



Original Article

Detection of muscle activity with forearm pronation exercise using T₂-map MRI

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Abstract. [Purpose] We aimed to detect muscle activity during a forearm pronation exercise using a 0.2 T MRI system. [Participants and Methods] We recruited healthy adult volunteers (7 males, 4 females). Transverse relaxation time (T₂) values for 10 forearm muscles were obtained from transverse multiple-spin-echo MR images of one-third of the ulna, lengthwise from the olecranon, in the resting state and after isotonic forearm pronation exercise at three strength levels (5, 15, and 25% of the maximum voluntary contraction). Z values were calculated as (T_{2e} - T_{2r})/SD_r, where T_{2e}, T_{2r} and SD_r were T₂ after exercise, 34 ms, and 3 ms, respectively. A Z value of 2.56 was used as the threshold for defining muscle activation. [Results] T₂ values increased significantly in the pronator teres muscle (agonist), while those in the supinator muscle (antagonist) showed no change. The sensitivity and specificity values obtained were high and low, respectively, for all of the three exercise strength levels employed. In some of the participants, activity was detected in the flexor carpi radialis, extensor carpi ulnaris, and extensor digitorum. [Conclusion] Using T₂-map MRI, we detected activity in primary and secondary mover muscles. We also found individual variations in the use of forearm muscles during pronation.

Key words: Forearm pronation, Magnetic resonance imaging, Transverse relaxation time

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INTRODUCTION

The analysis of the muscles involved in motion is important to obtain the basic knowledge necessary for the proper design of rehabilitation treatment. Kinesiology, electromyography (EMG), real-time ultrasound scanning (US) and magnetic resonance imaging (MRI) have all been applied to analyze muscle activity^{1, 2)}. From the literature available on manual muscle tests (MMT), the prime movers of a movement can be identified, and while secondary or accessory movers may be equally important, definitive studies remain incomplete³⁾. Compared with EMG and US, MRI can provide images with all of the muscles in a single field of view (FOV) in the arm, and we observed 10 forearm muscles in 1 slice simultaneously⁴⁾. Transverse relaxation time weighted MRI (T_{2w}-MRI) is useful to detect activities of the forearm muscles including the extensor digiti minimi muscle using a 0.2 T MRI system^{5, 6)}. However, image intensity of T_{2w}-MRI is hard to treat quantitatively. Therefore, in a previous study, we defined Gaussian T₂ distribution and reference values (T_{2r} and SD_r) in the resting state for forearm muscles, and a threshold (Z_T=2.56) for detecting exercised muscles using a one-sample t-test⁴⁾. Based on receiver operating characteristic (ROC) analysis, we detected muscle activity that was not expected: 70% of participants used the

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supinator muscle as one of the synergist muscles for palmar flexion of the wrist joint⁴).

In this study, we focused on the motion associated with forearm pronation. In order to detect muscle activity with forearm pronation exercise, we measured T_2 of 10 muscles in the forearm before and after isotonic forearm pronation exercise, and activated muscles were detected using a one-sample t-test. Sensitivity, specificity and ROC curves were examined for the 3 workload levels usually employed for rehabilitation.

PARTICIPANTS AND METHODS

The participants in this study were healthy adult volunteers (7 males and 4 females). The age, height, and weight of the participants averaged 34.0 ± 9.4 years, 171.2 ± 7.9 cm, and 67.3 ± 13.1 kg (means \pm SD), respectively. Eight participants were randomly selected in 3 workload groups. Therefore, 4 participants were included in all 3 workloads. The procedures, purpose, and risks associated with the study were explained to all of the participants, and written consent was obtained prior to the commencement of the study. The study was approved by the Human Research Review Board at the Dokkyo Medical University School of Medicine (No. 24003).

