Magnetic Resonance Imaging 57 (2019) 95–102

Contents lists available at ScienceDirect

Magnetic Resonance Imaging

journal homepage: www.elsevier.com/locate/mri

Technical note

Simultaneous acquisition of magnetic resonance elastography of the supraspinatus and the trapezius muscles

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ARTICLE INFO

Keywords:
MR elastography
Shoulder
Supraspinatus
Trapezius
Skeletal muscle
Stiffness

ABSTRACT

We developed a Magnetic Resonance elastography (MRE) technique using a conventional magnetic resonance imaging (MRI), which allows a simultaneous elastography of the supraspinatus and trapezius muscles, by designing a new wave transducer (vibration pad) and optimizing the mechanical vibration frequency. Five healthy volunteers underwent an MRE. In order to transmit the mechanical vibration (pneumatic vibration) to the supraspinatus and trapezius muscles, a new vibration pad was designed using a three-dimensional (3D) printer. The vibration pad was placed on the skin 2 cm medial and 2 cm cephalad the deltoid tubercle. MRE acquisition was performed with a multi-slice gradient-echo type multi-echo MR sequence, which allows MREs even in a conventional MRI; two oblique axial images of the supraspinatus and trapezius muscles were obtained simultaneously. Vibration frequencies were set at 50–150 Hz, with a 25 Hz step. Wave image quality in each frequency was analyzed using a phase-to-noise ratio (PNR) and clarity of propagating wave that was assessed by two readers qualitatively. In the supraspinatus muscle, the wave images were of good quality especially at frequencies > 75 Hz. In the trapezius muscle, the wave images were of better quality at low frequencies (50 and 75 Hz) compared with high frequencies (100–150 Hz). The PNR of both muscles were higher at low frequencies. The mean stiffness in the trapezius muscle (7.26 ± 2.13 kPa at 75 Hz) was larger than those in the supraspinatus muscle (4.16 ± 0.50 kPa at 75 Hz). The results demonstrated that our MRE technique allows simultaneous assessment of the stiffness in the supraspinatus and trapezius muscles using a conventional MRI, and that optimal vibration frequency for simultaneous MRE of these muscles is 75 Hz. This technique provides a new means for early detection of abnormality in the shoulder.

1. Introduction

Rotator cuff tears are among the most common injuries of the shoulder [1] and usually initiate at the anterosuperior portion of the supraspinatus muscle and extend posteriorly [2]. The rotator cuff is susceptible to repetitive damages due to eccentric contraction in the deceleration phase during throwing and overhead hand use, and eventually rotator cuff tear occurs [3]. Eccentric contraction leads to stiff and sore muscles within a day or two of the activity, leading to a prolonged reduction in force generation capacity [4]. In the most initial mild stage of muscle damages (i.e., Type I muscle injury), one of main symptoms is muscle firmness or an increase in muscle tone with minimal changes in MRI findings [5]. After a tear of the supraspinatus tendon, the musculotendinous unit retracts, atrophies, undergoes fatty infiltration, and loses elasticity [6]. Even after successful rotator cuff repair, these muscle changes were irreversible [7,8].

Thus, eccentric contraction induces muscle damages such as sarcomere disruption, and mechanical properties such as muscle stiffness and

Abbreviations: MRE, magnetic resonance elastography; PNR, phase-to-noise ratio; MEG, motion encoding gradient; SNR, signal-to-noise ratio; ROI, region of interest; SD, standard deviation

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https://doi.org/10.1016/j.mri.2018.11.011
Received 4 September 2018; Received in revised form 21 October 2018; Accepted 17 November 2018

force are altered [4,9–11]. Therefore, quantitative evaluation of stiffness of the supraspinatus muscle could assist the diagnosis of muscle pathologies and assess effects of treatments of rotator cuff tears. Clinically, palpation is used to diagnose abnormal stiffness changes in skeletal muscles [12,13]. However, palpation depends on the examiner's clinical skills for muscle identification, and it is impossible to detect stiffness changes in deep tissues by palpation. Since the supraspinous muscle is located under the trapezius muscle, it is difficult to differentiate stiffness of the supraspinatus and trapezius muscles by palpation. Therefore, a new technique is required to detect rotator cuff abnormalities before rotator cuff tears occur.

Magnetic resonance elastography (MRE) is a phase-contrast technique that applies an oscillating motion encoding gradient (MEG) to detect tissue wave displacements introduced by external vibration [14]. The displacement image (wave image) is then used to reconstruct the mechanical properties of the tissue via inversion algorithms [15]. MRE allows measurement of mechanical properties of both superficial and deep tissues only if vibrations reach these tissues. For vibration to reach the tissues, the vibration system should be adequately designed. Over the years, several vibration systems have been developed; for example, the electromechanical, piezo-electric-stack and pneumatic vibration [16]. Among them, a pneumatic vibration system is often used for MRE in clinical practice or situation [17–19]. This system is easily available in high magnetic field and has high penetration ability if the wave transducer (vibration pad) adheres tenaciously to the skin. Therefore, it is important for the MRE to appropriately design the vibration pad according to the imaging object. Vibration frequency is also an important factor to determine penetration ability of the vibration. Higher frequencies have shorter wavelengths and better resolution of the stiffness, but lower penetration ability. Therefore, it is necessary to adjust vibration frequency according to size of an imaging object and its depth from the body surface.

