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The Ability of Muscle Functional MRI to Detect the Slight Effect of Exercise on Trunk Muscle Activity

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Purpose: In this study, we provide a way to assess even a slight effect of exercise on trunk-muscle activity.
Materials and Methods: Seven healthy male participants (mean age, 24.7 ± 3.2 years; height, 171.2 ± 9.8 cm; and weight, 63.8 ± 11.9 kg) performed 15 sets of an exercise with 20 repetitions of 90° hip and right-knee flexion while lying supine. The exercise intensity was measured using the 10-point Rating of Perceived Exertion Scale after the first and 15th sets of exercises. Although cross-sectional areas and functional T2 mapping using ultrafast imaging (fast-acquired muscle functional magnetic resonance imaging, fast-mfMRI) have been proposed for imaging to evaluate exercise-induced muscle activity in real time, no previous studies have reported on the evaluation of trunk-muscle activity using functional T2 mapping. As a method for assessing trunk-muscle activity, we compared functional T2 mapping using ultrafast imaging (fast-mfMRI) with cross-sectional areas.
Results: Although the muscle cross-sectional areas were increased by the exercise, there was no significant difference at rest. On the other hand, for all sets, the changes in T2 were significant compared with those at rest ($P < 0.01$). These results demonstrate that T2, calculated from fast-mfMRI images can be used to detect even a small amount of muscle activity induced by acute exercise, which was impossible to do with cross-sectional areas.
Conclusion: Fast-mfMRI, which can also display functional information with detailed forms, enabled non-invasive real-time imaging for identifying and evaluating the degree of deep trunk-muscle activity induced by exercise.

Keywords: Exercise; Muscle functional magnetic resonance imaging (mfMRI); Spin-echo echo-planar imaging (SE-EPI); True imaging with steady-state progression (True-FISP); Transverse relaxation time (T2)

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INTRODUCTION

Evaluation of exercise-induced muscle activity, especially of the trunk muscles, is essential in sports and rehabilitation medicine (1). H-magnetic resonance imaging (MRI) can evaluate not only the superficial muscle but also deep muscles. In addition, exercise produces changes in human muscle tissue that can be documented by MRI

(1-8). In contrast to non-exercising tissue, muscles that are recruited during exercise appear hyperintense as MRI signal intensity increases with exercise and subsequently declines in recovery. Exercise-induced signal changes result primarily from increases in the transverse relaxation time (T2) of tissue water, and they are most pronounced on T2-weighted images (1, 2, 7, 9). Exercise-induced T2 increase has been associated with increased muscle volume and is mainly related to an accumulation of intracellular water (10, 11). During exercise, intracellular water accumulation may result from an osmotically (11, 12) and/or hydrostatically driven fluid shift. A greater level of metabolite accumulation and larger T2 changes in predominantly glycolytic than in predominantly oxidative situations have been reported (13). Intracellular acidification also contributes to muscular T2 changes (14), demonstrating that muscle metabolic activity could be involved in exercised-induced changes in T2 (15). Accordingly, intracellular *p*H-induced T2 variations are related to changes in the magnetization transfer rate between macromolecules and free intracellular delivery (14). In addition, Adams et al. (16) reported that T2 is correlated with electromyographic (EMG) activity during both concentric and eccentric actions during elbow flexion under different loads. Therefore, this technique is also useful in evaluating muscle use after short periods of resistance training.

Moreover, many studies have shown that muscle activity induced by exercise can be visualized as the changes in T2 (17-22). For example, Adams et al. (17) used contrast shifts in magnetic resonance (MR) images in an attempt to map regions of the thigh muscle that had been stimulated by transcutaneous electro-myostimulation. In addition, Akima et al. (20) tested the coactivation patterns of individual muscles and the neuromuscular compartments of the quadriceps femoris during knee-extension exercises. Notably, they proposed a technique called muscle functional magnetic resonance imaging (mfMRI) (21, 22). The differences between functional MRI (fMRI) and mfMRI are as follows: fMRI uses the change in the blood oxygenation level-dependent signal to measure the brain's activity. In contrast, mfMRI uses T2 changes to distinguish the muscle that is associated with an exercise. In other words, mfMRI involves T2 mapping of muscle activities, and thus can describe the function of muscle activity. Hence, orthopedists and athletic trainers can use it to evaluate the effects of strength training on the muscles. However, for calculating T2, mfMRI uses a spin echo (SE) or multiple spin-echo (MSE) sequence. SE or MSE requires an acquisition time of a few minutes, and the conventional imaging technique is restricted in terms of time resolution. Hence, mfMRI can be used only for the limbs. In addition, mfMRI's ability to detect T2 change is limited if exercise is not performed until fatigue sets in. Therefore, it is difficult to use this approach for efficient evaluation during rehabilitation.

