., Tokyo, Japan) for the fine-wire and line-connected electrodes and a Web-1000 multichannel telemetry system (Nihon Kohden Corp., Tokyo, Japan) for the surface electrodes. All EMG data were synchronized using the RMT-1000. The EMG signals from the fine-wire and surface electrodes were sampled at 2000 Hz.

Procedure

All participants stood with their feet shoulder-width apart, shoulders relaxed, and eyes directed forward. They performed 5 trials of 11 types of rapid shoulder movements: (1) left shoulder flexion 60°, (2) right shoulder flexion 60°, (3) left shoulder abduction 60°, (4) right shoulder abduction 60°, (5) left shoulder extension 40°, (6) right shoulder extension 40°, (7) bilateral shoulder flexion 60°, (8) bilateral shoulder abduction 60°, (9) bilateral shoulder extension 40°, (10) left shoulder flexion 60° and right shoulder extension 40°, and (11) left shoulder extension 40° and right shoulder flexion 60°. Starting from 0° abduction, the participants performed each shoulder movement to the designated angle as fast as possible in response to a short, high-pitched sound stimulus. To perform accurate shoulder movements, the target bar is placed at a height consistent with each defined shoulder movement. The participants were instructed to raise their arms until they touch the target bar. After 2–5 seconds of silence, another sound stimulus was played, prompting them to start the next movement. Different sound stimuli were used as cues to start shoulder flexion, extension, and abduction. All measurements were performed under randomized conditions so that the direction of movement was not predictable, and each movement was

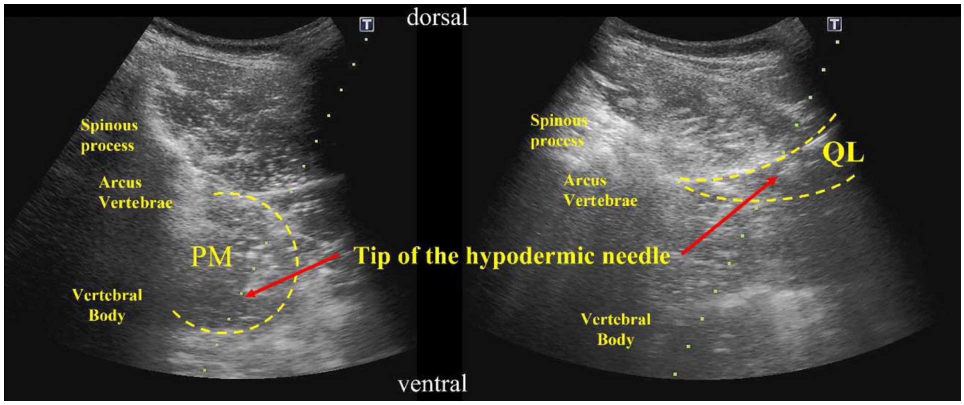

Figure 1 Ultrasonography image of the wire insertion into the PM and QL muscles. *PM*, psoas major; *QL*, quadratus lumborum.

performed for 5 trials. Several practice trials were performed to ensure the correct shoulder movement in response to each sound stimulus. The participants rested for at least 1 minute between trials to minimize fatigue.

Data analysis

The EMG data were collected and analyzed using LabChart version 7 (ADInstruments, Tokyo, Japan). The raw EMG data from all the electrodes were bandpass filtered in the 20–1000 Hz range to remove any artifacts. All filtered EMG data were full-wave rectified before being used in the analysis. We calculated the EMG onset for each muscle based on previous studies.[30] The mean and SD of the EMG amplitude in the resting state for 50 ms were calculated, and the point at which the mean + 2 SD of the EMG amplitude exceeded the threshold for at least 50 ms was defined as the onset of EMG activity. Linear envelope of each muscle was created from the rectified EMG data using a moving average with 50-ms integrated EMG. The onset was detected using a combination of computer algorithms and visual inspection. Time 0 (T0) was defined as the onset of activity of the left or right deltoid muscle, and the onset of activity of the rest of the muscles was expressed relative to T0. To calculate T0 for unilateral and bilateral shoulder movements, we used the anterior, middle, and posterior deltoid muscles for shoulder flexion, abduction, and extension, respectively. The deltoid muscle on the side with earlier onset and the anterior deltoid muscle on the shoulder flexion side were used for analysis during bilateral shoulder movements and asymmetrical movements, respectively.[22] The mean onset time of the 5 trials for each muscle was calculated and used in the analysis. We defined the onset of activity of each muscle before T0 or within +50 ms as feedforward activation and that after T0 + 50 ms as feedback activation.[32] Figure 2 shows typical rectified EMG data during left shoulder flexion.