Our previous study developed an MRE technique that can be applied to the supraspinatus muscle [20]. Chen et al. [21] performed MRE of the trapezius muscle in order to evaluate myofascial taut band, a contracted or shortened muscle fiber band with increased muscle tone. However, as far as we know, no previous studies have applied MRE simultaneously to the supraspinatus and trapezius muscles. Simultaneous MRE of the supraspinatus and trapezius muscles would allow not only more accurate and objective assessment of stiffness of the supraspinatus muscles but also identification of the muscle with higher stiffness, either the supraspinatus or trapezius muscles. In addition, simultaneous MRE of the supraspinatus and trapezius muscles can reduce examination time greatly, because both acquisition and setting times of a vibration pad can be reduced. The purpose of this study was to develop an MRE technique to be applied to the supraspinatus and trapezius muscles simultaneously. We used a conventional gradient-echo type multi-echo MR sequence [22] in order to conduct an MRE of the supraspinatus and trapezius muscles in a conventional magnetic resonance imaging (MRI). To perform the simultaneous MRE of the supraspinatus and trapezius muscles, it is necessary to supply vibrations to both muscles efficiently. We have previously demonstrated that MRE can be applied to the supraspinatus muscle and found the best excitation location [20,23]. Hence, this study developed a technique for simultaneous MRE of the supraspinatus and trapezius muscles by adjusting the shape of a vibration pad and vibration frequency.

2. Materials and methods

2.1. Participants

Five healthy volunteers (5 men, mean age: 22.0 ± 1.22 years, age range: 20–23 years, mean BMI: 21.6 ± 1.87) with no history of skeletal muscle disease, shoulder trauma, and recent/present shoulder pain were enrolled in this MRE study. We instructed the volunteers to relax during imaging and to lightly bend the elbow joint by 30° and put the hand on the abdomen in order to keep the body position constant among volunteers and relax the supraspinatus and trapezius muscles. All studies were performed after obtaining informed consents from the participants and after receiving an approval from our institutional ethical review board.

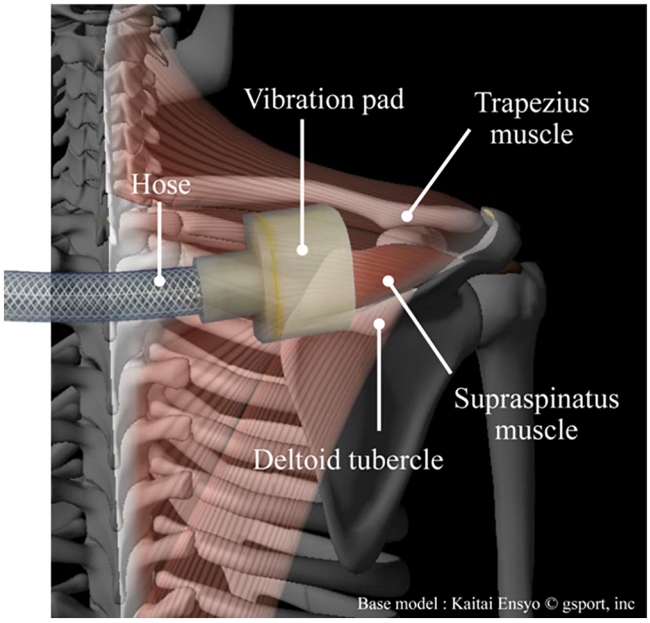

Fig. 1. Setup of the vibration pads. The shape of the vibration pad (size, W 4.5 cm × D 6 cm × H 3.5 cm) was adjusted to efficiently excite the supraspinatus and trapezius muscles simultaneously.

2.2. Experimental setup

All MRI and MRE experiments were performed on a clinical MR imager (Achieva 3.0 T, Philips Healthcare, Best, The Netherlands) while using a surface coil with the subject in the supine position. This study used custom-designed pneumatic wave transducer (vibration pad) made by a three-dimensional (3D) printer (3Dtouch, 3D Systems, Inc., Rock Hill, SC, USA), where is specifically optimized for the supraspinatus and trapezius muscles. The vibration pad was placed on the skin 2 cm medial and 2 cm cephalad the deltoid tubercle (Fig. 1) and was secured with the same method that has been described previously [20]. In this study, a vibration waveform was generated by a self-built waveform generation system (LabVIEW and USB-6221, National Instruments Corporation, Austin, TX, USA). This system can generate sinusoidal waveforms with arbitrary frequencies and phases. To synchronize the vibration with TR, the transistor-transistor logic signal from the MRI system (RF pulse power amplifier) was used as a trigger to start the vibration.

2.3. Anatomical MRI

A series of oblique coronal and sagittal proton-density-weighted images through the supraspinatus and trapezius muscles were acquired with a Turbo Spin Echo MRI sequence (Fig. 2). The acquired data were used as a reference for the muscle shape to accurately obtain the wave images. In the supraspinatus muscle, the imaging plane was set to the superior portion of the supraspinatus muscle to obtain clear wave image [20]. In the trapezius muscle, the imaging plane was set at over the supraspinatus muscle so that it covers as wide portion as possible of the trapezius muscle.