In this study, we focused on the left forearms of the participants. In order to measure the maximum isometric muscle contraction, a muscle dynamometer (μ Tas F-1, Anima, Tokyo, Japan) was set on the palmar side of the forearm 1 cm from the wrist, and the force was measured during maximum voluntary isometric contraction for 5–6 s. The average force of 3 measurements was used for the maximum voluntary contraction (MVC). Three levels of exercises (5, 15 or 25% of the MVC) were applied in random order at intervals longer than 1-week. First, T_2 was measured before the muscle exercise. The forearm was then moved to the anterior side of the MRI magnet. A plastic cuff was set on the palm and all of the fingers were kept in an extended position. Then, a string connected to a weight (5, 15 or 25% of the MVC) was connected on the dorsal side of the cuff. The forearm pronated against the weight, and we had the participants keep that position for 1 s. This isotonic forearm pronation was repeated at 2 s intervals until the participant was unable to continue the forearm pronation. Immediately after the exercise, the arm position was restored to the original position and the T_2 values were measured again at an interval of 5 min until 25 min after the exercise.

MR images of each forearm were obtained with a 0.2 T compact MRI system (MRTechnology, Tsukuba, Japan) equipped with an oval ^1H solenoidal radiofrequency probe. Each left forearm was fixed by a shell-type holder for the forearm⁵). The transverse T_2 weighted MR (T_{2w} -MR) images were measured using a T_2 multi-slice spin-echo MR image sequence, and the slice position was set at one-third of the length of the ulna from the olecranon. The parameters for the T_2 multiple-spin-echo MRI were set as follows: a 20×20 cm field of view (FOV), a data matrix of 128×128 , a single slice of 9.5 mm for the slice thickness, a 2,000 ms relaxation delay (TR), 8 echo-times (TE) from 10 ms to 80 ms with a 10 ms step, 1 accumulation, and a total image acquisition time of 4 min 16 s. Images were Fourier transformed with a data matrix 256×256 after zero filling of data. The T_2 values in each pixel were calculated by non-linear fitting to single exponential decay, and the T_2 images (T_2 -map) were reconstructed using iPlus software (MRTechnology, Tsukuba, Japan), and were presented in a range of T_2 from 0 to 500 ms.

The MR images were evaluated by 2 physical therapists with more than 6 years' experience using 0.2 T MRI. Ten muscles were assigned using a T_{2w} -MR image in comparison with an MRI atlas of the human forearm (Fig. 1A)^{4, 7}): including the pronator teres muscle (PT) (agonist muscle), the supinator muscle (SM) (antagonist muscle), the flexor carpi radialis muscle (FCR), the flexor carpi ulnaris muscle (FCU), the palmaris longus muscle (PL), the flexor digitorum superficialis muscle (FDS), the flexor digitorum profundus muscle (FDP), the extensor carpi radialis longus/brevis muscle (ECU), the extensor carpi ulnaris muscle (ECR) and the extensor digitorum muscle (ED). In each of the T_2 -map images, the ROIs with 16 pixels (9.8 mm^2) were set near the center of the muscle, but we excluded visible fat tissue and vessels. The means and SDs of the T_2 values were obtained using iPlus software and Image J software (v1.44p, NIH, Bethesda, MD, USA). Z values were calculated by $(T_{2e} - T_{2r})/SD_r$, where T_{2e} , T_{2r} and SD_r were T_2 after exercise, 34 ms and 3 ms, respectively, and activated muscles were detected by the one-sample t-test with a threshold ($Z_T=2.56$)⁴.

RESULTS

Workloads for 5, 15 or 25% of the MVC were 0.65 ± 0.1 kg, 2.1 ± 0.4 kg and 3.5 ± 0.9 kg, respectively ($n=8$). The number of exercises conducted until the participants were unable to continue pronation of forearm were 883 ± 234 times, 333 ± 159 times and 130 ± 57 times for 5, 15 or 25% of the MVC, respectively. In the T_2 -map images obtained 5 min after 5, 15 or 25% of the MVC, the PT muscle (agonist muscle) was depicted with higher T_2 values compared with the SM muscle (antagonist muscle) (Fig. 1B). As shown in Fig. 1C and 1D, activation of the FCR, ECU and ED muscles were detected in some participants. T_2 values obtained before and 5 min after the exercise are shown in Table 1. Activated muscles for the 3 workload levels were detected by the one-sample t-test with $Z_T=2.56$, and the number of activated muscles are shown in Table 2. The sensitivity and specificity required for detection of agonist muscles (PT) compared with the antagonist muscle (SM) are shown summarized in Table 3. The cumulative curves and ROC curves for the PT and SM muscles are shown in Fig. 2A and 2B, respectively. The Area Under the Curve (AUC) values were 0.96 and 0.67 for the PT and SM muscles, respectively. Workload dependent changes in the ROC curves for the FCR, ECU and ED muscles are shown in Fig. 2C, 2D

