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Ability of Magnetic Resonance Elastography to Assess Taut Bands

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Abstract

Background—Myofascial taut bands are central to diagnosis of myofascial pain. Despite their importance, we still lack either a laboratory test or imaging technique capable of objectively confirming either their nature or location. This study explores the ability of magnetic resonance elastography to localize and investigate the mechanical properties of myofascial taut bands on the basis of their effects on shear wave propagation.

Methods—This study was conducted in three phases. The first involved the imaging of taut bands in gel phantoms, the second a finite element modeling of the phantom experiment, and the third a preliminary evaluation involving eight human subjects—four of whom had, and four of whom did not have myofascial pain. Experiments were performed with a 1.5 Tesla magnetic resonance imaging scanner. Shear wave propagation was imaged and shear stiffness was reconstructed using matched filtering stiffness inversion algorithms.

Findings—The gel phantom imaging and finite element calculation experiments supported our hypothesis that taut bands can be imaged based on its outstanding shear stiffness. The preliminary human study showed a statistically significant 50–100% ($p=0.01$) increase of shear stiffness in the taut band regions of the involved subjects relative to that of the controls or in nearby uninvolved muscle.

Interpretation—This study suggests that magnetic resonance elastography may have a potential for objectively characterizing myofascial taut bands that have been up to now detectable only by the clinician's fingers.

Keywords

Magnetic Resonance Elastography; Myofascial Pain; Wave Propagation; Finite Element Modeling

Introduction

Myofascial pain is estimated to affect as many as nine million people in the United States (Alvarez and Rockwell; 2002, Gerwin; 2001). The characteristics of the syndrome, however, remain highly debated as its hallmark findings of taut bands (localized areas of increased muscle tone and tenderness) and trigger points (smaller areas of increased tenderness within

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the bands that produce referred pain on pressure) depend on the examiner's clinical skills for identification. The identification of taut bands and trigger points was not only important for diagnosis, but also potential treatment (Graboski; 2005). The upper trapezius is accepted as one the most frequent locations of these findings (Alvarez and Rockwell; 2002, Simons; 1993, Simons; 2004). However, what else is known is limited. Taut bands are currently thought to represent is a discrete group of muscle fibers that have contracted for unknown reasons. The nature of trigger points remains even less established as they have proven even more elusive and difficult to quantitate (Wheeler; 2004).

This situation is compounded by the fact that, with the exception of some progress with the quantification of pain, there are no laboratory tests or imaging techniques capable of identifying or characterizing the nature of these phenomena. In addition, clinical examinations themselves (Simons; 2004) are flawed by a high subjectively and poor inter-examiner reliability (Alvarez and Rockwell; 2002, Hsieh, et al.; 2000, Lew, et al.; 1997, Nice, et al.; 1993, Nioo and Van der Does; 1994, Wolfe, et al.; 1992).

Magnetic resonance elastography (MRE) is a non-invasive MR-based phase contrast imaging technique that applies an oscillating motion sensitizing gradient to detect tissue vibratory displacements that have been introduced into a tissue by an external source of shear vibration (Muthupillai, et al.; 1995). The displacement data is then used to reconstruct the stiffness of the material being study via inversion algorithms (Manduca, et al.; 2001, Sack, et al.; 2002) that utilize the fact that shear waves travel more rapidly (and hence display a longer wavelength) in stiffer than softer tissues. Initial efforts were devoted to the application of the approach to soft tissues such as the breast (Muthupillai, et al.; 1995, Plewes, et al.; 2000, Sinkus et al.; 2000; McKnight et al.; 2002). More recent work has begun to assess its utility in the study of skeletal muscles in the upper and lower extremities (Heers, et al.; 2003, Basford, et al.; 2002, Sack, et al.; 2002, Uffmann, et al.; 2004, Bensamoun, et al.; 2005, Bensamoun, et al.; 2007).