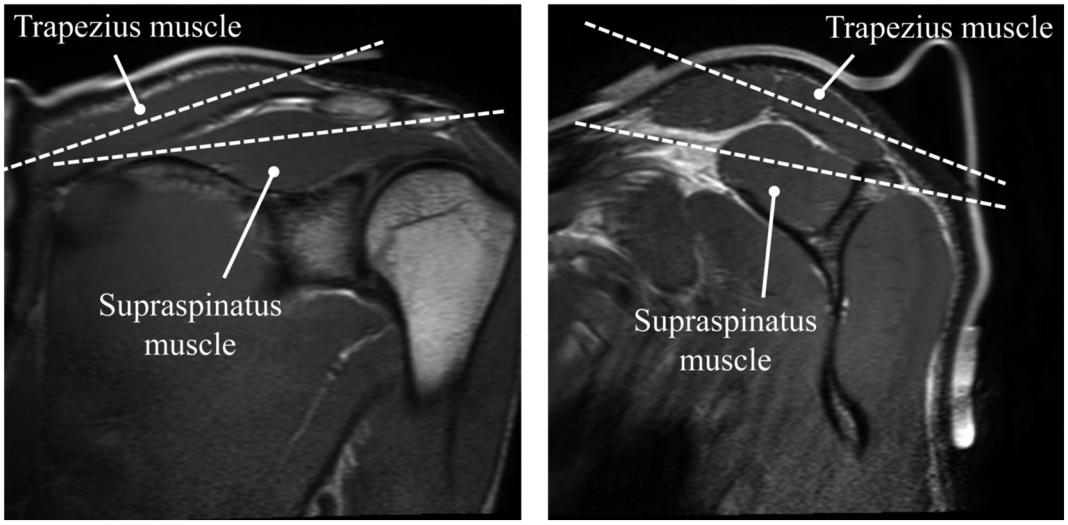

Fig. 2. Oblique coronal and sagittal proton-density-weighted images for determining MRE imaging planes of the supraspinatus and trapezius muscles (white dash lines).

2.4. MR elastography

MRE acquisitions were performed with a gradient-echo type multi-echo MR sequence [22] and each oblique axial image of the supraspinatus and trapezius muscles was obtained simultaneously by multi-slice imaging. In a gradient-echo type multi-echo MR sequence, multiple symmetrical gradient-echoes were acquired with the symmetrical bipolar readout gradient lobes. Those gradient lobes achieve a similar function to MEG (MEG-like effect), in other words, sensitization to motion due to the vibration. When those gradient lobes are synchronized with vibrations, MEG-like effect is maximum. This synchronization can be easily achieved by adjusting the period of bipolar readout gradient lobes and the gap between the first and next echo (δTE) of a multi-echo sequence. Then, the later generated echo has greater MEG-like effect (1st echo < 2nd echo < 3rd echo, etc.).

In this study, a continuous (steady state) acoustic vibration at 50–150 Hz (with a 25 Hz step) was introduced and they were synchronized with readout gradient lobes. MRE acquisitions were performed with the following parameter: 128 × 128 acquisition matrix, 2 number of averages, 20° flip angle, 180 mm^2 field of view, 2 mm slice thickness, AP readout direction (MEG-like direction), 3 ms 1st TE, 3.33/4.00/5.00/6.66/10.0 ms δTE (150/125/100/75/50 Hz), 40 ms repetition time, and 40 s total acquisition time (4 phase offsets). In this study, the second echo data were used because MEG-like effect of the first echo data was not enough to visualize wave propagation and those later than the third echo data were affected by transverse relaxation and phase wrapping due to a magnetic susceptibility effect. Previous studies have reported that shear wave displacements were induced primarily perpendicular to the muscle fibers [15,20,24] because of anisotropy of the muscle. Therefore, readout gradient direction was set perpendicular to the fibers in the supraspinatus and trapezius muscles.

2.5. Image processing and analysis

All phase images were processed by a phase unwrapping based on minimum discontinuity algorithm and a Gaussian spatial filter (low- and high-frequency cutoff are 5 and 12 waves/FOV) and were converted to reflected wave displacement images (wave images) (MRE/Wave, Mayo Clinic, Rochester, MN, USA). This study assessed wave image quality in each vibration frequency with two indices. One is a visual inspection of clarity of propagating wave that affects measurement of the wavelengths for stiffness measurement. Two independent readers (with over 2 years of experience with MRE researches on skeletal muscles) evaluated quality of shear waves on wave images. Since the shear wave propagates primarily along fiber direction within a given muscle [15,20,24] and shear wave velocity (one of factors affected by muscle stiffness) depends on the direction of wave propagation to the muscle [25,26], a following five-point subjective scale, which incorporates the wave propagation direction, was used (Fig. 3): A score of 1 indicated no visible waves; a score of 2, barely visible wave propagation; a score of 3, clearly visible waves propagating along fiber direction with fewer than one wavelength penetrating the muscle; a score of 4, clearly visible waves propagating along fiber direction with more than one less than two wavelengths penetrating the muscle; and a score of 5, clearly visible waves propagating along fiber direction with more than two wavelengths penetrating the muscle [27,28]. An image quality score was calculated by averaging the two readers' scores. Mean quality scores of the supraspinatus and trapezius muscles in each frequency were calculated by averaging the image quality scores across the subjects in each muscle and each frequency. Another index to assess wave image quality was a phase-to-noise ratio (PNR) in the wave image, where PNR is proportional to the signal-to-noise ratio (SNR) and to the phase shift (wave amplitude) [29]. The PNR in each vibration frequency was defined as the product of the SNR of the magnitude image multiplied by the wave amplitude of the wave image in the second echo data. The relative PNRs of the supraspinatus and trapezius muscles in each frequency were computed by normalizing with the PNR value at 50 Hz in each subject, and then relative PNR was averaged across the subjects in each muscle and each frequency. The SNR values were defined as the ratios of the average signal in the region-of-interests (ROIs) along the inner surface of the supraspinatus or trapezius muscles to the standard deviation (SD) in the same ROIs (average signal/SD). The wave amplitudes were also measured in the same ROIs on the wave amplitude images which were obtained by a discrete Fourier transformation on the time series data (4 offset wave images).