To assist with the understanding of shoulder movement and trunk muscle activity, directions of the trunk motion associated with each shoulder movement are shown in Figure 3, *A* and *B* according to a computer model study by Hodges et al.[12] For example, left shoulder flexion or abduction generates reactive moments of trunk flexion, left trunk lateral flexion, and left trunk rotation, and the activity of trunk muscles in response to the reactive moments causes trunk extension, right trunk lateral flexion, and right trunk rotation for controlling the posture (Fig. 3, *A*). Similarly, only trunk extension or flexion occurred during bilateral shoulder flexion or extension, respectively, and only trunk rotation occurred during asymmetrical shoulder movements (Fig. 3, *B*). The EMG data of the trunk muscles in this study were interpreted based on trunk motion patterns associated with shoulder movements.

Statistical analysis

All statistical analyses were performed using SPSS Statistics version 25.0 software (IBM Corp., Armonk, NY, USA). The onset data for each muscle were examined using the Shapiro-Wilk test, and all the data were normally distributed. A 1-way analysis of variance was performed to compare the onset of each muscle during each shoulder movement with the muscle as an independent variable and the onset time as the dependent variable. Bonferroni correction was applied to a post hoc test. The ES (Cohen's d) was calculated and defined as small (0.20), medium (0.50), and large (0.80).[9] The significance level was set at $P < .05$.

Some EMG data for each shoulder movement were excluded from the analyses when the onset time could not be identified because of motion artifacts, noise, or not satisfying the onset criteria of the EMG amplitude.

Results

The onsets of EMG activity (mean ± SD ms) for each right trunk muscle relative to the onset of activity of the deltoid muscle for each shoulder movement are shown in Figure 4, *A–D* and Table I. Since some EMG data for each shoulder movement were excluded, the number of participants in the analysis is showed as n = XX below each muscle in Figure 4, *A–D*.

Comparison of the onset of activity of each trunk muscle during shoulder movements

Shoulder flexion

In shoulder flexion, the onset of activity of the right PM, QL, TrA, MF, and IO demonstrated feedforward activation during left shoulder flexion, and the onset of activity of these muscles occurred significantly earlier than that of the right RA ($P < .001$, ES = 2.76-4.24) (Fig. 4, *A*; Table I). The onset of activity of the right MF and EO demonstrated feedforward activation during right shoulder flexion, and the onset of activity of these muscles occurred significantly earlier than that of the right PM ($P < .001$, ES = 2.01, 2.89), QL ($P < .001$, ES = 1.78, 2.41), TrA ($P < .001$, ES = 2.52, 3.84), and RA ($P < .001$, ES = 4.70, 6.54) (Fig. 4, *A*; Table I). The onset of activity of the right PM, MF, EO, and IO demonstrated feedforward activation during bilateral shoulder flexion, and the onset of activity of the right PM and MF occurred significantly earlier than that of the right

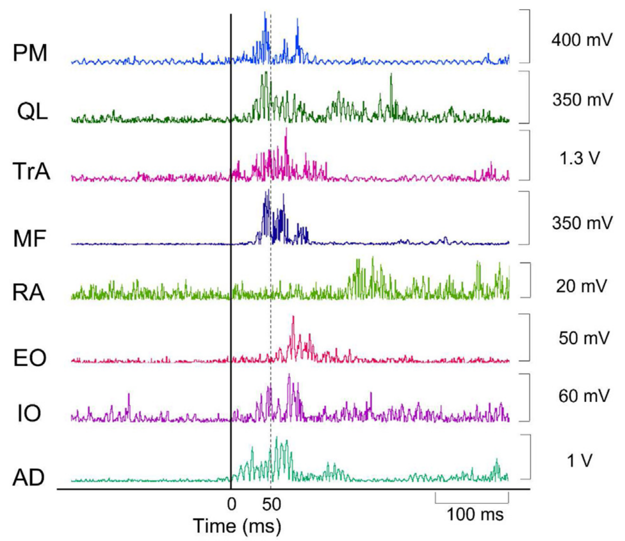

Figure 2 Typical electromyographic activity of each muscle during left shoulder flexion. The vertical line shows AD onset (time 0), and the dotted line shows +50 ms from time 0. *PM*, psoas major; *QL*, quadratus lumborum; *TrA*, transverse abdominis; *MF*, multifidus; *RA*, rectus abdominis; *EO*, external oblique; *IO*, internal oblique; *AD*, anterior deltoid.