For evaluation of trunk-muscle activity, the physician or trainer needs to know what the normalized and calibrated muscle activation levels in different tasks in choosing specific training exercises and making rehabilitation decisions. Numerous related studies have used EMG (23-28) and muscle cross-sectional areas (CSA) on MRI (29-33). However, although EMG can be used to evaluate muscle activity during exercise, it is invasive for approaches to the deeper muscles. Likewise, CSA can investigate only muscle morphology. In addition, CSA cannot be used to judge the effect of training in the acute phase. Therefore, in sports and rehabilitation medicine, we need a noninvasive method of assessing trunk-muscle activity that can provide both morphological evaluation and functional evaluation.

Previous studies proposed and verified the feasibility of mfMRI using ultrafast imaging (fast-acquired mfMRI and fast-mfMRI) (34, 35). Fast-mfMRI is mfMRI that improves temporal resolution by using SE echo-planar imaging (SE-EPI) for the pulse sequence for T2 acquisition. Fast-mfMRI can shorten the acquisition time to 1/12 that of the MSE method. Fast-mfMRI provides not only morphological but also functional information, and can be applied to human trunk muscles with limited scan time. There has been a growing interest in T2 mapping using SE-EPI (36-38), because SE-EPI has excellent temporal resolution and can be applied to assess activity in the human trunk muscles. However, these experiments do not represent real situations in which mfMRI can be used to detect the bare minimal effect of exercise on the activity of the human trunk muscles. Therefore, our purpose in this study was to evaluate mfMRI's ability to detect even a slight effect on trunk-muscle activity during acute exercises, and we simultaneously compared the T2 images with CSA.

MATERIALS AND METHODS

Subjects and Exercise Protocol

Seven healthy male participants (mean age, 24.7 ± 3.2 years; height, 171.2 ± 9.8 cm; and weight, 63.8 ± 11.9 kg) performed the exercises. All participants gave written informed consent, and the ethics committee of the Japan

Institute of Sports Sciences approved this study. The participants performed 15 sets of an exercise while lying supine (Fig. 1). One exercise set consisted of the participant doing 90˚ right hip and knee flexions 20 times. Participants bent one knee to 90˚ for 1 s and then extended the leg for 1 more sec. We measured the exercise intensity using the 10-point Rating of Perceived Exertion (CR-10: RPE) (39) scale that is shown in Table 1. We measured only the first set and the last set.

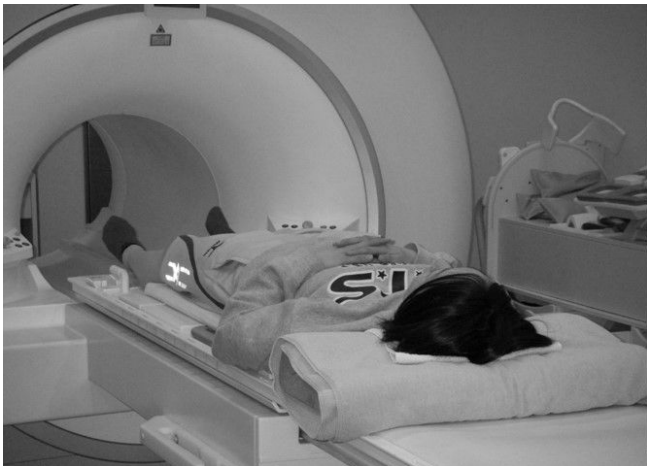
MR Imaging and Data Analysis

We did all measurements of the psoas major muscles using a 1.5-Tesla whole-body scanner (Symphony; Siemens AG, Erlangen, Germany) with a six-channel body-array coil. We employed true fast imaging with steady-state precession (TrueFISP) and SE-EPI. The parameters for TrueFISP were as follows: repetition time (TR), 4.72 msec; echo time (TE), 2.36 msec; matrix size, 256 × 256; flip angle (FA), 50; and bandwidth (BW), 501 Hz/Px, with an acquisition time of 12 sec. The parameters for SE-EPI were as follows: TR, 2000 msec; TE, 30, 45, 60, 75 ms (4 echoes); matrix size, 256 × 256 (after interpolation); FA, 90; and BW, 1392 Hz/Px, with an acquisition time of 2 s (in one echo). The common conditions for the two sequences were 10-mm slice thickness, field of view of 400 mm × 400 mm, and one excitation. MR images were acquired at rest (pre-exercise) and once after every exercise. The time between the end of the exercise and the start of imaging was less than 1 minute.