The stiffness of the supraspinatus and trapezius muscles were calculated by measuring the wavelengths manually in the region of propagating clear wave and using following equation:

$$\mu = \rho f^2 \lambda^2 \quad (1)$$

where ρ is the muscle density (≒1 g/cm^3), f is the frequency and λ is the wavelength. The rectangular ROIs were used for wavelength measurement, where MRE data were converted into scatter diagrams in which peaks of the waves were manually detected (Fig. 4). The mean values of the displacements in the direction perpendicular to the wave propagation were calculated, and the wavelengths were measured from the

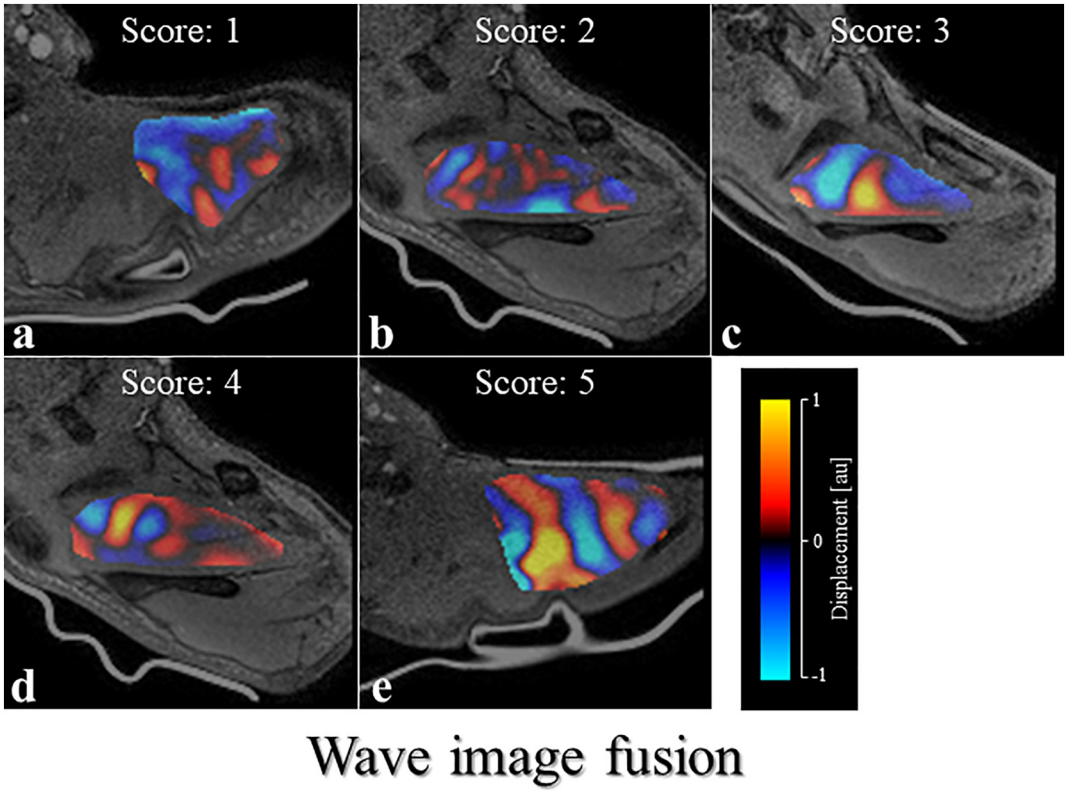

Fig. 3. Examples of the wave images in each image quality score (a,e: trapezius muscle, b–d: supraspinatus muscle).

distance between peaks of these values and then the average value (obtained 4 offsets) was calculated. If the wave images were unclear (i.e., mean quality score was < 3), those images were excluded from the data analysis of the stiffness.

2.6. Statistical analysis

Concordance of mean quality scores between the two readers was assessed using quadratic weighted Cohen's kappa coefficient (CI 95%). Concordance was evaluated as follows: poor if < 0, slight if 0–0.20, fair if 0.21–0.40, moderate if 0.41–0.60, substantial if 0.61–0.80, and almost perfect if 0.81–1 [30]. The significance of statistical differences of SNR, wave amplitude and PNR were assessed using nonparametric Friedman's test, followed by Dunnett's post-hoc test between 50 Hz and other frequencies (75–150 Hz). Statistical significance was set at $P < 0.05$. All data were analyzed using IBM SPSS version 24 (Armonk, NY, USA).