TrA (P = .002 and <.001, respectively, ES = 1.60, 3.12) and RA (P < .001, ES = 2.69, 4.31) (Fig. 4, *A*; Table I).

Shoulder extension

In shoulder extension, the onset of activity of the right TrA, RA, and EO demonstrated feedforward activation during left shoulder extension, and the onset of activity of the right RA and EO occurred significantly earlier than that of the right PM (P < .001, ES = 1.80, 2.02), QL (P = .005 and <0.001, respectively, ES = 1.81, 2.07), and MF (P < .001, ES = 3.52, 3.75) (Fig. 4, *B*; Table I). The onset of activity of the right TrA, RA, EO, and IO demonstrated feedforward activation during right shoulder extension, and the onset of activity of these muscles occurred significantly earlier than that of the right PM (P < .001, <.001, .0123, and <.001, respectively, ES = 1.09-1.96), QL (P < .001, <.001, .01, and <.001, respectively, ES = 1.39-2.55), and MF (P < .001, ES = 2.93-4.30) (Fig. 4, *B*; Table I). In addition to right shoulder extension, the onset of activity of the right TrA, RA, EO, and IO demonstrated feedforward activation during bilateral shoulder extension, and the onset of activity of these muscles occurred significantly earlier than that of the right PM (P < .001, <.001, <.001, and .006, respectively, ES = 1.31-1.97), QL (P < .001, <.001, <.001, and .003, respectively, ES = 1.74-2.66), and MF (P < .001, ES = 3.14-3.88) (Fig. 4, *B*; Table I).

Shoulder abduction

In shoulder abduction, the onset of activity of the right PM, QL, TrA, and EO demonstrated feedforward activation during left shoulder abduction, and the onset of activity of the right PM, QL, and TrA occurred significantly earlier than that of the right MF (P = .012, .008, and .004, respectively, ES = 0.99-1.03) and IO (P = .003, .001, and <.001, respectively, ES = 1.75-1.78) (Fig. 4, *C*; Table I). During right shoulder abduction, the onset of activity of right IO only demonstrated feedforward activation, and the onset of activity of the right IO occurred significantly earlier than that of the PM (P < .001, ES = 3.51), QL (P < .001, ES = 3.04), MF (P < .001. ES = 2.91), RA (P < .001, ES = 3.01), and EO (P < .001, ES = 2.18) during right shoulder abduction. In addition to right shoulder abduction, the activity of the IO occurred significantly earlier than that of the PM (P = .030, ES = 1.92), QL (P = .012, ES = 2.33), TrA (P = .024, ES = 1.74), MF (P < .001, ES = 1.70), and RA (P < .001, ES = 2.65) during bilateral shoulder abduction (Fig. 4, *C*; Table I).

Asymmetrical shoulder movements

In asymmetrical shoulder movements, the onset of activity of the right TrA and IO demonstrated feedforward activation during left shoulder flexion-right shoulder extension (Fig. 4, *D*; Table I), and the onset of activity of these muscles occurred significantly earlier than that of the right PM (P = .003 and .005, respectively, ES = 1.52, 1.50), QL (P < .001, ES = 2.07, 2.06), MF (P < .001, ES = 2.92, 2.98), RA (P < .001, ES = 1.99, 1.98), and EO (P < .01 and .002, respectively, ES = 1.86, 1.84) (Fig. 4, *D*; Table I). The onset of activity of the right MF and EO demonstrated feedforward activation during left shoulder extension-right shoulder flexion, and the onset of activity of the right MF occurred significantly earlier than that of the right PM (P = .030, ES = 1.26), TrA (P < .001, ES = 1.38), and RA (P < .001, ES = 2.19) (Fig. 4, *D*; Table I).

Discussion

This study measured the onset of the deep and superficial trunk muscle activities during rapid shoulder movements using wire and surface electrodes. We found that the right PM, QL, and TrA demonstrated feedforward activation during the left shoulder flexion and abduction, and the right PM and QL demonstrated feedback activation during all right shoulder movements. The right TrA and IO demonstrated feedforward activation during the left shoulder flexion-right shoulder extension, and the right MF and EO demonstrated feedforward activation during the left shoulder extension-right shoulder flexion. These results demonstrate the activation pattern of trunk muscles during each shoulder movement.