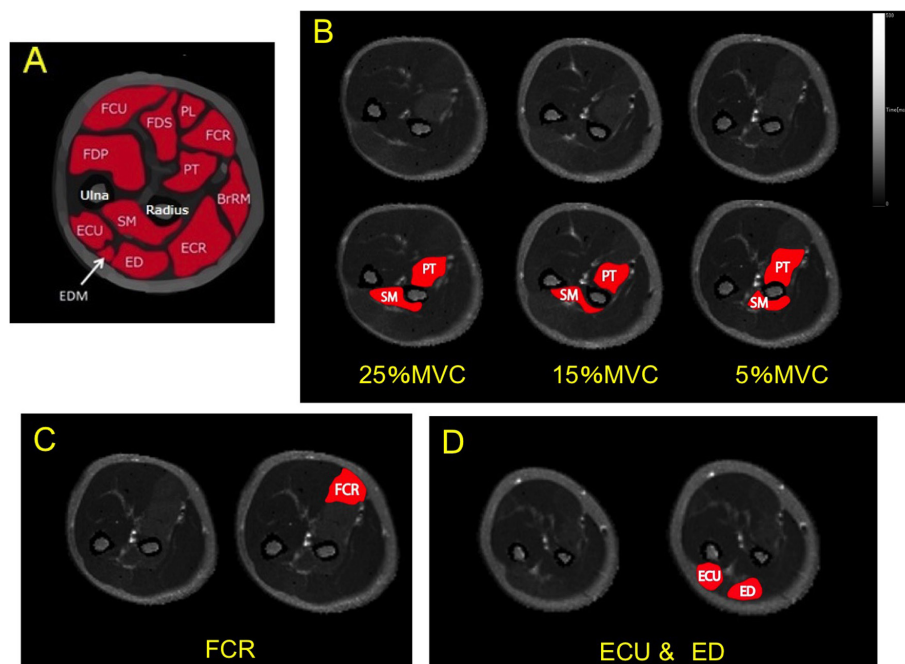


Fig. 1. Transverse T_2 -map MR images of the forearm at one-third of the length of the ulna from the olecranon. A. Muscle traces⁴⁾. B. T_2 -maps observed 5-min after the exercise at workload of 25%, 15% and 5% of the MVC. The upper and lower panels are original images and images with traces of the PT and SM muscles. The gray scale represented T_2 from 0 to 500 ms. C. Typical T_2 -map image of activation of the FCR muscle (the left panel) and image with a trace of the FCR muscle (the right panel). D. Typical T_2 -map image of activation of the ECU and ED muscles (the left panel) and image with a trace of the ECU and ED muscles (the right panel).

Table 1. T_2 in 10 forearm muscles after the forearm pronation exercise

Exercise			25%MVC		15%MVC		5%MVC	
Muscle	Abbreviation	Function	Mean (ms)	SD (ms)	Mean (ms)	SD (ms)	Mean (ms)	SD (ms)
Flexor carpi radialis	FCR	Synergist	39.46	3.78	37.44	3.64	36.72	6.44
Flexor carpi ulnaris	FCU		36.59	3.78	35.87	2.68	33.21	2.77
Palmaris longus	PL		36.10	3.48	36.75	1.56	34.13	2.81
Flexor digitorum superficialis	FDS		34.81	3.65	36.03	2.35	32.89	1.89
Flexor digitorum profundus	FDP		34.24	3.50	34.72	2.56	30.42	2.76
Extensor carpi radialis longus/brevis	ECR		36.46	3.25	37.18	1.47	34.40	1.77
Extensor carpi ulnaris	ECU		41.65	3.84	42.09	5.67	36.63	1.90
Extensor digitorum	ED		43.68	4.93	39.24	2.20	37.21	2.11
Supinator	SM	Antagonist	36.34	3.54	36.84	1.55	35.65	3.60
Pronator teres	PT	Agonist	49.52	5.38	51.58	3.36	45.93	3.48