3. Results

Fig. 5 shows mean quality scores in the supraspinatus and trapezius muscles in each frequency. The value of Cohen's kappa concordance coefficient was almost perfect (k = 0.82; CI 95% 0.71; 0.93). In the supraspinatus muscle, the mean quality score was high at the all frequencies and was > 4 for frequencies > 75 Hz. In the trapezius muscle, the mean quality score was high at 50 and 75 Hz (3.7 and 4.1). However, it was decreased in higher frequencies and the scores were < 3 for frequencies over 75 Hz. The mean relative SNR, wave amplitude and PNR in each vibration frequency are indicated in Table 1. There was no significant difference in mean relative SNRs of the supraspinatus muscle among vibration frequencies (Friedman's test, $P = 0.065$). The mean relative SNRs of the trapezius muscle were significantly greater at

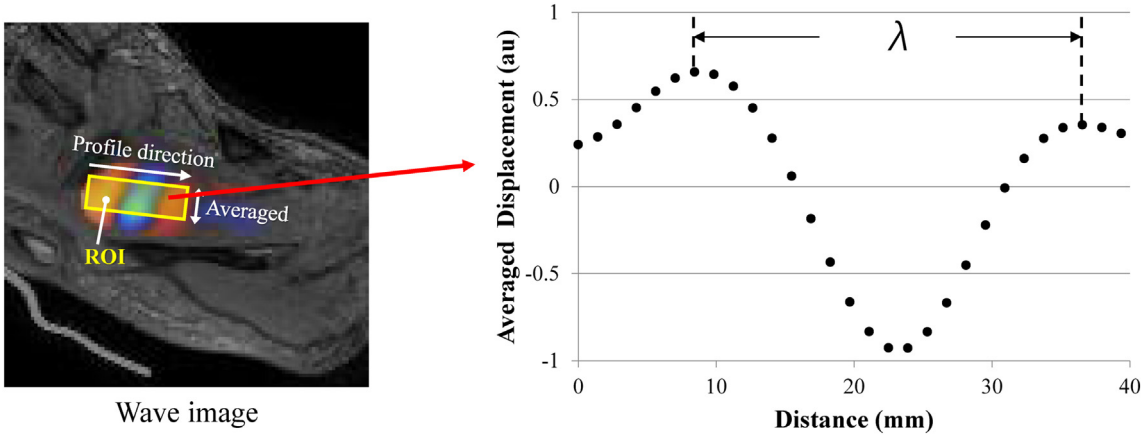

Fig. 4. An example of measurement of wavelength of wave propagation along the region of interest (ROI).

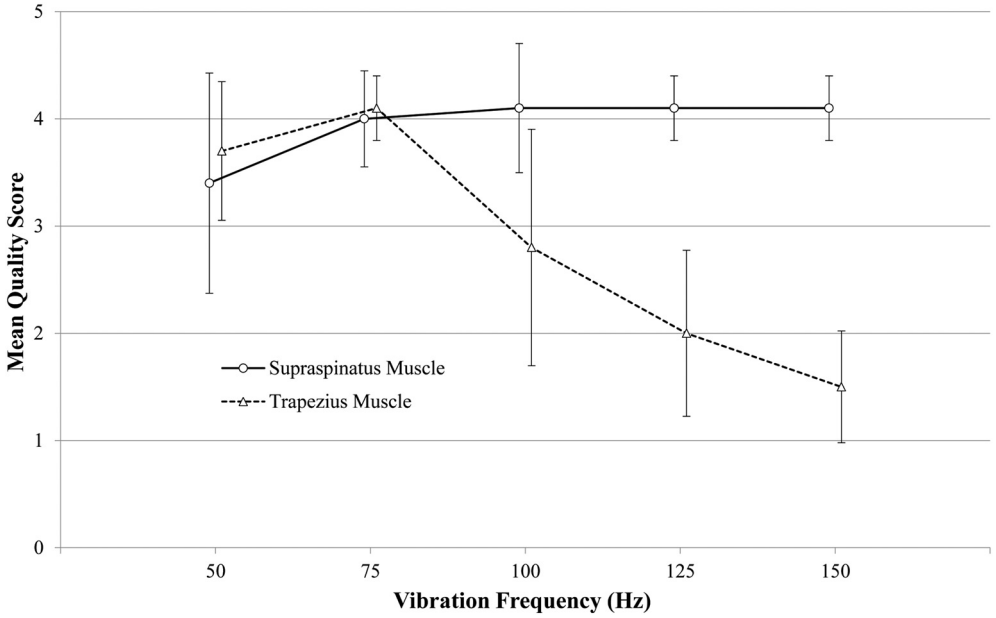

Fig. 5. Clarity of the wave images in mean quality scores (averaging two readers' scores) in the supraspinatus and trapezius muscles across the mechanical vibration frequencies. Error bars show standard deviations.

higher frequencies (Dunnett's test after Friedman's test, $P < 0.05$; 50 Hz vs. 125 and 150 Hz). The mean relative wave amplitudes of both muscles were significantly lower at higher frequencies (Dunnett's test after Friedman's test, $P < 0.05$; 50 Hz vs. 100, 125 and 150 Hz). The mean relative PNRs of both muscles were significantly lower at higher frequencies (Dunnett's test after Friedman's test, $P < 0.05$; 50 Hz vs. 125 and 150 Hz).

The wave images of the supraspinatus and trapezius muscles from one volunteer were shown in Figs. 6 and 7, respectively. The chroma of the wave images indicates displacement of the propagating shear waves in the muscles. Shear waves propagated from one direction at all frequencies in the supraspinatus muscle and at low frequencies (50 and 75 Hz) in the trapezius muscle; however, it propagated from multi-directions at high frequencies (100–150 Hz) in the trapezius muscle.

The mean stiffness values of the supraspinatus and trapezius muscles in each frequency are listed in Table 2. In the supraspinatus muscle, 2 images with scores < 3 were excluded at only 50 Hz. In the trapezius muscle, 1, 3, 4 and 5 images with scores < 3 were excluded at 50, 100, 125 and 150 Hz, respectively. In other words, there was no wave image with score < 3 at only 75 Hz in the trapezius muscle. Mean stiffness values of both the supraspinatus and trapezius muscles were larger in higher frequencies. Moreover, mean stiffness values of the trapezius muscle were larger with larger standard deviation than those of the supraspinatus muscle.