Shoulder flexion

The results of this study showed that the PM, QL, TrA, MF, and IO demonstrated feedforward activation during contralateral shoulder flexion. Since trunk extension, ipsilateral trunk lateral flexion, and ipsilateral trunk rotation occur during contralateral shoulder flexion, it may be considered that the PM and QL contributed to ipsilateral trunk lateral flexion, the TrA and IO contributed to ipsilateral trunk rotation, and the MF contributed to trunk extension. Thus, coordinated feedforward activation of contralateral deep trunk muscles may be involved in shoulder flexion. The MF always demonstrated feedforward activation during shoulder flexion regardless of left, right, or bilateral shoulder movements, suggesting that it is involved in trunk extension.

Shoulder extension

The results of this study showed that the trunk flexor muscles (TrA, RA, and EO) demonstrated feedforward activation during unilateral (contralateral or ipsilateral) and bilateral shoulder extension, while the PM, QL, and MF demonstrated feedback activation; this may be explained by considering that the trunk flexor muscles contribute to trunk flexion associated with shoulder extension. The onset of activity of the TrA, EO, and IO varied from earlier or later because the direction of trunk rotation is opposite in contralateral and ipsilateral shoulder extension. The RA always demonstrated feedforward activation during shoulder extension regardless of left, right, or bilateral shoulder movements, suggesting that it is involved in trunk flexion. The PM, QL, and MF, which