Means and standard deviation (SD) of 8 participants.

and 2E, respectively. The AUC values for the FCR muscles were 0.78, 0.70 and 0.54 for the 5%, 15% and 25% of the MVC, respectively. The AUC values for ECU muscle were 0.84, 0.82 and 0.69 for the 5%, 15% and 25% of the MVC, respectively. The AUC values for ED muscle were 0.85, 0.82 and 0.72 for the 5%, 15% and 25% of the MVC, respectively.

DISCUSSION

In this study, muscle activity was detected with forearm pronation exercise. Pronation of the forearm is a common motion in daily life, and it is often seen when someone takes food, turns a key, or closes the cap of a bottle, etc. The prime and accessory mover muscles are the pronator teres muscle and the flexor carpi radialis muscle, respectively, and the supinator

Table 2. Number of activated muscles with the forearm pronation exercise

Exercise		25%MVC	15%MVC	5%MVC	
Muscle	Function	Number of participants	Number of participants	Number of participants	
FCR	Synergist	8	3	1	
FCU		8	0	0	
PL		8	0	0	
FDS		8	0	0	
FDP		8	0	0	
ECR		8	0	0	
ECU		8	4	3	
ED		8	5	2	
SM		Antagonist	8	1	0
PT			8	8	7

FCR: Flexor carpi radialis; FCU: Flexor carpi ulnaris; PL: Palmaris longus; FDS: Flexor digitorum superficialis; FDP: Flexor digitorum profundus; ECR: Extensor carpi radialis longus/brevis; ECU: Extensor carpi ulnaris; ED: Extensor digitorum; SM: Supinator; PT: Pronator teres.

Table 3. Performance of detection agonist (PT) muscle compared with antagonist (SM) muscle