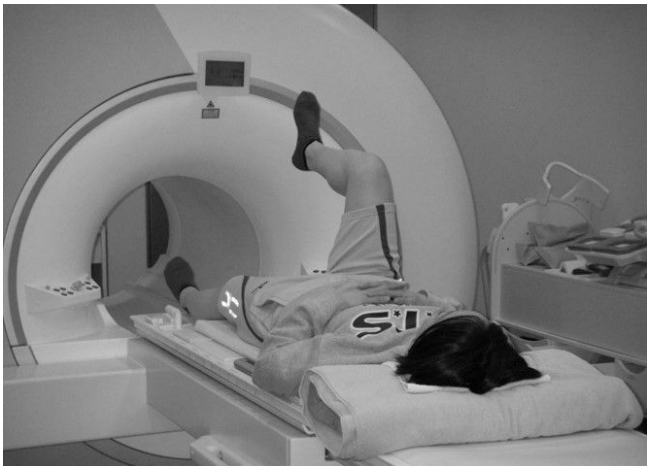
We did all calculations of T2 relaxation time by using Interactive Data Language (IDL: L3Harris Geospatial, Boulder, CO, USA) with mono-exponential least-squares fitting of the SE-EPI images. We calculated ΔT2 by subtracting the T2 image at pre-exercise (rest) from that after exercise. We identified the center of the images by selecting the center of the disk between the fourth lumbar vertebra (L4) and the fifth lumbar vertebra (L5). In the coronal localizer image, we selected the front of the disk between L4 and L5, and then the sagittal localizer image. In the pre-experiment, we did not reach consensus about the position gap between the pre-exercise images and the after-exercise images. We extracted CSA and T2 of the right psoas major muscle from images obtained at rest and

Table 1. The 10-Point Rating of Perceived Exertion Scale (39)

Rating	Description
0	Rest
1	Very, very easy
2	Easy
3	Moderate
4	Somewhat hard
5	Hard
6	
7	Very hard
8	
9	
10	Maximal



a



b

Fig. 1. Practical demonstration of exercises. The exercise pattern was repeated between (a) and (b). The time of one repetition was 3 s.

after various exercise durations. For regions of interest, we selected the right psoas major muscles after confirming their anatomical location on SE-EPI images, using obtained TrueFISP images as morphological reference images. We acquired TrueFISP and SE-EPI at rest and/or after the exercise, while the participant held his breath. We did not reach consensus about the position gap when regions of interest were selected based on simultaneous acquisition of SE-EPI and TrueFISP.

Statistical Analysis

We used a paired *t*-test to compare the psoas major muscle differences between the T2 at rest and that after exercise. We considered differences with $P < 0.05$ to be statistically significant.

RESULTS

For the CR-10: RPE, after the first set of exercises, all participants graded their perceived exertion as 1 or 2 (minimum). On the other hand, after the 15th set, all participants rated their exertion as 8 to 10 (maximum).

Figure 2 shows a representative fast-mfMRI after the first, fifth, 10th, and 15th exercise sets. These results indicate that T2 of only the muscle that was induced in the exercise increased. In fast-mfMRI, the areas of the activated right psoas major muscle were enlarged and the morphological details were preserved. Figure 3a shows the changes in CSA after each set, and Figure 3b shows the changes in T2. Although the CSA was increased after the exercise, there was no significant difference at rest. For all sets, the changes in T2 were significant compared with T2 at rest ($P < 0.01$). Moreover, both CSA and T2 after seven sets of exercise approached a plateau (Fig. 3).

DISCUSSION

Our purpose in this study was to evaluate the ability of mfMRI to detect the slightest effect of acute exercise on trunk-muscle activity. We measured the strength of the exercise by using the CR-10: RPE, which is a subjective method for evaluating exercise fatigue.

In general, SE-EPI is an image sequence whose SNR is lower than that of SE. However, a previous study (40) reported that there is no problem in calculating T2. In addition, the T2 that we calculated in this study was almost in agreement with the value in the previous study. Therefore, the low SNR of SE-EPI collected under appropriate imaging conditions does not affect the calculated T2.