In summery, myofascial taut band is considered a contracted or shortened muscle fiber band with increased muscle tone. Critics remain on the repeatability and subjectivity of palpation examination of myofascial taut band. MRE may offer an ideal solution to this problem because of its ability to objectively differentiate tissue stiffness. We envision that myofascial taut band, because of its higher stiffness compared to the surrounding muscle fiber bundles, would result in longer wavelength and hence chevron-shaped wave fronts. In the present study we examine the validity of the above ideas using computer simulation, gel phantom experiment, and MRE experiments on upper trapezius of patients with myofascial pain. In the computer simulation, finite element method was utilized to model wave propagation in an elastic solid with a taut band inclusion embedded in the middle. Wave propagation predicted by this finite element model was then validated by MRE experiment on a bovine gel phantom. Results from the finite element modeling and the gel phantom MRE experiment served as a proof of concept of the chevron-shaped wave front formation due to the presence of taut band. In the MRE experiments on human subjects, MRE phase images as well as stiffness images of patients with myofascial pain were compared to those of healthy subject. In our previous study, observation of the chevron-shaped shear wave front in the MRE phase image of the upper trapezius of one myofascial pain patient was reported (Chen et al.; 2007). This paper extends that work by presenting stiffness image using stiffness inversion, increasing the sample size, statistical analysis, and providing much more technical details in finite element modeling and gel phantom experiment for validation.

Methods

Magnetic Resonance Elastography on Bovine Gel Phantom

Taut band gel phantoms consisted of a 4-cm central region of stiffer 18 % (weight/volume) bovine gel bounded on its sides by contiguous 5-cm widths of softer 8% gel. The phantoms were contained in a previously described 30 cm long $\times$ 7 cm deep $\times$ 14 cm deep custom-made acrylic mold with the long axis of the taut band parallel to that of the mold (Chen, et al; 2007).

Imaging was conducted in a 1.5T scanner (Signa, General Electric, Fairfield, CT, USA). An electromechanical driver phase-coupled with oscillating the motion sensitizing gradient was placed at one end of the phantom and introduced shear waves into the gel by tapping in its surface with a bar-like applicator. The gel was tested at excitation frequencies of 250 Hz. A single slice sequence was used with a flip angle of 60° , a 24×24 cm field of view with a 256×256 resolution. The TR was 100 ms and the TE corresponded to the minimum spin echo time allowing for motion encoding at 250 Hz (Ringleb, et al.; 2005). Eight offsets of two-dimensional MRE phase image data were collected in z-motion sensitization direction (i.e., the direction of vibratory displacements).

Two standard pre-processing techniques, phase unwrapping (Manduca, et al.; 2001) and directional filtering (Manduca, et al.; 2003) were applied to each MRE phase image. Tissue stiffness was reconstructed from the pre-processed images by an in-house developed program (MREVIEW) using matched filtering technique (Oliphant, et al.; 2001) that uses an adaptive smoothed matched filter and its second derivative to solve a Helmholtz wave equation. After the tissue shear stiffness image was obtained, mean and standard deviation of stiffness in the region of interest were calculated.

Finite Element Modeling

The mechanical properties of the bovine taut band gel phantom were simulated by a $14 \times 30 \times 7$ cm deep rectangular prism model generated with ABAQUS Standard 6.4-1. The bottom surface of the prism was constrained in the vertical direction and eight-node linear brick elements (C3D8) were used uniformly throughout the model. Element dimensions were $2 \times 2 \times 2$ mm and the prism was modeled as isotropic elastic solid with Poisson's ratio $\nu=0.495$ (i.e., almost incompressible). The shear modulus of a 40-mm central channel was defined as 50KPa and that of its two laterals as 15KPa. Material damping was assumed to be zero. This is primarily because the current stiffness inversion algorithms available to the team assume no material damping in the object. A uniform sinusoidal vibration at 250 Hz was applied to one edge of the model to generate shear waves propagating along the axis of the central channel. A transient dynamic analysis procedure with direct integration method (Chen, et al.; 2005) was used to simulate the shear wave propagation in the model. The time increment in the dynamic analysis was set as 4×10^{-4} seconds in order to sufficiently catch the wave motion during a cycle. Nodal vibratory displacements were extracted at the same level as that in the gel phantom experiment and were displayed using a customer written MATLAB program. Phase image pre-processing and stiffness inversion were performed in the same as in the gel phantom MRE.

Magnetic Resonance Elastography on Human Subjects

This study was approved by our institutional review board and involved four women with (age 44.7 ± 10.5) and four without (age 28 ± 7.5) myofascial pain. Subjects with myofascial pain were examined by a physician experienced in the diagnosis and treatment of condition who palpated and traced the locations of their taut bands before undergoing MRE examination.