Workload	Sensitivity	Specificity
25% MVC	1	0.12
15% MVC	1	0
5% MVC	0.85	0

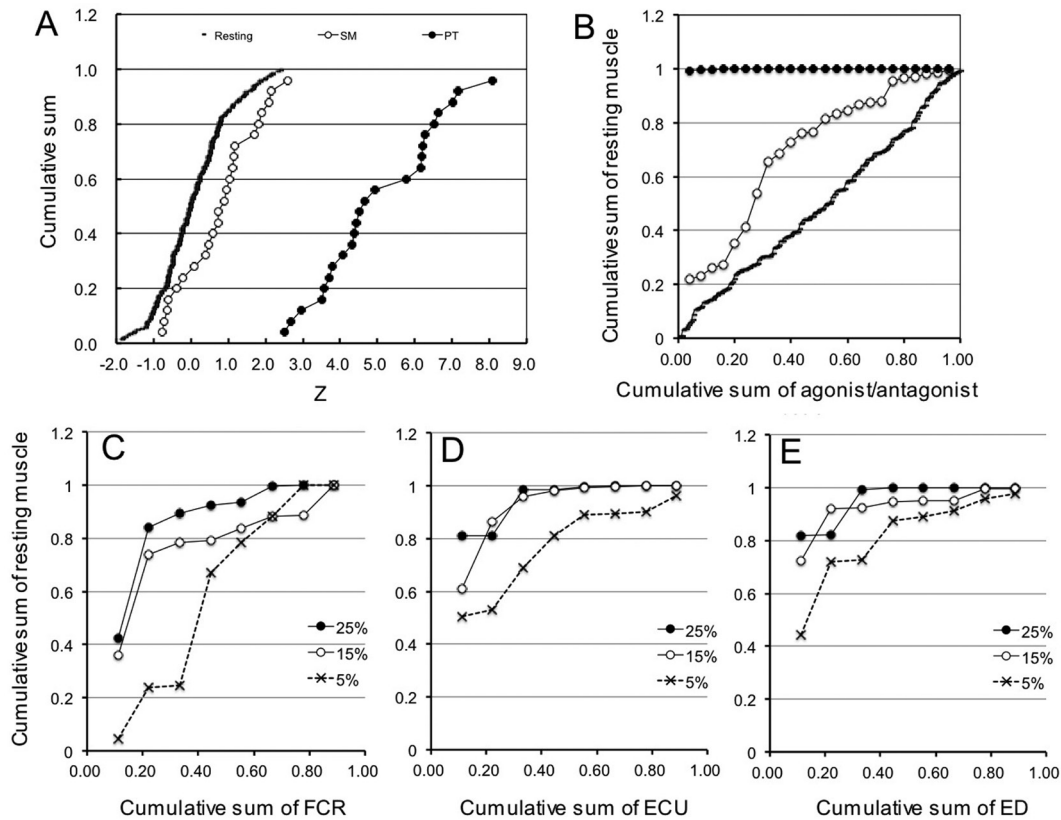


Fig. 2. Receiver Operating Characteristics (ROC) analysis of the Z value. A–B. Cumulative curves and ROC curves for the PT and SM muscles. The distribution of Z for resting muscle is used as the reference ($T_{2r} \pm SD_r = 34 \pm 3 \text{ ms}^4$). C–E. Workload dependent changes in the ROC curves for the FCR, ECU and ED muscles.

muscle is the antagonist muscle³). After the forearm pronation exercise, the T_2 values increased significantly in the PT muscle (agonist), while those in the SM muscle (antagonist) showed no change. The sensitivity and specificity were high and low, respectively, at 5, 15 and 25% of the MVC. The AUC (0.96) for the PT muscles also suggests a high accuracy for the detection of muscle activation. Therefore, the threshold ($Z_T=2.56$)⁴ is useful for detecting exercised muscles by a one-sample t-test with the forearm pronation exercise. Visual inspection of the T_2 -map images showed that the increase in the T_2 in the PT muscle was detectable, even at 5% of the MVC (Fig. 1B). Because 3 workload levels are usually used for rehabilitation in a clinical setting, T_2 -map images would be useful for the evaluation of activated muscles by MMT.

We detected some individual variations in the muscle activity. At 25% of the MVC, the activation of the antagonist muscle was detected in 1 of the 8 participants. In addition, from the cumulative curve for the SM muscle, the Z values for 4 participants were also distributed at around 2 (Fig. 2A). The contraction of the antagonist muscle has been reported as the coactivation of muscles during strong or fast exercise⁸). Therefore, it is likely that coactivation of the SM muscle was detected at 25% of the MVC, which also suggested that there are individual variations in the threshold for coactivation. In addition, we detected an accessory mover muscle, and also muscles that were not expected. At 5% of the MVC, activation of the FCR muscles were detected in 2 of the 8 participants, but the rest of the muscles were not activated. This finding supports the concept that the FCR muscle is the accessory mover muscle for pronation of the forearm³). When workloads increased to 15 and 25% of the MVC, there was an increase in the number of participants that used the FCR muscle and the AUC values also showed a tendency for an increase. Unexpectedly, activation of the ECU and ED muscles were detected at 15 and 25% of the MVC. AUC values higher than 0.8 suggested the activation of muscles. The ECU and ED muscles extend the wrist and fingers. In daily life, for instance, when wringing out a wet towel, or when standing up using the hands, forearm pronation and wrist extension occur simultaneously. Therefore, some people might form a habit of using the ECU and ED muscles as accessory movers for pronation of the forearm. Alternatively, it could be suggested that the ECU and ED muscles act as a collaboration action of the antagonist muscle. Due to the small number of participants in this study, it is necessary to increase the number of participants in future studies in order to reach any final conclusions in this regard.

In conclusion, in this study we detected not only primary and accessory mover muscles, but also some individual variations of in the use of forearm muscles during pronation. The results obtained suggest that along with the results of MMT, T_2 -map images and ROC analysis are very useful in the analysis of the activity of muscles.

Conflict of interest

None.

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