Noninvasive Evaluation of Trunk Muscle Recruitment after Trunk Exercises using Diffusion-weighted MR Imaging

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Purpose: We evaluated trunk muscle recruitment in abdominal and back exercises with magnetic resonance (MR) diffusion-weighted imaging.

Methods: Twelve men performed bent-knee sit-up, crunch, trunk lateral flexion, and trunk extension exercises. We obtained axial diffusion-weighted images of the trunk before and after each exercise using a 1.5-tesla MR system, calculated apparent diffusion coefficient (ADC) values from the right and left rectus abdominis, lateral abdominal, psoas major, quadratus lumborum, and intrinsic back muscles to evaluate the activity of these muscles during each exercise, and compared ADC values before and after exercise using a paired t-test.

Results: The ADCs of the rectus abdominis (right, +19.1%; left, +11.7%), lateral abdominal (right, +15.5%; left, +14.1%), and psoas major (right, +14.8%; left, +15.9%) muscles on both sides increased after the bent-knee sit-up (P < 0.01). The ADCs of the rectus abdominis (right, +16.8%; left, +10.2%) and lateral abdominal (right, +8.4%; left, +7.0%) muscles on both sides increased after the crunch exercise (P < 0.01). Trunk lateral flexion resulted in increased ADC on only the right side of all of the muscles (rectus abdominis, +12.3%; lateral abdominal muscles, +20.3%; quadratus lumborum, +17.1%; intrinsic back muscles, +12.0%; psoas major, +15.4%) (P < 0.01). The ADCs of the lateral abdominal (right, +5.2%; left, +5.6%), quadratus lumborum (right, +6.0%; left, +3.0%), and intrinsic back (right, +13.2%; left, +14.6%) muscles on both sides were elevated after trunk extension (right lateral abdominal muscles and left quadratus lumborum, P < 0.05; other muscles, P < 0.01).

Conclusion: Diffusion-weighted imaging reveals the recruitment patterns of superficial and deep trunk muscles in abdominal and back exercises through exercise-induced activation in intramuscular water movement.

Keywords: abdominal muscles, apparent diffusion coefficient, back muscles, muscle activity, trunk exercise

Introduction

In the clinical setting, a wide variety of trunk exercises are used for the rehabilitation of injured trunk muscles, treatment and prevention of low back pain, and as a component of training programs to enhance athletic performance. Proper exercise selection and effective design of exercise programs requires an understanding of the trunk muscles recruited in these exercises. However, the recruitment patterns of the trunk muscles, especially those of the deeply situated muscles, have not been sufficiently revealed in certain exercises. Methodological difficulty may be one reason.

Electromyography (EMG) has been typically
used to evaluate trunk muscle activity during various forms of trunk exercise. It is a useful tool but is reported to have some methodological limitations. Surface EMG data may be affected by the confounding myoelectric signal resulting from crosstalk among adjacent muscles, variability in the myoelectric signal attributed to subcutaneous tissue, and electrode type and placement. With regard to needle/wire EMG, the insertion of an electrode into muscle makes the measurement complicated and time-consuming and may cause mental and physical discomfort that affect the movement patterns of subjects. In particular, the invasiveness of this method may be a significant barrier to the further clarification of the function and role of deep trunk muscles.

Magnetic resonance (MR) imaging allows the simultaneous noninvasive investigation of the activity of superficial and deep muscles in a specific exercise as well as evaluation of the activity of an isolated muscle over an entire area of muscle at arbitrary slice planes without the influence of surrounding tissues. In particular, the T2 value has been used to evaluate the muscle recruitment pattern in various exercises of the upper or lower extremities. Tawara and associates used the T2 value to assess the activity of the psoas major muscle before and after hip flexion exercise, but we believe few studies have used the value to evaluate the recruitment pattern of abdominal muscles in a specific trunk exercise. One likely reason is the frequent appearance of a motion artifact on the ventral side in the abdominal region in response to respiration during the scan. Technically, acquisition of MR images while subjects hold their breath (breath-hold scan) can solve this problem, but the breath-hold scan cannot be used in a conventional imaging sequence for calculating the T2 value of muscle because of its long scan duration.