4. Discussion

The results demonstrated that our MRE technique enables simultaneous acquisition of MRE information of the supraspinatus and trapezius muscles using a conventional MRI. In this study, clarity of the wave images across the vibration frequencies was different between the supraspinatus and trapezius muscles. Anatomical locations of these muscles suggest that the waves would propagate more easily in the trapezius muscle that is located closer to the surface than the supraspinatus muscle. However, the resultant wave images of the trapezius muscle were unclear at high frequencies (100–150 Hz) although those of the supraspinatus muscle were clear. The following three factors might explain this discrepancy. First, the trapezius muscle is more curved than the supraspinatus muscle. This difference of the structures might affect wave propagation. Second factor is the spine of the scapula. Some wave images at high frequency showed waves propagating not only from the vibration pad but also from near the spine of the scapula in the trapezius muscle (white dash arrows in Fig. 7d–f). In this study, the vibration pad was located at very near the spine of scapula. Therefore, this suggests that the vibration pad directly vibrated the spine of the scapula, which might in turn generate the waves propagating from the spine of the scapula. At low frequency (50 and 75 Hz), the waves from the vibration pad may propagate dominantly to the trapezius muscle because of high penetration ability in the soft tissue (i.e., trapezius muscle). At high frequency (100–150 Hz), however, the waves from the vibration pad cannot propagate deeply because of low

Table 1
Mean relative SNRs, wave amplitudes and PNRs (normalized with those at the 50 Hz, respectively) in the supraspinatus and trapezius muscles at each vibration frequency (50–150 Hz).

Vibration frequency (Hz)	Supraspinatus muscle			Trapezius muscle		
	Mean relative SNR	Mean relative amplitude	Mean relative PNR	Mean relative SNR	Mean relative Amplitude	Mean relative PNR
50	1.00	1.00	1.00	1.00	1.00	1.00
75	1.04 ± 0.03	0.98 ± 0.10	1.03 ± 0.11	1.10 ± 0.07	0.97 ± 0.43	1.08 ± 0.51
100	1.09 ± 0.03	0.75 ± 0.21	0.82 ± 0.25	1.16 ± 0.11	0.57 ± 0.29	0.68 ± 0.35
125	1.07 ± 0.05	0.24 ± 0.06	0.26 ± 0.07	1.24 ± 0.13	0.16 ± 0.05	0.20 ± 0.07
150	1.07 ± 0.07	0.13 ± 0.03	0.14 ± 0.03	1.32 ± 0.16	0.09 ± 0.03	0.11 ± 0.04

Data are presented as mean ± SD.

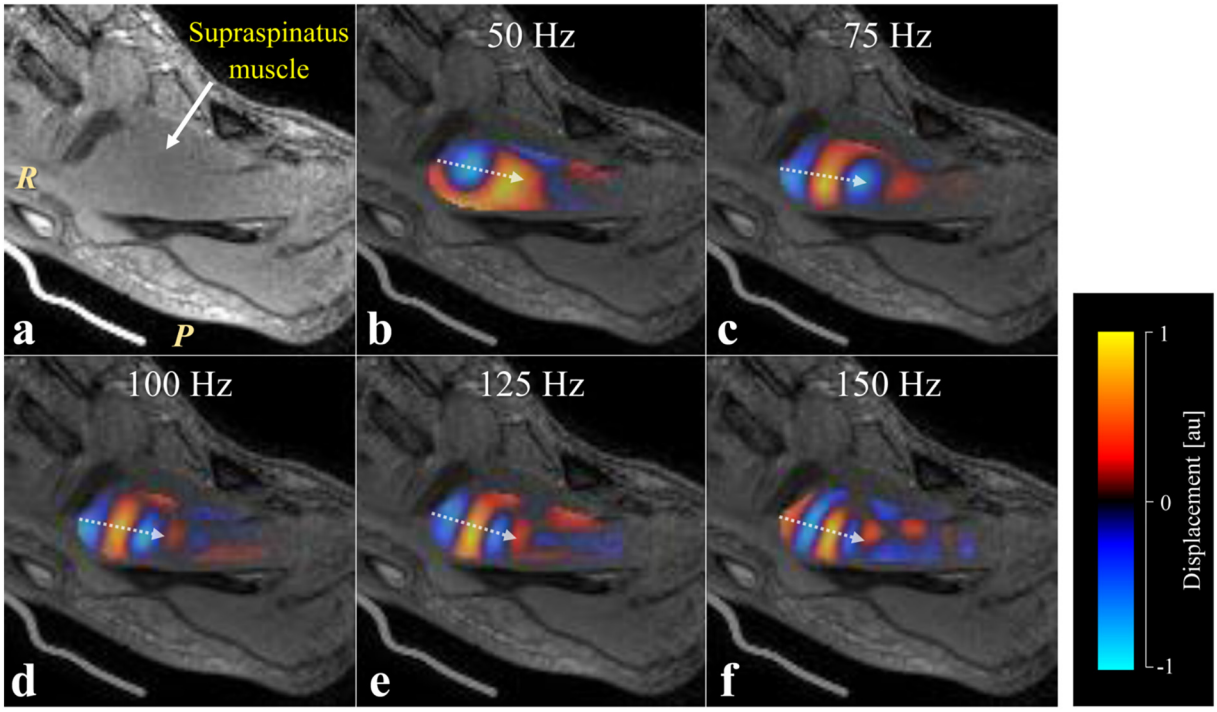

Fig. 6. Images of the supraspinatus muscle in one volunteer. (a) Magnitude image. (b–f) Wave images at each vibration frequency (50–150 Hz). The white dotted arrows indicate wave propagation direction within the supraspinatus muscle. P: posterior direction, R: right direction.