MRE imaging was performed in a manner similar to that previously reported (Bensamoun, et al.; 2005, Chen, et al.; 2007). The volunteers lay prone in the 1.5T MRI machine. A custom-made pneumatic driver was phase-coupled with an oscillating motion sensitizing gradient and generated the mechanical shear waves needed for MRE observations. The pneumatic driver was composed of a remote pressure driver made of a large active loudspeaker, a Plexiglas pressure chamber, and 25 mm inner diameter Tygon® tubing to connect the pressure chamber to the loudspeaker. The pressure chamber was 20 mm in height and 67 mm in diameter. A 0.25 mm-thick Lexan® film covered the surface of the pressure chamber and an acrylic bar-like vibrator in the dimensions of 6 (width) × 83 (length) × 22 (height) mm was rigidly adhered to the film and placed over the skin. The chamber was fixed to a custom made positioning jig via a ball joint with adjustable height to allow for flexible orientation. A 7-inch diameter surface coil (Midwest RF, Hartland, WI, USA) was placed over the right upper trapezius. Shear waves were generated by the pneumatic driver that was positioned over the mid-portion of the spine of scapula, perpendicular to the gross muscle fiber direction in upper trapezius. Eight offsets of MRE phase image data were collected in z- motion sensitization direction. Total testing sessions, including subject set up, scout scanning, and MRE imaging required about an hour. After the MRE phase images were acquired, a region of interest was selected and shear stiffness distribution in the region of interest was reconstructed using matched filtering (Oliphant, et al.; 2001).

Mean stiffness value in the stiffness images of each healthy subject was calculated. Mean stiffness value in the taut band region, if any, was obtained. Mean stiffness value in the left and right side surrounding normal tissue was also obtained. A paired t-test of the means for the taut band region versus the surrounding normal tissue of the patients with myofascial pain was performed. A two-sample t-test of the means assuming unequal variances for the taut band region in the patients with myofascial pain versus the tissue in healthy controls was performed. For both statistical analyses, $P < 0.05$ was considered significant difference.

Results

Magnetic Resonance Elastography on Bovine Gel Phantom

MRE phase images of the bovine gel phantoms revealed chevron-shaped wave pattern in the region of the stiffer bovine gel (Figure 1a) suggesting higher wave velocity in the central section than the two lateral sections (Chen, et al.; 2007). This is in sharp comparison to the previously reported planar wave fronts in a homogenous gel phantom caused by a bar-like vibration driver (Ringleb, et al.; 2005). Stiffness Results of matched filtering stiffness inversion in the region of interest showed 51.0 ± 3.7 KPa for the central section and 17.4 ± 3.6 KPa and 18.6 ± 2.3 KPa for the two lateral sections, respectively (Figure 1b).

Finite Element Simulation

Simulated wave fronts in the finite element model revealed a chevron-shaped pattern of waveform (Figure 2a), suggesting higher wave velocity in the region of taut band than the lateral matrices. This was consistent with the chevron-shaped wave pattern observed in the gel phantom MRE experiment. In contrast, results of homogeneous finite element model showed planar wave fronts. Matched filtering inversion results in the region of interest showed shear modulus of 36.3 ± 3.7 KPa for the taut band region, and 13.1 ± 4.8 KPa and 13.1 ± 5.9 KPa for the two lateral matrix regions, respectively (Figure 2b).

Magnetic Resonance Elastography on Human Subjects

Wave fronts in MRE wave image of patients with myofascial pain revealed a chevron-shaped pattern (Figure 3a). Locations of the chevron-shapes are in general coincident with the marked location of taut bands, as opposed to the planar wave front region in the surrounding muscle

tissue. This again suggested faster wave propagation in the taut band than surrounding muscle tissues. Since tissue density is assumed constant throughout the trapezius muscle, faster wave propagation in a region indicates higher stiffness of that area. MRE phase images of all healthy volunteers showed planar wave fronts (Figure 3b). Reconstructed shear stiffness values in the regions of interest of healthy volunteers were shown in Table 1.

Consistently, reconstructed shear stiffness images of the patients with myofascial pain showed that the region where chevron-shaped wave front was observed had significant higher stiffness than the surrounding regions (Table 1), forming a taut band region in the reconstructed stiffness image. In the grey scaled stiffness images the taut band can be visually identified as a band-like region with outstanding brightness, indicating outstanding stiffness (Figure 4a). Paired t-test of the means for the taut band region versus surrounding tissue indicated significant difference ($p=0.014$). In contrast, reconstructed stiffness images of the healthy volunteers showed uniformly distributed shear stiffness (Figure 4b). The two-sample t-test of the means for the taut band region in patients with myofascial pain versus normal tissue in healthy subjects showed significant difference, too ($p=0.04$).