In contrast, diffusion-weighted (DW) imaging is a fast imaging technique that allows for the use of the breath-hold scan. Similarly to the T2 value, an apparent diffusion coefficient (ADC) value obtained from DW image has been used for evaluating muscle activity in a specific exercise of the upper or lower extremities. Therefore, DW imaging is expected to enable the assessment of abdominal muscle activity in trunk exercises.

We used DW imaging to evaluate the recruitment of trunk muscles in exercises of the trunk. DW imaging is expected to be a potential additional technique for the assessment and visualization of trunk muscle recruitment patterns, regardless of the superficial and deep muscles, in various trunk exercises.

Materials and Methods

Subjects

This study included 12 healthy male volunteers (aged 23.6 ± 3.7 years; height, 170.1 ± 5.9 cm; body mass, 61.9 ± 4.8 kg) who did not regularly perform abdominal and back exercises. All subjects were free of low back pain at the time of the experiment and had no history of lumbar spine disorders, neurological disorders, trunk muscle strain, or spinal surgery. They were instructed to refrain from participating in any physical exercises for 2 days before the measurements were taken.

Our institutional review board approved this study. Prior to the examination, all subjects were given a brief description of the study, examination procedures, and potential risks. Each subject provided written informed consent, and subjects’ rights were fully protected.

Trunk muscle exercises

Subjects performed 4 basic trunk exercises at the side of the MR imaging room (Fig. 1). They performed the exercises in random order on 4 separate occasions with an interval of one week between exercises.

Bent-knee sit-up exercise: The subject assumed a supine position on an exercise mat with the hips flexed to approximately 45°, knees flexed to approximately 90°, arms folded on the chest, and feet supported on the floor by an exercise assistant. From this starting position, the subject almost simultaneously flexed the spine and hips until the upper body was perpendicular to the floor and then returned to the starting position.

Crunch (curl-up) exercise: The subject started the crunch exercise from a supine position on an exercise mat with the hips and knees flexed to approximately 90°, arms folded on the chest, and feet unsupported on an exercise box. The subject flexed the spine without hip flexion until the scapulae were raised just off the mat and then returned to the starting position. The pelvis was not allowed to rotate.

Trunk lateral flexion exercise: The subject assumed a side-lying position with the spine flexed laterally to the left at the edge of a portable massage table and the hands placed behind the head. An exercise assistant held the subject’s legs crossed on the table during the exercise. The subject was instructed to flex the spine laterally to the right until full lateral flexion, keeping the upper body parallel to a coronal plane (no trunk rotation). After pausing for a moment at full lateral flexion, the subject returned to the starting position.

Trunk extension exercise: The subject began from
a prone position with the hips flexed to approximately 90° at the edge of a portable massage table and the hands placed behind the head. An exercise assistant supported the subject’s legs on the table during the exercise. The subject extended the spine and hips until the upper body was parallel to the floor, paused for a moment, and returned to the starting position. Another assistant provided tactile feedback for the subject to reach a standardized horizontal position.

These exercises consisted of 3 sets of 20 repetitions (15 repetitions for trunk lateral flexion exercise) with one minute of rest between sets. One repetition consisted of 2 s to raise the upper body and 2 s to lower the upper body to the starting position. We used a metronome to ensure appropriate timing and instructed subjects to refrain from moving in reaction at the switch of each repetition.