penetration ability in the soft tissue. Therefore, the waves from the spine of the scapula may be visualized clearly on the wave image at high frequency compared with those of low frequency. Furthermore, wave interference between these waves might lead to unclear wave images in the trapezius muscle. Third factor is excitation location. The previous study has performed the MRE of the trapezius muscle at 150 Hz vibration by placing the wave transducer near the observation area [21]. In contrast, we performed MRE at the best excitation location for the supraspinatus muscle. Therefore, shear waves may propagate to the supraspinatus muscle more easily than to the trapezius muscle. Moreover, image quality was relatively low at 50 Hz compared with that at 75 Hz in both the muscles, which might be ascribed to longer wavelength at 50 Hz that were more difficult to be recognized as propagating shear waves. In addition, the PNRs of both muscles were

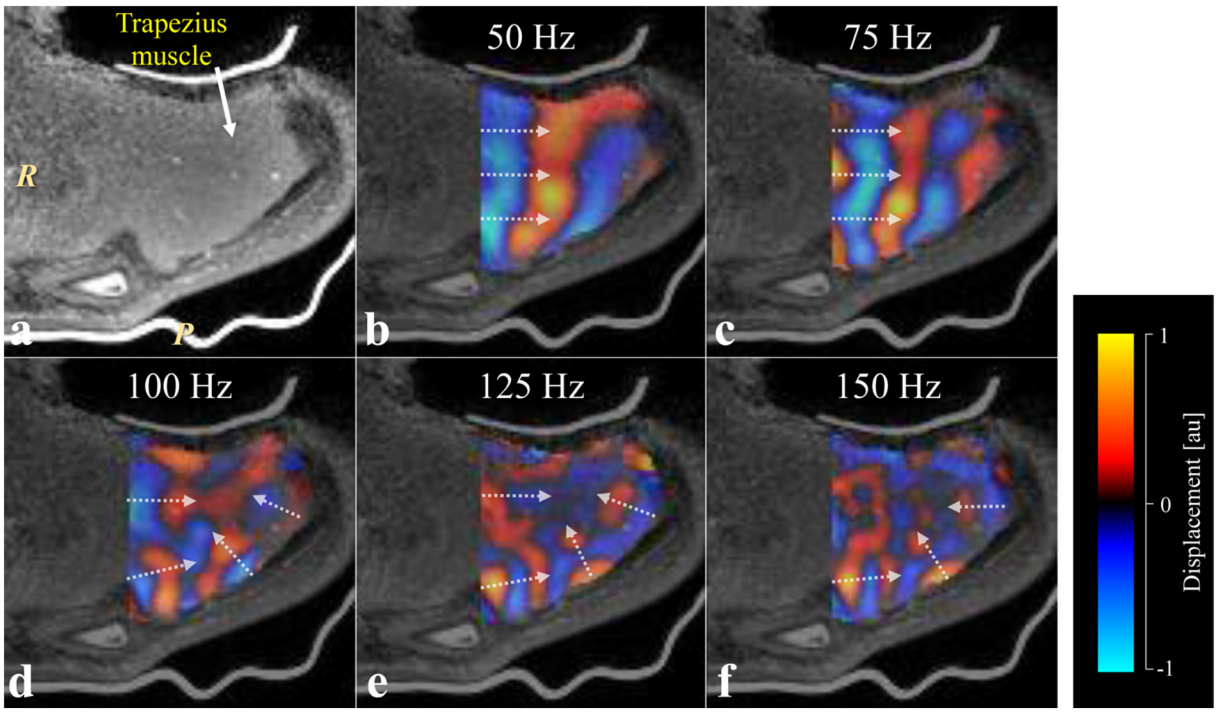

Fig. 7. Images of the trapezius muscle in one volunteer. (a) Magnitude image. (b-f) Wave images at each vibration frequency (50–150 Hz). The white dotted arrows indicate wave propagation direction within the trapezius muscle. P: posterior direction, R: right direction.

Table 2
Mean stiffness values of the supraspinatus and trapezius muscles at each vibration frequency (50–150 Hz).

	Stiffness (kPa)				
	50 Hz	75 Hz	100 Hz	125 Hz	150 Hz
Supraspinatus	2.74 ± 0.29 (n = 3)	4.16 ± 0.50 (n = 5)	5.28 ± 0.75 (n = 5)	6.54 ± 0.63 (n = 5)	7.94 ± 1.08 (n = 5)
Trapezius	6.07 ± 2.02 (n = 4)	7.26 ± 2.13 (n = 5)	7.14 and 12.20 (n = 2)	14.73 (n = 1)	–

Data are presented as mean ± SD.

higher at low frequencies. In this study, the mechanical vibration in each frequency was synchronized with readout gradient lobes to obtain a maximum MEG-like effect. In other words, the δTE was set to the half period of vibration period. Since the δTE becomes slightly shorter at higher frequency when the MEG-like effect is maximum, the echo time of the n-th echo data in each vibration frequency becomes slightly shorter at higher vibration frequency. Those lead to slightly higher SNR at higher frequencies. The present results of larger relative SNR at higher frequencies in the trapezius muscle with no such differences in the supraspinatus muscle might suggest that the transverse relaxation time is shorter in the trapezius muscle than the supraspinatus muscle. On the other hands, the wave amplitudes of both muscles were lower at higher frequencies especially at those > 125 Hz because of lower penetration ability of the vibration. Accordingly, the PNR should be lower at higher frequencies (125–150 Hz) compared with those at 50–100 Hz. Based on clarity of propagating waves and the PNR, optimal vibration frequency may be 75 Hz in MRE of the supraspinatus and trapezius muscles.