Although the position of the gap between the TrueFISP and SE-EPI images remains an issue, in the morphological arrangement on fast-mfMRI, there was no major difference between the anatomical image (TrueFISP) and functional image (SE-EPI). The scan time of fast-mfMRI is 22 seconds, enabling acquisition under a single breath-hold that maintained the same timing as much as possible. In addition, we took care to keep the same position as much as possible by using morphological information with localizer images, as shown in the method. Furthermore, the TrueFISP images had a high spatial resolution, and the SE-EPI images had a low spatial resolution. The spatial resolution when we acquired data from SE-EPI images was never as high as 128 × 128. Therefore, after augmenting the resolution to 256 × 256, the images were smoothed by zero filling, and we considered misregistration to have a small influence. Therefore, there was little position shift caused by breathing. Because the spatial resolution of the functional images was not high, misregistration had a small effect when the two images were overlaid.

When the T2 image was captured, background noise interfered with subtraction of the T2 image after exercise from the image at rest. Therefore, we considered ways to eliminate the background noise. We used the threshold of the background noise and positional information in the T2-weighted images to eliminate the background noise from the T2 images. In addition, previous studies reported that the T2 change of the exercise-induced line is lower than 20 ms. In contrast, T2 of the bowel loop is higher than 20 ms. Therefore, artifacts caused by the bowel loop can be eliminated if we apply this knowledge to threshold processing. By using the fast-mfMRI techniques and implementing threshold processing for T2 images, we were able to eliminate background noise and artifacts from the bowel loop with high water content.

Previous studies on exercise and muscle activity mainly evaluated the changes in CSA. Tracking the changes of muscle immediately after each exercise was not possible with CSA. Therefore, the effect of strength training could not be evaluated for some time (18, 29, 41, 42). As shown in Figure 2, fast-mfMRI enables us to identify the involved muscle after each exercise. T2 has certain correlations with intensity and duration of exercise (3). Using these correlations, fast-mfMRI enables real-time imaging for identifying and evaluating the degree of muscle activity