**MR imaging**

We obtained axial DW images of the trunk before and immediately after each trunk exercise using a 1.5-tesla MR system (Signa Excite XIV, GE Healthcare, Milwaukee, WI, USA) with an 8-channel body array coil. The DW imaging sequence (spin-echo type single-shot echo-planar imaging) included the parameters: repetition time, 2,500 ms; echo time, 76.3 ms; 128 × 128 matrix; number of excitations, 3; field of view (FOV), 400 mm; rectangular FOV, phase FOV, 0.6; slice thickness, 20 mm; b-value, 700 s/mm²; scan time, 33 s; and water excitation mode. We chose a rectangular FOV to minimize geometric distortions resulting from differences in susceptibility. We applied a motion-probing gradient with a b-value of 700 s/mm² sequentially in each of the 3 main orthogonal orientations (x-, y-, and z-axes). We used this comparatively high b-value to exclude as much of the effect of perfusion as possible for the calculation of muscle ADC and limited the b-value to 700 s/mm² because of the low signal-to-noise ratio in our setting. DW image acquisition produced one baseline echo-planar T₂-weighted image (b-value, 0 s/mm²) without a motion-probing gradient and one isotropic DW image (b-value, 700 s/mm²) that was generated by averaging the information (ADC value) from each DW image in the 3 orthogonal orientations. MR image scanning was performed with the subjects in supine position. The scan position was set at the center of the L4 vertebral body. Subjects were asked to hold their breath at inspiration to prevent ventral motion artifact caused by respiration during the scan. We could obtain a post-exercise image within a few minutes after each exercise because all the exercises were performed at the side of a MR imaging room.

To calculate the ADC value of each muscle before and immediately after exercise, we constructed pre- and post-exercise ADC maps using the FuncTool 2.
software program (GE Healthcare) built into the MR device. We obtained the ADC map using one baseline echo-planar T2-weighted image and one isotropic DW image. The intensity of the pixels on the map corresponded to the absolute ADC values of tissue. A region of interest (ROI) was drawn so that it completely surrounded the right and left rectus abdominis, lateral abdominal (external oblique, internal oblique, and transversus abdominis), psoas major, quadratus lumborum, and intrinsic back (multifidus and erector spinae) muscles on an echo-planar T2-weighted image obtained at a b-value of 0 s/mm². The ROI was then copied to the ADC map. We considered the lateral abdominal muscles or intrinsic back muscles as a single muscle because they could not be clearly separated.

The ADC value of each trunk muscle was calculated using the equation: \( \text{ADC} = \ln \left( \frac{S_{I_0}}{S_{I_{700}}} \right) / (b_{700} - b_0) \) [Eq. 1], where \( S_{I_0} \) is the signal intensity (SI) in the ROI without a motion-probing gradient (b-value, 0 s/mm²; \( b_0 \)), and \( S_{I_{700}} \) is the SI in the ROI with a b-value of 700 s/mm² (\( b_{700} \)).

**Statistical analysis**

We calculated the means and standard deviations for all measurements and analyzed the measured ADC values for each muscle before and after exercise for statistical significance using a paired t-test (Excel Statistics 2012 for Windows, Social Survey Research Information, Tokyo, Japan). Statistical significance was set at \( P < 0.05 \).

**Results**

Figure 2 displays the changes in ADC values before and after bent-knee sit-up for all the muscles. Immediately after bent-knee sit-up, ADC values were significantly increased for the right and left side rectus abdominis, lateral abdominal, and psoas major muscles (\( P < 0.01 \)) and significantly decreased for the intrinsic back muscles on both sides (right side, \( P < 0.05 \); left side, \( P < 0.01 \)).

Figure 3 summarizes the changes in ADC values before and after the crunch exercise for all muscles. Immediately after the exercise, ADC values were significantly increased for the rectus abdominis and lateral abdominal muscles on both sides (\( P < 0.01 \)) and significantly decreased for the intrinsic back muscles on both sides (\( P < 0.05 \)).

Immediately after trunk lateral flexion, for all muscles, ADC values increased significantly only on the right side (\( P < 0.01 \), Fig. 4) and showed no significant change on the left (rectus abdominis, \( P = 0.14 \); lateral abdominal muscles, \( P = 0.06 \); psoas major, \( P = 0.14 \); quadratus lumborum, \( P = 0.50 \); intrinsic back muscles, \( P = 0.09 \)).