Discussion

Existence of myofascial taut bands and trigger points was controversial, mostly because no laboratory method or imaging technique was able to directly visualize or prove the existence of the myofascial taut bands or trigger points. The goal of this study was to assess the potential of MR Elastography to detect and quantify the nature of myofascial taut bands. Our findings are encouraging. First, as a proof of concept, finite element simulation of shear wave propagation in a taut band embedded elastic composite material revealed the presence of chevron-like wave fronts under a bar-like vibrator. Such chevron-like wave fronts were then confirmed by a gel phantom experiment. Further more, stiffness inversion of the gel phantom did indicate significantly higher shear stiffness in the taut band than the matrix. In contrast, planar wave fronts and homogenous stiffness distribution were observed in homogenous finite element model as well as homogenous gel phantom. Finally, MRE examinations on upper trapezius of myofascial pain patients were conducted. Results showed: (1) chevron-shaped wave fronts in a band region, as anticipated by the proof-of-concept finite element modeling and gel phantom MRE experiment; and (2) significantly higher stiffness in the band region than its surrounding muscle tissues ($p=0.014$) as well as the normal tissue in healthy controls ($p=0.04$); and (3) locations of the band region grossly match with the myofascial taut band marked by the palpation examination. Due to limited availability of patients with myofascial pain, sample size was small in this pilot study. However, when applying the above mentioned parametric analyses, significant difference was detected.

Not only does MRE examination confirm the existence of myofascial taut band detected by palpation examination, but it also offers several potential advantages over palpation examination in that: (1) MRE scan assesses the stiffness value of myofascial taut band and its surrounding muscle tissues, while palpation examination cannot provide any quantitative information about myofascial taut band. (2) MRE scan has the potential of high repeatability and objectivity, while palpation examination is considered much less so (Alvarez and Rockwell; 2002, Hsieh, et al.; 2000, Lew, et al.; 1997, Nice, et al.; 1993, Nioo and Van der Does; 1994, Wolfe, et al.; 1992).

Matched filtering algorithm, like many other inversion algorithms, assumes elastic isotropic material. Muscle is well known to be anisotropic, usually simplified as transverse isotropy. To overcome this, in the present study we utilized a barlike vibrator as the vibration source. The advantage of doing this is as following: When applying the bar-like vibrator to a healthy subject (i.e., with no presence of myofascial taut band), a large bunch of muscle fibers was affected

instantaneously (Sack, et al.; 2002), resulting in planar wave fronts within the effected region, just as if wave was propagating in an isotropic material. Therefore, the challenge of tissue anisotropy is largely eliminated when performing the matched filtering inversion. By contrast, a point vibration source would lead to elliptical or taped wave fronts even for even healthy subjects (Sack, et al.; 2002, Papazoglou, et al.; 2005), attributed to the muscle anisotropy, making it hard to differentiate the effect of tissue inhomogeneity (e.g., myofascial taut band) from that of tissue anisotropy.

Matched filtering had been previously proven to be a reliable stiffness inversion method (Oliphant, et al; 2001). In the present study, stiffness inversion by matched filtering appeared to underestimate the shear modulus of the taut band mimicking finite element model. This was thought to due to two factors: Firstly, the relatively rough element mesh of the finite element model (2mm×2mm×2mm), causing modest numerical oscillation in the simulated waveform. It is expected that further reducing the element size will lead to smoother displacement filed in the finite element results, and therefore improve the performance of matched filtering. Due to the hardware limitation of our computational resources, further refining of the element mesh was not pursued. Secondly, the current version of matched filtering algorithm, like many other available inversion algorithms, assumes boundary conditions to be infinite media. This assumption inevitably causes certain error when finite boundary conditions are presented, as the case of the gel phantom and finite element model in this study. Nevertheless, results of the stiffness inversion by matched filtering did show significantly higher shear stiffness in the taut band region than the lateral matrices.

In both the finite element simulation and gel phantom experiment, geometry, boundary condition, and physical bonding between taut band and matrix were different from the real conditions in skeletal muscle tissue. It should be noted that in the present study neither the finite element model nor the gel phantom experiment were made in an attempt to simulate the material properties of real skeletal muscles. Instead, they were utilized to simply validate the concept of chevron-shape formation as a result of outstanding stiffness of a taut band “inclusion” as compared to it surrounding tissue matrix. Therefore, although the results do not allow final deduction about the physiology of skeletal muscle tissue, the finite element models and the gel phantom studies may aid in understanding the appearance of experimentally observed shear wave patterns in MR elastography on skeletal muscles (Sack, et al.; 2002).