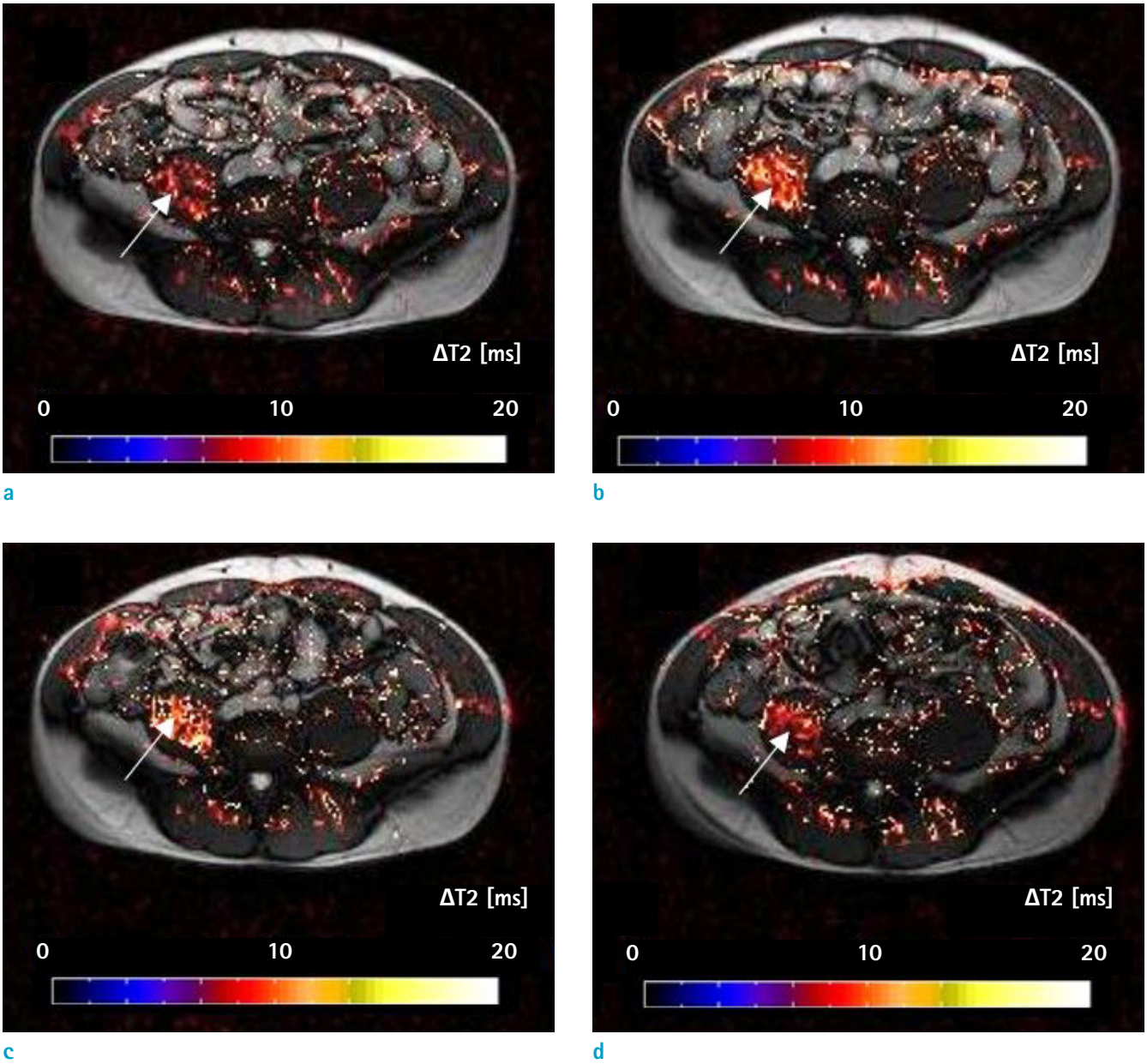
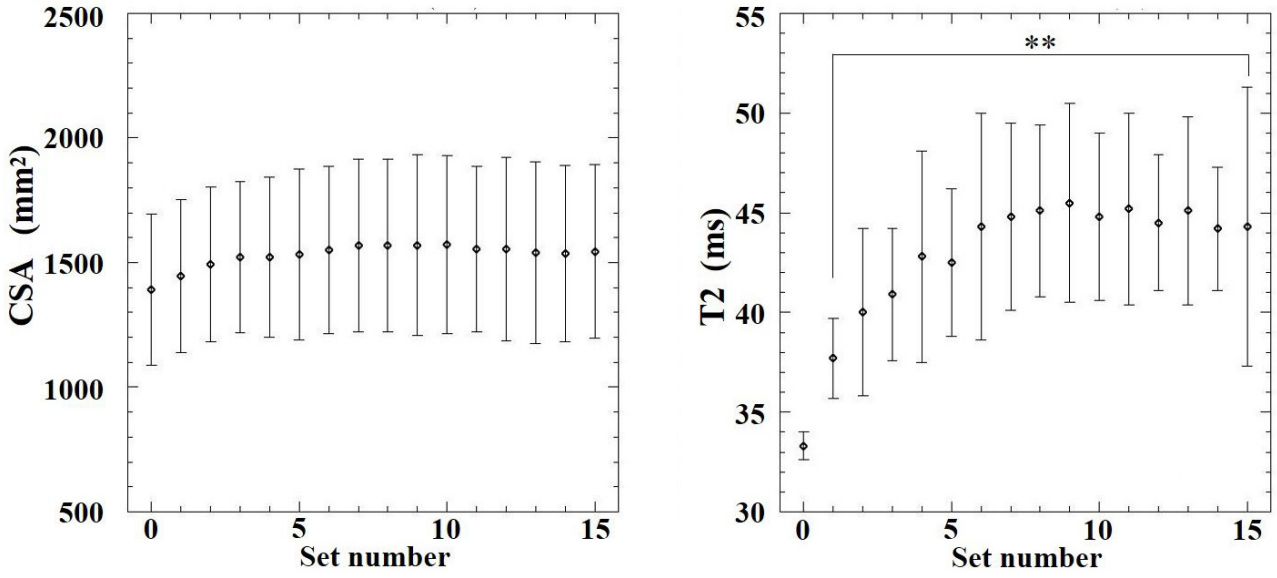


Fig. 2. Representative fast-mfMRI induced by exercise 2 obtained after 1 set (a), 5 sets (b), 10 sets (c), and 15 sets (d). The color bar reflects the differences in T2 (ΔT2). The arrows denote the activated right psoas major muscle.

that is induced by exercise.