Figure 5 shows the changes in the ADC values before and after trunk extension for all muscles.
After trunk extension, ADC values were significantly elevated for the lateral abdominal, quadratus lumborum, and intrinsic back muscles on both sides (right lateral abdominal muscles and left quadratus lumborum, $P < 0.05$; other muscles, $P < 0.01$).

Figure 6 displays changes in the DW image and ADC map from before to after bent-knee sit-up for a representative subject. The post-exercise DW image showed increased SI within the right and left rectus abdominis, lateral abdominal, and psoas major muscles, which may be related to elevated muscle $T_2$ values from exercise ($T_2$ shine-through). The
Fig. 5. The apparent diffusion coefficient (ADC) value of each trunk muscle before and after trunk extension exercise (mean ± standard deviation). The lateral abdominal muscles include the external oblique, internal oblique, and transversus abdominis muscles. The intrinsic back muscles include the multifidus and erector spinae muscles. Asterisks indicate significant changes (*P < 0.05, **P < 0.01).

Fig. 6. Changes in diffusion-weighted (DW) images (a, b) and apparent diffusion coefficient (ADC) maps (c, d) before and after bent-knee sit-up for a representative subject. Signal intensity (SI) within the right and left rectus abdominis, lateral abdominal, and psoas major muscles increased on the post-exercise DW image (b) compared with that on the pre-exercise DW image (a). In the ADC maps, the color code indicates the absolute ADC values of each trunk muscle and ranges from red (high) to blue (low). Compared with the pre-exercise ADC map (c), the post-exercise map (d) showed an increase in the red region within the right and left rectus abdominis, lateral abdominal, and psoas major muscles (d). In addition, the size of these muscles appeared to increase after the exercise. We used image-editing software (Adobe Photoshop CS5.1, Adobe Software Inc., San Diego, CA, USA) to erase other organs, except the skeletal muscles, on the ADC maps.
ADC maps demonstrated changes in muscle ADC values with color coding. An increase in the red region of the post-exercise ADC map reflected elevated ADC values within the rectus abdominis, lateral abdominal, and psoas major muscles on both sides.

**Discussion**

An increase in the ADC value implied the elevation of water movement within muscles induced by exercise, including both water diffusion in the extravascular spaces and capillary network microcirculation. Repetitive muscle contractions cause a temporal increase in intramuscular microcirculation, and elevated capillary pressure and permeability, increased osmotic pressure due to metabolite accumulation in the extravascular space, or a combination of these factors can increase extravascular water within an exercised muscle. Consequently, this water accumulation should contribute to easier diffusion of water molecules within an exercised muscle. Exercise-induced increases in muscle temperature should also be associated with elevated ADC values in recruited muscles because the extent of water diffusion depends on the changes in tissue temperature.

Increased ADC values in the rectus abdominis and lateral abdominal muscles after bent-knee sit-up and crunch exercises indicate the recruitment of these muscles during both exercises. Our findings resemble those of previous EMG studies that demonstrated the efficacy of bent-knee sit-up and crunch exercises in recruiting the rectus abdominis and external/internal oblique muscles. The transversus abdominis also shows moderate EMG activity during the crunch exercise. On the other hand, the ADC values of the intrinsic back muscles significantly decreased after bent-knee sit-up and crunch exercises. Because we obtained DW images with a comparatively high b-value (700 s/mm²), these decreased ADC values may reflect decreased water diffusion rather than reduced microcirculation within the intrinsic back muscles. However, the detailed mechanism remains unclear.

ADC values were elevated on both sides of the psoas major after the bent-knee sit-up exercise. Because the psoas major can produce hip flexor movement, intramuscular EMG demonstrated greater activation of the psoas major by sit-up with hip flexion than by crunch (curl-up) without hip flexion. Using the T₂ value on MR imaging, Tawara’s group also revealed activation of the psoas major by hip flexion exercise. Clinicians have frequently highlighted the effectiveness of the bent-knee sit-up for training the abdominal muscles with minimal activity of the psoas major. However, our study revealed significant activation of the psoas major by bent-knee sit-up.