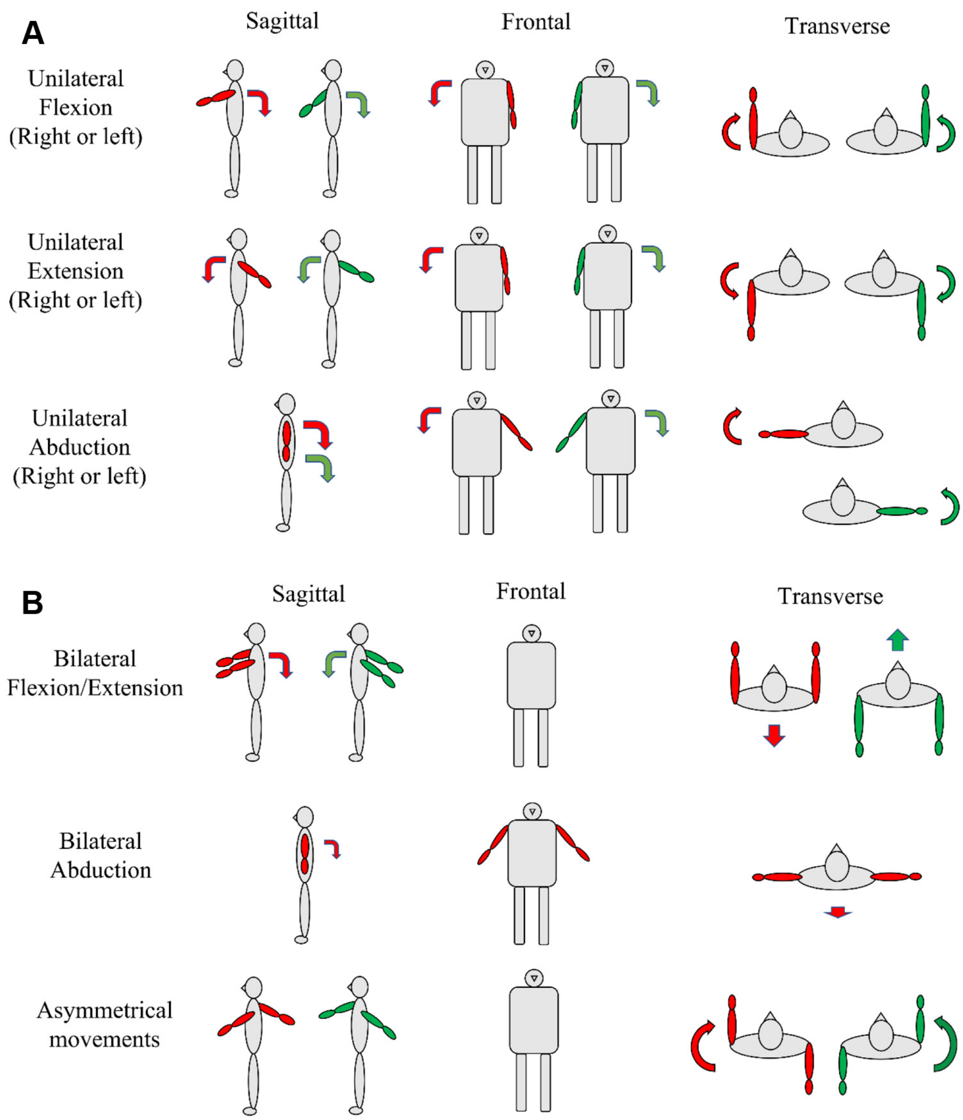

Figure 3 Eleven types of shoulder movements and expected trunk motions associated with shoulder movements. (**A**) Right and left shoulder flexion, extension, and abduction. (green arrow and red arrow) indicate directions of expected trunk motion during the right and left shoulder movements, respectively. (**B**) Bilateral shoulder flexion, extension, abduction, and shoulder asymmetrical movements (left shoulder flexion-right shoulder extension and left shoulder extension-right shoulder flexion). (green arrow and red arrow) indicate directions of expected trunk motion during bilateral shoulder flexion, extension, and abduction; left shoulder flexion-right shoulder extension and left shoulder extension-right shoulder flexion, respectively.

are involved in trunk extension, demonstrated feedback activation and were significantly later in onset than trunk flexor muscles, which may contribute for the trunk to return to a neutral position after the preceded trunk flexion.

Shoulder abduction

The results of this study showed that the PM, QL, TrA, and EO demonstrated feedforward activation during contralateral shoulder abduction. Moreover, all muscles except IO demonstrated feedback activation during ipsilateral and bilateral shoulder abduction. The PM and QL demonstrated feedforward activation for ipsilateral trunk lateral flexion during contralateral shoulder abduction. The PM and QL demonstrated feedback activation during ipsilateral and bilateral shoulder abduction because ipsilateral shoulder abduction causes contralateral trunk lateral flexion, while bilateral shoulder abduction does not cause trunk lateral flexion. A previous study reported that trunk extension occurred during shoulder abduction (Fig. 1, *A*).[12] However, the MF demonstrated feedback activation in this study, indicating that trunk extension may not occur during shoulder abduction. Considering previous reports that shoulder abduction is mainly composed of movement in the frontal plane,[8] the coordinated activation of the PM, QL, TrA, and EO contributed to ipsilateral trunk lateral flexion and maintained trunk posture.

Asymmetrical shoulder movements

The results of this study showed that the TrA and IO which are involved in ipsilateral trunk rotation demonstrated feedforward activation during left shoulder flexion-right shoulder extension. The MF and EO which are involved in trunk contralateral rotation demonstrated feedback activation during left shoulder extension-right shoulder flexion. Additionally, the PM and QL demonstrated feedback activation during 2 asymmetrical shoulder movements. It may be considered that either trunk flexion-extension or lateral trunk flexion does not occur and that only trunk rotation occurs during asymmetrical shoulder movements. Although previous