Although mfMRI, which is a conventional method, can identify sites of muscle activity that are induced by exercise, its application has been limited to the extremities because of its long acquisition time. However, in general medicine and sports medicine rehabilitation, the training of trunk muscles has been considered increasingly important (43-46), and a method for verifying these training effects is desired. Nevertheless, a technique that enables the non-invasive, functional evaluation of the deep trunk muscles is needed; conventionally, the only method that has been evaluated was needle EMG (23, 47) to stab directly at the target muscle with the needle electrode. In this study, we demonstrated that fast-mfMRI could be used to non-invasively evaluate the muscle activity of the deep trunk muscles, which was not possible with the conventional method. Since the effect of exercise on trunk-muscle activity remains unclear, our results can potentially clarify



a b

Fig. 3. Cross-sectional area and T2 at rest (set number 0) and after exercise in the seven participants. (a) Cross-sectional area (CSA). (b) T2. ** Significantly different from the value at rest, $P < 0.01$.

the characteristics of trunk-muscle activity induced by exercise.

The CR-10: RPE result suggests that the effect of the first set of the exercise was slight and that all 15 sets of the exercise were high-loading. The change in CSA was about 10%, even after the whole set of exercises had been done, and no significant difference was recognized. Therefore, mfMRI could not detect the slightest effect of acute exercise on muscle activity. On the other hand, T2 detected the change even during the first exercise set, which is a slight-impact exercise. In addition, Figure 3 shows that both CSA and T2 approached a plateau after seven sets. These results agree substantially with the signal-intensity data of a previous study (48), which suggested that both CSA and T2 of an exercised muscle increase exponentially to a plateau that depended on exercise intensity. Therefore, this study supports the experimental rule about the evaluation of muscle activity using T2.

In addition, SE-EPI involves pulse sequences with the application of fat saturation until RF pulse is achieved. Therefore, we suppressed the fat MR signal on SE-EPI images. Intramyocellular triglyceride (IMCL) and extramyocellular triglyceride (EMCL) exist in skeletal muscle. Therefore, IMCL and EMCL affected the muscle T2 images. However, in the 1.5-T MRI scans, we demonstrated that there was no significant difference of T2 in terms of whether or not MSE images included fat suppression (40). As a result, in the 1.5-T imaging, the calculation of muscle T2 images might not have been affected by IMCL and EMCL.

This technique has certain limitations. Because fast-mfMRI uses SE-EPI as the pulse sequence for T2 acquisition, image distortion easily results from the heterogeneity of the magnetic field. However, in the preliminary and present studies, in the images of the trunk with SE-EPI, image distortion did not occur, at least in the portion located in the deep-layer muscles. Therefore, in this study, the muscle located at the edge of the trunk (e.g., the rectus abdominis or the oblique abdominal muscle) was also likely to cause defective representations because of image distortion. We did not evaluate this issue in detail in this study. Therefore, further studies are needed to evaluate these issues.

We demonstrated the ability of fast-mfMRI (functional T2 mapping of trunk-muscle activity) that has functional information on detailed morphology to detect even a slight effect of acute exercise on trunk-muscle activity, and the ability of T2 to detect the post-exercise plateau reached above a certain intensity. T2 that was calculated from SE-EPI images indicated that imaging could detect the slightest muscle activity induced by acute exercise. In addition, we confirmed that fast-mfMRI could evaluate the function of the deep-layer muscles of the trunk that could not be detected with surface EMG or ultrasound imaging.