We believe that in the gel phantom test the central taut band mimicking gel section was physically bonded to the two lateral sections. Had there be no physical bonding, one can image that the wave propagating in the central taut band would be totally isolated from the waves in the lateral matrix gel, forming a sharp “stepwise” wave front instead of the chevron-shaped wave front observed in the present gel phantom study. This indirectly confirms that the two gel concentrations were physically bonded. No additional test was performed to quantify the exact strength of physical bonding between the two gel concentrations in the gel phantom test. However, since the purpose of this gel phantom MRE experiment is a proof-of-concept of chevron-shaped wave front formation in the presence of taut band, the exact degree of bonding does not appear to be an important consideration.

Although no clinical evidence suggests that age difference among the subjects would be a cause of the stiffness differences between the taut band region and the surrounding muscle tissues, the fact that that the myofascial pain patients and the healthy controls were not age matched could be a limitation in the present study. Besides that, further research in the following areas needs to be done towards applying the proposed MRE method a useful diagnostic tool of myofascial pain in clinical routine: (1) An improved determination of the correlation between the localization of myofascial taut bands that are identified by MRE and clinical examination, (2) Thorough intra- and inter- operator repeatability study of MRE scans on upper trapezius

of myofascial pain subjects. (3) Further improvement of the MR Elastography experiment to quantitatively identify myofascial trigger points which was more difficult to isolate.

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Figure 1.

(a) MRE phase image of the bovine gel phantom with taut band, showing chevron-shaped wave fronts. (b) The reconstructed stiffness image of the taut band mimicking gel phantom, showing the central band region with outstanding stiffness, $48.6 \pm 10.8 \text{ KPa}$, versus the two lateral regions, $13.5 \pm 2.0 \text{ KPa}$ and $13.4 \pm 2.1 \text{ KPa}$, respectively.

Figure 2.

(a) Finite element simulation of the wave fronts in bovine gel phantom with taut band. Chevron-shaped wave propagation was observed. (b) The reconstructed stiffness image of the taut band embedded finite element model, showing the central band region with outstanding stiffness, $36.3.6 \pm 3.7$ KPa, versus the two lateral regions, 13.1 ± 4.8 KPa and 13.1 ± 5.9 KPa, respectively.

Figure 3.

(a) Typical MRE phase image of upper trapezius of a patient with myofascial pain superimposed to the MR image of the same subject, showing chevron-shaped wave fronts under the band-like vibration.

- I.** Spine of Scapula
- II.** MRE phase image with chevron-shaped wave fronts observed in the region of taut band palpated by the physician.
- III.** Myofascial taut band identified by the palpation examination.
- IV.** Cervical Spine

(b) Typical MRE phase image of upper trapezius of a healthy human subject superimposed to the MR image of the same subject, showing planar wave propagation under the band-like vibration.

- I.** Spine of Scapula
- II.** MRE phase image with planar wave fronts observed in the upper trapezius.
- III.** Cervical Spine

Figure 4.

(a) Typical MRE stiffness image of upper trapezius of a patient with myofascial pain superimposed to the MR image of the same subject, showing a significantly stiffer taut band region in the upper trapezius. The dashed line indicates the location of myofascial taut band in that subject marked by palpation examination.

- I.** Spine of Scapula
- II.** Taut Band Region
- III.** Myofascial taut band identified by the palpation examination.
- IV.** Cervical Spine

(b) Typical MRE stiffness image of upper trapezius of a healthy human subject superimposed to the MR image of the same subject, showing uniformly distributed shear stiffness.

- I.** Spine of Scapula
- II.** Upper Trapezius
- III.** Cervical Spine

Table 1

Reconstructed shear stiffness in various regions in upper trapezius of the patients with myofascial pain, showing significantly higher mean stiffness values in taut band region than its surrounding muscle tissues. Values of standard deviation were shown in the parenthesis. Stiffness values of all healthy volunteers were also listed for comparison.

Healthy Volunteers Mean stiffness and standard deviation (Kpa)	patients with myofascial pain		
	Mean stiffness and standard deviation (Kpa)		
	Left Side Surrounding (normal tissue)	Taut Band Region	Right Side Surrounding (normal tissue)
4.1 (0.6)	3.5 (0.27)	6.0 (0.85)	3.9 (0.18)
4.4 (0.78)	5.6 (0.82)	10.9 (1.24)	5.9 (0.74)
4.9 (0.71)	6.1 (0.69)	9.6 (0.29)	5.8 (0.7)
3.3 (0.42)	4.7 (0.63)	7.1 (0.82)	4.5 (0.65)