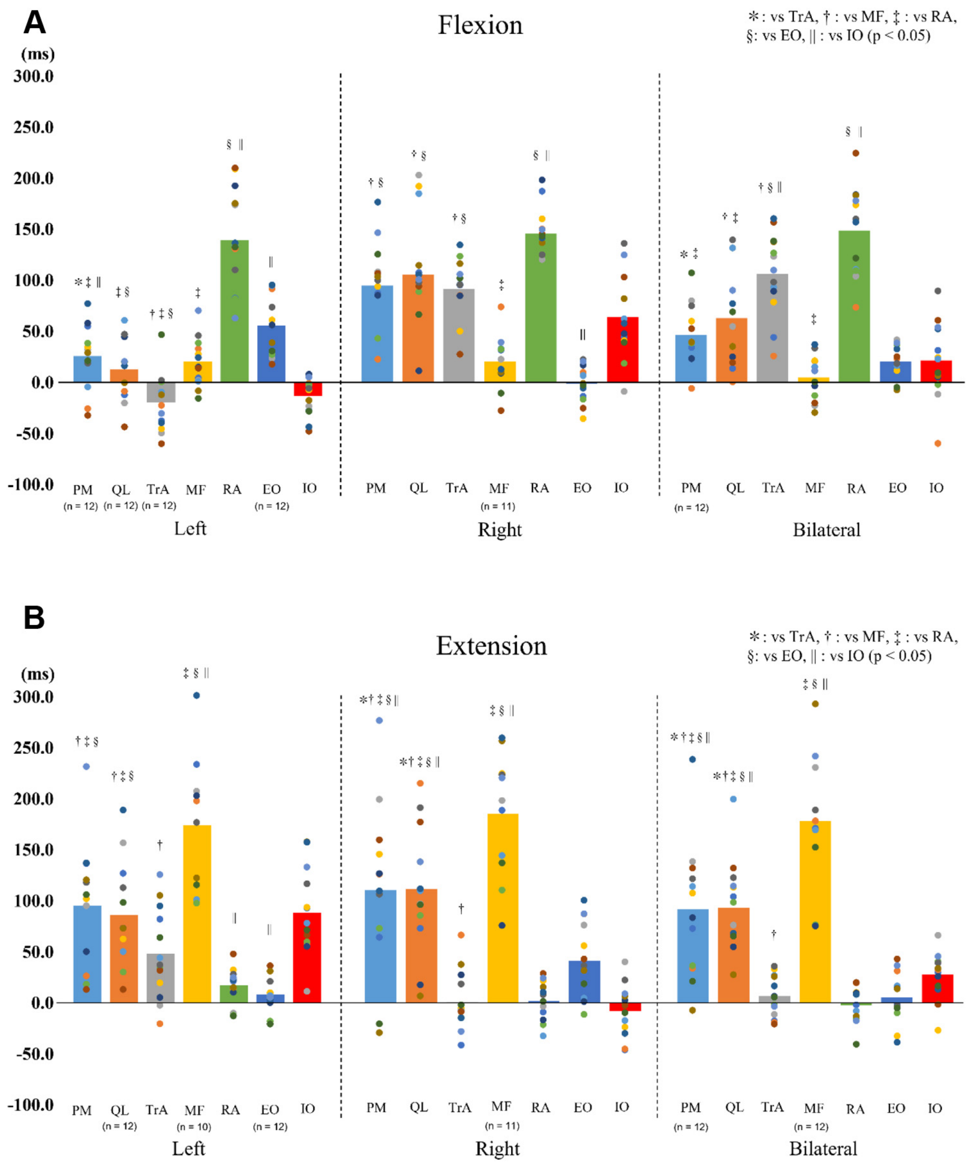

Figure 4 The onset of all right trunk muscle activity during each shoulder movements. (**A**) shoulder flexion, (**B**) shoulder extension, (**C**) shoulder abduction, and (**D**) asymmetrical shoulder movement. The vertical axis expresses the onset latencies of the trunk muscles with respect to the deltoid (time 0). Data expressed by bars indicate the means. The number (n = XX) below the muscle indicates the number of participants used in the analysis in Figure 3, *A–D*. The symbols *, †, ‡, §, || each indicates statistical significance ($P < .05$) compared to the designated muscle. *PM*, psoas major; *QL*, quadratus lumborum; *TrA*, transverse abdominis; *MF*, multifidus; *RA*, rectus abdominis; *EO*, external oblique; *IO*, internal oblique.

studies have reported that the PM and QL have a role in ipsilateral trunk rotation,[3,27] the results of this study did not clarify whether the PM and QL contribute to trunk rotation during 2 asymmetrical shoulder movements because of large variability. In asymmetrical shoulder movements, however, coordinated activation of the PM and QL along with the TrA and IO or the MF and EO may be important keys for trunk rotation.

Clinical application for improving rapid shoulder movements

Since the shoulder movements measured in this study were unilateral or bilateral shoulder flexion, extension, and abduction with elbow extension, the conditions did not exactly match the asymmetric shoulder movement like short-distance sprint or throwing motion. However, since the activity of trunk muscles during the rapid shoulder movements in specific direction is shown, it is possible to estimate the trunk muscle activities during shoulder movements in daily activity, jobs, and sports.

It has already been reported that exercises of the trunk muscles can improve shoulder movements.[17,31,33] Based on the results of this study, we discuss the trunk muscle exercises that may improve each shoulder movement.