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REFERENCES

1. Fleckenstein JL, Canby RC, Parkey RW, Peshock RM. Acute effects of exercise on MR imaging of skeletal muscle in normal volunteers. AJR Am J Roentgenol 1988;151:231-237
2. Fleckenstein JL, Bertocci LA, Nunnally RL, Parkey RW, Peshock RM. 1989 ARRS Executive Council Award. Exercise-enhanced MR imaging of variations in forearm muscle anatomy and use: importance in MR spectroscopy. AJR Am J Roentgenol 1989;153:693-698
3. Fisher MJ, Meyer RA, Adams GR, Foley JM, Potchen EJ. Direct relationship between proton T2 and exercise intensity in skeletal muscle MR images. Invest Radiol 1990;25:480-485
4. Fleckenstein JL, Haller RG, Lewis SF, et al. Absence of exercise-induced MRI enhancement of skeletal muscle in McArdle's disease. J Appl Physiol (1985) 1991;71:961-969
5. Archer BT, Fleckenstein JL, Bertocci LA, et al. Effect of perfusion on exercised muscle: MR imaging evaluation. J Magn Reson Imaging 1992;2:407-413
6. Fleckenstein JL, Watumull D, Bertocci LA, Parkey RW, Peshock RM. Finger-specific flexor recruitment in humans: depiction by exercise-enhanced MRI. J Appl Physiol (1985) 1992;72:1974-1977
7. Fleckenstein JL, Watumull D, McIntire DD, Bertocci LA, Chason DP, Peshock RM. Muscle proton T2 relaxation times and work during repetitive maximal voluntary exercise. J Appl Physiol (1985) 1993;74:2855-2859
8. Akima H, Kinugasa R, Kuno S. Recruitment of the thigh muscles during sprint cycling by muscle functional magnetic resonance imaging. Int J Sports Med 2005;26:245-252
9. Enocson AG, Berg HE, Vargas R, Jenner G, Tesch PA. Signal intensity of MR-images of thigh muscles following acute open- and closed chain kinetic knee extensor exercise - index of muscle use. Eur J Appl Physiol 2005;94:357-363
10. Reid RW, Foley JM, Jayaraman RC, Prior BM, Meyer RA. Effect of aerobic capacity on the T(2) increase in exercised skeletal muscle. J Appl Physiol (1985) 2001;90:897-902
11. Damon BM, Gregory CD, Hall KL, Stark HJ, Gulani V, Dawson MJ. Intracellular acidification and volume increases explain R(2) decreases in exercising muscle. Magn Reson Med 2002;47:14-23
12. Meyer RA, Prior BM, Siles RI, Wiseman RW. Contraction increases the T(2) of muscle in fresh water but not in marine invertebrates. NMR Biomed 2001;14:199-203
13. Prior BM, Ploutz-Snyder LL, Cooper TG, Meyer RA. Fiber type and metabolic dependence of T2 increases in stimulated rat muscles. J Appl Physiol (1985) 2001;90:615-623
14. Louie EA, Gochberg DF, Does MD, Damon BM. Transverse relaxation and magnetization transfer in skeletal muscle: effect of pH. Magn Reson Med 2009;61:560-569
15. Patten C, Meyer RA, Fleckenstein JL. T2 mapping of muscle. Semin Musculoskelet Radiol 2003;7:297-305
16. Adams GR, Duvoisin MR, Dudley GA. Magnetic resonance imaging and electromyography as indexes of muscle function. J Appl Physiol (1985) 1992;73:1578-1583
17. Adams GR, Harris RT, Woodard D, Dudley GA. Mapping of electrical muscle stimulation using MRI. J Appl Physiol (1985) 1993;74:532-537
18. Akima H, Takahashi H, Kuno SY, et al. Early phase adaptations of muscle use and strength to isokinetic training. Med Sci Sports Exerc 1999;31:588-594
19. Akima H, Kuno S, Takahashi H, Fukunaga T, Katsuta S. The use of magnetic resonance images to investigate the influence of recruitment on the relationship between torque and cross-sectional area in human muscle. Eur J Appl Physiol 2000;83:475-480
20. Akima H, Takahashi H, Kuno SY, Katsuta S. Coactivation pattern in human quadriceps during isokinetic knee-extension by muscle functional MRI. Eur J Appl Physiol 2004;91:7-14
21. Liu M, Bose P, Walter GA, Anderson DK, Thompson FJ, Vandenborne K. Changes in muscle T2 relaxation properties following spinal cord injury and locomotor training. Eur J Appl Physiol 2006;97:355-361
22. Akima H. Functional imaging of human skeletal muscle during movement: implications for recruitment, metabolism and circulation. International Journal of Sport and Health Science 2005;3:194-207
23. Andersson E, Oddsson L, Grundstrom H, Thorstensson A. The role of the psoas and iliacus muscles for stability and movement of the lumbar spine, pelvis and hip. Scand J Med Sci Sports 1995;5:10-16
24. McGill S, Juker D, Kropf P. Quantitative intramuscular myoelectric activity of quadratus lumborum during a wide variety of tasks. Clin Biomech (Bristol, Avon) 1996;11:170-172
25. Andersson EA, Nilsson J, Thorstensson A. Intramuscular