It is well known that higher frequency results in shorter wave length, but increases storage modulus and loss modulus [31]. This study also indicated increases in stiffness values in higher frequencies. On the other hand, the mean stiffness values and its standard deviation in the supraspinatus muscle in the present study (a mean value of 5.28 ± 0.75 kPa at 100 Hz in the supraspinatus muscles of 5 volunteers) were smaller than those in our previous study [20] (a mean value of 10.6 ± 3.17 kPa at 100 Hz in the supraspinatus muscles of 7 volunteers). This difference might be ascribed to the difference in the age of subjects and the body position during image acquisition. Gajdosik et al. have reported changes in physical properties of skeletal muscles associated with aging [32]. The small standard deviation of the stiffness in the supraspinatus muscle in the present study might be attributed to a narrow age range (20–23 year) in the present study compared with our previous study (20–42 year). Furthermore, in the present study, we instructed the volunteers to lightly bend the elbow joint by 30° and put the hand on the abdomen so that the position of the upper extremity was kept constant across the volunteers and tension would not be generated in the supraspinatus and trapezius muscles. On the other hand, in our previous study, we instructed the volunteers to relax the muscles during imaging, but did not instruct them to take a specific body position. In some volunteers, hence, weak tension might be generated in the supraspinatus muscle due to a specific position of the shoulder joint, such as external rotation of the upper arm, and then those might lead to changes in the stiffness in the supraspinatus muscle. In the trapezius muscle, a previous study reported that stiffness was about 4.2 kPa at 150 Hz for 4 healthy volunteers [21]. In MRE, stiffness of skeletal muscles varies based on pathological and physiological states, fiber orientation and experimental setups including positioning of muscles and vibration frequencies [33]. Since vibration frequencies (stiffness was not measured at 150 Hz because of unclear wave propagation in this study), stiffness calculation method, imaging planes and body positions (supine or prone) in this study are different from those in the previous study, it is difficult to compare the results between the present and previous studies.

The mean stiffness and standard deviation in the trapezius muscle (7.26 ± 2.13 kPa at 75 Hz) were larger than those in the supraspinatus muscle (4.16 ± 0.50 kPa at 75 Hz). This difference might be ascribed to effects of mechanical neck pain. Mechanical neck pain is defined as pain in the cervical and/or shoulder area with symptoms provoked by neck posture, neck movement, or palpation of the cervical muscles. Neck pain constitutes a significant health care problem affecting 45% to 54% of the general population [34]. Extensive previous studies reported that the trapezius muscle is major causes of neck pains [35–37]. Therefore, stiffness of the trapezius muscle may vary largely even in healthy volunteers.

There are five limitations in the present study. First, we subjectively but not objectively assessed clarity of the wave images. However, the readers were very familiar with the MRE of the skeletal muscles. Moreover, the concordance between the readers was very high, suggesting highly accurate evaluation. Second, wave distortion and attenuation due to wave reflection from the boundaries are not considered. However, effects of distortion on calculation of wavelength may be small if the wave images are clearly recognized as indicated in the data at 75 Hz in this study. Third, a directional filter was not used in this study. Since a directional filter passes the wave propagating in one specific direction, it may be effective for MRE of muscles. In this study, direction of the wave propagation to the supraspinatus and trapezius muscle was different for each subject, because directions of muscle fibers may be different for each subject [20]. Therefore, the best direction in directional filter would be different for each subject, and it is very difficult to set up the best direction in advance. Based on these findings, MRI signals were processed with a normal Gaussian bandpass filter that cuts off both ultralow- and ultrahigh-frequency components (such as random noise, longitudinal waves and bulk motion) instead of directional filters (see Materials and Methods). Fourth, we used a gradient-echo type multi-echo MR sequence in order to conduct the MRE in a conventional MRI. Hence, the echo time, in other words, SNR is slightly different in phase images at each frequency. However, the change in the SNR at each frequency was small in this study. Finally, the number of healthy volunteers (n = 5) was small. Furthermore, only one experimenter performed MRE and 2 readers rated image quality scores. Thus, repeatability and reproducibility of the data were not strictly assessed using multiple experimenters and readers. However, the purpose of this study was to develop the MRE technique of simultaneous acquisition of the supraspinatus and trapezius muscles. Further studies with larger sample size as well as multiple experimenters and readers who perform MRE and rate image quality score are required to determine normal values in the supraspinatus and trapezius muscles of heathy subjects and to evaluate repeatability and reproducibility of the data using the present technique.

5. Conclusion

We demonstrated that our MRE techniques can simultaneously assess stiffness of the supraspinatus and trapezius muscles using a conventional MRI. The vibration frequency of 75 Hz in our technique was suitable to obtain the clear wave images of propagating shear waves in both muscles. This technique may provide a new technical means to detect rotator cuff abnormalities.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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