Previous studies reported greater activity of the ipsilateral PM, QL, and MF and ipsilateral and contralateral EO and IO during side-bridge exercises[16,18] and that of the left and right TrA, RA, EO, and IO during elbow-knee and elbow-toe exercises.[18,23] Since the coactivation of the PM, QL, MF, EO, and IO is required during contralateral shoulder flexion and abduction, side-bridge exercises may improve these contralateral shoulder movements. Moreover, since the coactivation of the TrA, RA, EO, and IO is required during shoulder extension, elbow-knee and elbow-toe exercises may improve shoulder extension. The activity of the

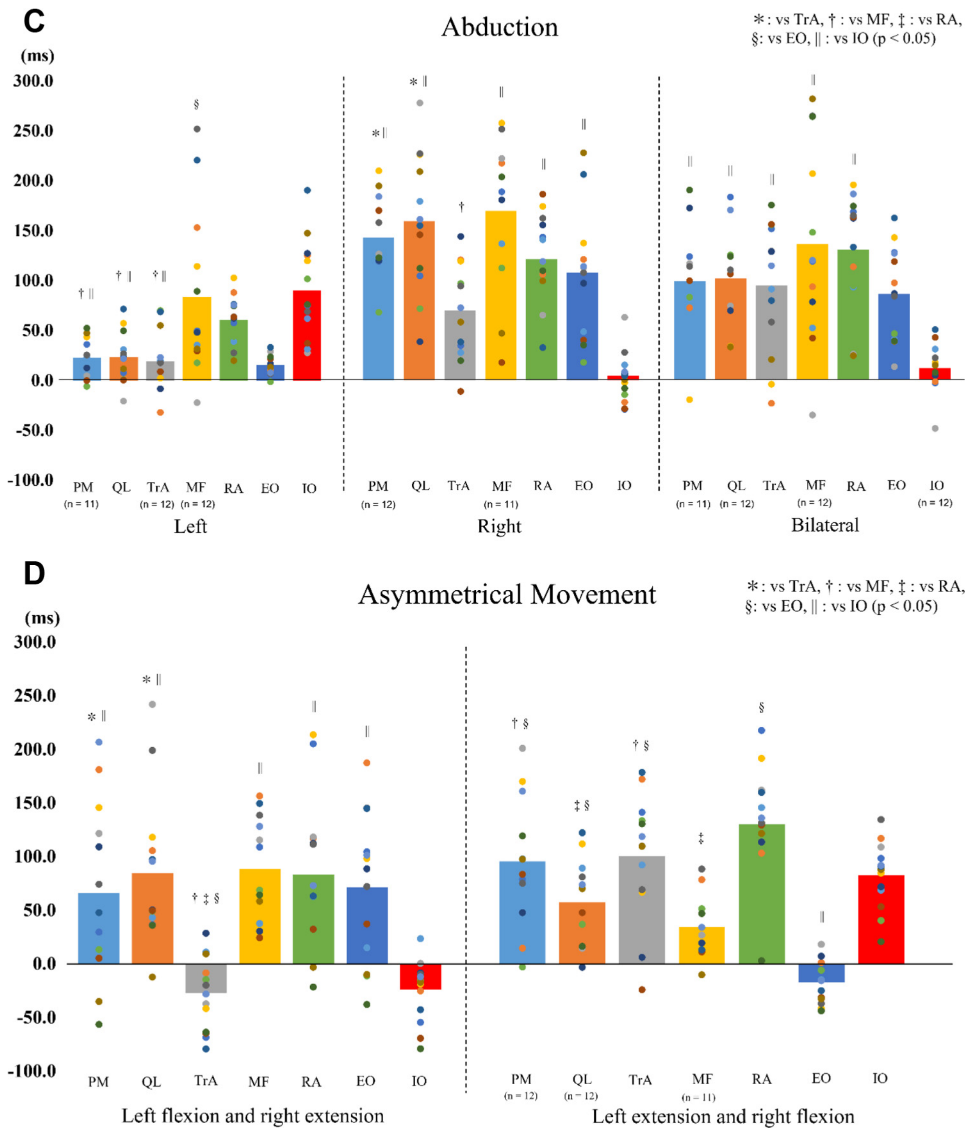

Figure 4 Continued

right TrA and IO is required during the left shoulder flexion-right shoulder extension movement, while that of the right MF and EO is required during the left shoulder extension-right shoulder flexion movement. During reciprocating asymmetrical shoulder movements such as shoulder flexion and extension (eg, sprinting and running), alternative left or right trunk rotations occur; therefore, trunk rotation (eg, torso twist) exercises may be facilitation examples for shoulder movements.