EMG from the hip flexor muscles during human locomotion. Acta Physiol Scand 1997;161:361-370
26. Juker D, McGill S, Kropf P, Steffen T. Quantitative intramuscular myoelectric activity of lumbar portions of psoas and the abdominal wall during a wide variety of tasks. Med Sci Sports Exerc 1998;30:301-310
27. Andersson EA, Grundstrom H, Thorstensson A. Diverging intramuscular activity patterns in back and abdominal muscles during trunk rotation. Spine (Phila Pa 1976) 2002;27:E152-160
28. Moraes AC, Pinto RS, Valamatos MJ, et al. EMG activation of abdominal muscles in the crunch exercise performed with different external loads. Phys Ther Sport 2009;10:57-62
29. Peltonen JE, Taimela S, Erkintalo M, Salminen JJ, Oksanen A, Kujala UM. Back extensor and psoas muscle cross-sectional area, prior physical training, and trunk muscle strength--a longitudinal study in adolescent girls. Eur J Appl Physiol Occup Physiol 1998;77:66-71
30. Takahashi K, Takahashi HE, Nakadaira H, Yamamoto M. Different changes of quantity due to aging in the psoas major and quadriceps femoris muscles in women. J Musculoskelet Neuronal Interact 2006;6:201-205
31. Hoshikawa Y, Muramatsu M, Iida T, et al. Influence of the psoas major and thigh muscularity on 100-m times in junior sprinters. Med Sci Sports Exerc 2006;38:2138-2143
32. Kubo T, Muramatsu M, Hoshikawa Y, Kanehisa H. Profiles of trunk and thigh muscularity in youth and professional soccer players. J Strength Cond Res 2010;24:1472-1479
33. Tanaka NI, Kanehisa H. Applicability of single muscle CSA for predicting segmental muscle volume in young men. Int J Sports Med 2014;35:608-614
34. Tawara N, Nitta O, Kuruma H, et al. Functional T(2) mapping of the trunkal muscle. Magn Reson Med Sci 2009;8:81-83
35. Tawara N, Nitta O, Kuruma H, Niitsu M, Itoh A. T2 mapping of muscle activity using ultrafast imaging. Magn Reson Med Sci 2011;10:85-91
36. Hiepe P, Gussew A, Rzanny R, et al. Interrelations of muscle functional MRI, diffusion-weighted MRI and (31) P-MRS in exercised lower back muscles. NMR Biomed 2014;27:958-970
37. Hiepe P, Gussew A, Rzanny R, et al. Age-related structural and functional changes of low back muscles. Exp Gerontol 2015;65:23-34
38. De Ridder EM, Van Oosterwijck JO, Vleeming A, Vanderstraeten GG, Danneels LA. Muscle functional MRI analysis of trunk muscle recruitment during extension exercises in asymptomatic individuals. Scand J Med Sci Sports 2015;25:196-204
39. Wallace LK, Slattery KM, Coutts AJ. The ecological validity and application of the session-RPE method for quantifying training loads in swimming. J Strength Cond Res 2009;23:33-38
40. Tawara N, Nitta O, Itoh A. Comparison of pulse sequences for T2 measurement of human skeletal muscle. Nippon Jiki Kyomei Igakkai Zasshi 2008;28:25-34
41. Kubota J, Ono T, Araki M, Torii S, Okuwaki T, Fukubayashi T. Non-uniform changes in magnetic resonance measurements of the semitendinosus muscle following intensive eccentric exercise. Eur J Appl Physiol 2007;101:713-720
42. O'Leary S, Jull G, Van Wyk L, Pedler A, Elliott J. Morphological changes in the cervical muscles of women with chronic whiplash can be modified with exercise-a pilot study. Muscle Nerve 2015;52:772-779
43. Borghuis J, Hof AL, Lemmink KA. The importance of sensory-motor control in providing core stability: implications for measurement and training. Sports Med 2008;38:893-916
44. Bjerkefors A, Carpenter MG, Cresswell AG, Thorstensson A. Trunk muscle activation in a person with clinically complete thoracic spinal cord injury. J Rehabil Med 2009;41:390-392
45. Okada T, Huxel KC, Nesser TW. Relationship between core stability, functional movement, and performance. J Strength Cond Res 2011;25:252-261
46. Escamilla RF, Lewis C, Pecson A, Imamura R, Andrews JR. Muscle activation among supine, prone, and side position exercises with and without a Swiss ball. Sports Health 2016;8:372-379
47. Andersson EA, Oddsson LI, Grundstrom H, Nilsson J, Thorstensson A. EMG activities of the quadratus lumborum and erector spinae muscles during flexion-relaxation and other motor tasks. Clin Biomech (Bristol, Avon) 1996;11:392-400
48. Jenner G, Foley JM, Cooper TG, Potchen EJ, Meyer RA. Changes in magnetic resonance images of muscle depend on exercise intensity and duration, not work. J Appl Physiol (1985) 1994;76:2119-2124