Lateral flexion of the trunk, biased to the right direction, resulted in elevated ADC values in the rectus abdominis, lateral abdominal muscles, psoas major, quadratus lumborum, and intrinsic back muscles on the right side. Similarly, previous EMG data showed moderate to high activity of the rectus abdominis, quadratus lumborum, and intrinsic back muscles on the ipsilateral side during lateral flexion of the spine relative to the pelvis. The above-mentioned studies suggested that these muscles laterally flex and stabilize the lumbar spine in the frontal plane. In our study, the trunk lateral flexion exercise appeared strenuous because the subjects were required to lift their upper body in the air to a point of maximal lateral flexion. Thus, lateral flexion and stabilization of the spine might require greater recruitment of all the trunk muscles.

This study showed increased ADC values in the quadratus lumborum and intrinsic back muscles after trunk extension exercise. Many studies have shown marked activity in these muscles during trunk extension using EMG or MR T₂ value. In addition, trunk extension exercise resulted in elevated ADC values of the lateral abdominal muscles in our study. Using biomechanical tests of unembalmed human lumbar segments, Barker and colleagues demonstrated that simulated moderate contraction of the transversus abdominis tenses the lumbar fascia and enhances sagittal segmental stiffness during trunk flexion. Thus, the lateral abdominal muscles possibly contributed to the segmental stability of the lumbar spine during trunk extension, especially when the upper body was lowered. The trunk extension exercise used in our study was apparently severe because the upper body was unsupported in the air, which might have increased the load on the lateral abdominal muscles for lumbar spinal control.

Our study had a number of limitations. First, we evaluated the external oblique, internal oblique, and transversus abdominis as a single muscle because we used a low DW imaging resolution. However, these muscles are thought to have different roles in the movement and control of the lumbar region because of their anatomical differences, such as in direction of muscle fibers and sites of origin and insertion. Thus, it would be desirable to evaluate these muscles separately in the future utilizing technical advances in MR imaging. Second, although our study assessed the activity of trunk muscles on-
ly at the slice level corresponding to the center of the L4 vertebral body, the extent of that activity may vary from site to site on the muscle. Therefore, it may be necessary to evaluate muscle activity at various levels of the spinal column to better understand the function and role of the trunk muscles. Third, MR imaging evaluation by ADC or T2 value frequently requires a relatively high level of muscle activity to evaluate the muscle recruitment pattern in a certain exercise. This is in contrast to EMG, which allows assessment of muscle activity during exercise almost regardless of the level of muscle activity.

Despite its limitations, the present study shows the potential of MR DW imaging as an additional tool for evaluating the recruitment pattern of the trunk muscles in abdominal and back exercises. Breath-hold DW imaging permits evaluation of the isolated activity of superficial and deep trunk muscles without artifact from ventral motion caused by respiration. In addition, a color-coded ADC map should be useful in assessing the different extent of activation within a specific muscle. Although a close relation between muscle ADC and T2 values has been reported immediately after exercise, DW imaging can be used to evaluate muscle activity with a considerably shorter scan time than that of the common MR sequence for the calculation of T2 value. Moreover, DW imaging allows the quantitative assessment of the intramuscular movement of water, providing dynamic information that cannot be sufficiently obtained from conventional T2-weighted imaging (T2 value), which mainly reflects the level of intramuscular water content, that is, static information. In the future, DW imaging would help elucidate the individual roles (agonist, synergist, antagonist, or stabilizer) of trunk muscles during various trunk exercises.

Conclusion

Trunk exercises activate water movement within the superficial and/or deep trunk muscles. MR DW imaging allows evaluation of the muscle recruitment pattern in abdominal and back muscle exercises through the exercise-induced activation of intramuscular water movement.

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References

14. Nordander C, Willner J, Hansson GA, et al. Influence of the subcutaneous fat layer, as measured by ultrasound, skinfold calipers and BMI, on the EMG am-
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