Limitations

This study has some limitations. First, we only included healthy men. The results of this study may not be generalizable to other populations; it is necessary to measure onset in people of different ages, sexes, and disease conditions to clarify any differences that may exist between diverse populations. Second, we did not incorporate a simultaneous 3-dimensional motion analysis into our study. We did not examine changes in trunk and pelvic kinematics and kinetics related to shoulder movements; it is necessary to investigate the relationship between these parameters and muscle activity. Third, we did not measure changes in the center of pressure (COP); therefore, we could not examine the relationship between COP changes and muscle activity. Further studies are needed to determine the relationship between COP changes and postural changes. Finally, we did not determine whether the dominant hand affected the activity of each muscle during shoulder movement because all the participants were right-handed in this study. In the future, it is necessary to conduct measurements in left-handed participants.

Conclusions

We measured the onset times of activity of the deep trunk muscle during 6 types of rapid unilateral, 3 symmetrical, and 2 asymmetrical shoulder movements. Feedforward activation of the PM, QL, and TrA contributed to early trunk motion during

Table I
The onset of muscle activity relative to time 0 at each shoulder movement.

	Unilateral						Bilateral			Asymmetrical	
	Flexion		Extension		Abduction		Flexion	Extension	Abduction	Left flexion-right extension	Left extension-right flexion
	Lt	Rt	Lt	Rt	Lt	Rt					
PM	26.0 ± 32.2	93.2 ± 42.7	95.5 ± 58.7	108.9 ± 80.1	22.9 ± 19.6	140.4 ± 49.8	45.9 ± 32.0	90.5 ± 65.2	96.0 ± 60.0	65.9 ± 80.1	93.6 ± 59.8
QL	13.1 ± 29.8	104.2 ± 59.1	86.1 ± 51.6	110.1 ± 60.2	23.0 ± 24.7	156.1 ± 66.3	62.0 ± 47.0	91.7 ± 46.6	98.9 ± 47.2	84.7 ± 68.9	56.0 ± 39.9
TrA	−19.7 ± 28.7	89.9 ± 28.6	48.7 ± 43.3	1.6 ± 28.4	18.9 ± 31.0	68.4 ± 45.0	104.2 ± 39.9	6.8 ± 19.9	92.1 ± 63.8	−27.6 ± 33.4	98.6 ± 58.0
MF	20.4 ± 23.4	20.4 ± 26.4	174.3 ± 65.0	182.1 ± 59.4	83.7 ± 83.0	166.5 ± 78.1	4.6 ± 21.1	175.5 ± 66.9	132.7 ± 98.1	88.5 ± 45.3	33.4 ± 29.5
RA	139.5 ± 47.8	143.0 ± 25.9	17.3 ± 17.9	1.9 ± 18.3	60.5 ± 23.2	118.9 ± 47.8	146.0 ± 41.3	−1.7 ± 17.3	127.3 ± 56.0	83.4 ± 71.3	127.9 ± 52.0
EO	56.0 ± 28.0	−1.0 ± 17.4	8.6 ± 15.8	40.8 ± 36.5	15.4 ± 9.4	105.8 ± 61.2	20.1 ± 14.8	5.6 ± 24.1	84.0 ± 46.5	71.5 ± 67.6	−17.2 ± 19.1
IO	−13.4 ± 17.7	62.9 ± 40.3	88.7 ± 42.2	−7.2 ± 24.6	90.3 ± 48.0	4.4 ± 24.5	21.2 ± 37.1	27.8 ± 22.8	10.9 ± 24.9	−23.9 ± 28.2	80.9 ± 30.7

PM, psoas major; *QL*, quadratus lumborum; *TrA*, transverse abdominis; *MF*, lumbar multifidus; *RA*, rectus abdominis; *EO*, external oblique; *IO*, internal oblique; *Lt*, left; *Rt*, right.
Each value is expressed as the mean ± standard deviation ms.

contralateral shoulder abduction and flexion, and feedback activation of the PM and QL contributed during all ipsilateral shoulder movements. Feedforward activation of the right TrA and IO occurred during left shoulder flexion-right shoulder extension, while feedforward activation of the right MF and EO occurred during left shoulder extension-right shoulder flexion, which contributed to early trunk rotations. Our findings suggest that feedforward activation of the deep trunk muscles play an important role in trunk motion during rapid shoulder movements.

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