Vibration Imaging for Functional Analysis of Flexor Muscle Compartments

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Introduction: The multitendoned forearm muscles that control the flexion of the interphalangeal joints, such as the flexor digitorum profundus (FDP), do not possess anatomically distinct compartments separated by fascicular boundaries specific for each finger (1). However, highly individuated and independent finger movements are possible due to selective activation of functional compartments within each muscle (2) that can be imaged with exercise-enhanced MRI (2). The localization of these compartments is critical for MR spectroscopy, electromyography or biopsy of the forearm musculature, and for the treatment of certain diseases like focal dystonia of the hand (3). Magnetic Resonance Elastography (MRE, 4) is a technique that maps the stiffness of tissues by imaging mechanical wave propagation in tissues due to externally induced vibrations. We hypothesized that since individual fingers are mechanically continuous with these forearm muscles' functional compartments through finger specific tendons, functional mapping and analysis of these muscles could be done by vibrating the fingers individually and measuring the resulting motion in these muscles. Here, we report the results obtained from experiments designed to test this hypothesis in normal human volunteers.

Materials and Methods: A 1.5-T whole-body scanner (GE Signa, Milwaukee, WI) was used in all of these experiments. The experiments were performed in accordance with the Mayo Clinic IRB and informed consent was obtained from all volunteers. To produce the selective vibration of individual fingers, the single-channel pressure-activated MRE driver system used in liver MRE (5) was modified to have four channels with small passive drivers as shown in figure 1a. The supply lines for each driver could be opened and closed independently of the others using the clamps in the middle of fig. 1a to vibrate individual fingers. The 60-Hz motion supplied to these passive drivers was created by an audio speaker kept outside the MR scan room that was connected to the passive drivers by a long plastic tube.. An axial slice of the forearm, whose location is shown in fig. 1b with respect to the deep-layer musculature of the forearm from Gray's anatomy, was selected as the imaging plane. A gradient echo MRE pulse sequence was used to encode the through-plane motion of the tissue into the phase of the MR images using a single 16.7-ms motion-encoding gradient pair. Other imaging parameters were FOV = 12 cm, acquisition matrix = 256x64, frequency-encoding direction = LR TR/TE = 100/26 ms, 4 phase offsets and slice thickness = 5 mm. Once the images were acquired, the amplitude of first harmonic of the four phase offsets was calculated using a Fourier transformation.

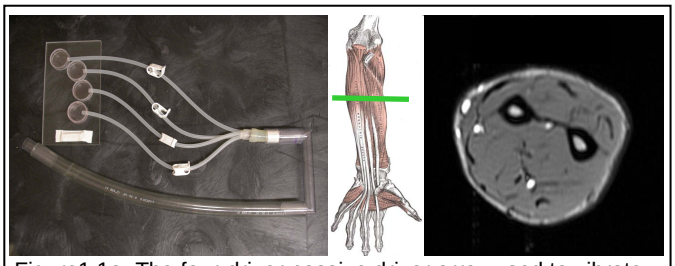

Figure1:1a. The four-driver passive driver array used to vibrate each finger individually. 1b. Anatomy of the forearm with the imaging slice indicated. 1c. MR magnitude image of the slice.

Results and Discussion: Figure 1c shows a conventional magnitude image of the cross section of the forearm. In this orientation, the lower portion of the image includes the flexor muscles flexor digitorum profundus and flexor digitorum superficialis (FDS) and the upper part, separated from the flexor region by the two bones (radius and ulna), includes the extensor muscles. Figure 2 shows the first-harmonic amplitude maps when digits 2-5 (the index, middle, ring and little fingers, respectively) were individually vibrated. It is evident from these images that spatially distinct and well-localized regions within the flexor muscles show maximal motion amplitude demonstrating the functional compartmentalization of these muscles. There are two core regions of high-amplitude motion for each of the fingers, representing the deep and superficial flexor muscle groups. It can also be seen that in addition to these core regions for each finger, compartments that primarily move adjacent fingers also had some low-amplitude motion suggesting an incomplete functional subdivision of these muscles, which agrees with the literature (6). The involvement of the extensor muscles is also noticeable from the individual finger motion amplitude maps, and similar to the flexor compartments, the extensor functional compartments are also spatially well localized. The displacement data show that the motion of the flexors are exactly opposite in phase to the extensor motion, as would be expected. Figure 3 shows a color-coded functional compartment map of the individual fingers (yellow: index; green: middle; blue: ring and orange: little finger) activated by the FDP and FDS obtained from the first-harmonic amplitude maps overlaid on the anatomy image of the forearm.

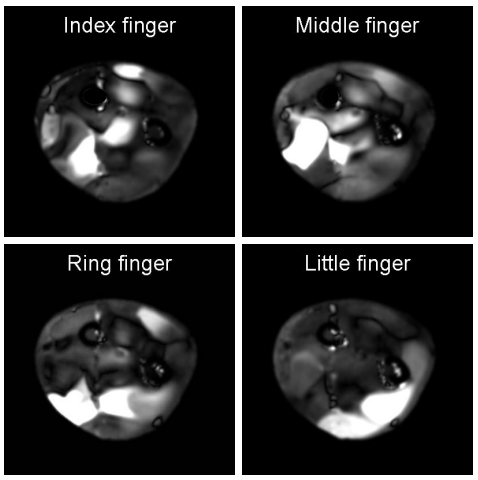

Figure 2: First-harmonic amplitude maps for the four fingers as indicated.

Conclusion: These results support our hypothesis that the functional compartments of the multitendoned forearm muscles can be analyzed using "Vibration Imaging" by vibrating individual fingers and imaging the resulting motion within the muscles. This technique could be useful for the localization of functional compartments applicable for studies involving MRS, electromyography etc. that are widely applied in exercise physiology. Future studies with this technique could quantify the relative amplitude of motions in the various muscles which could be useful in studying the pathophysiology of abnormal digit function (7) or as a surrogate marker for the diagnosis of carpal tunnel syndrome.

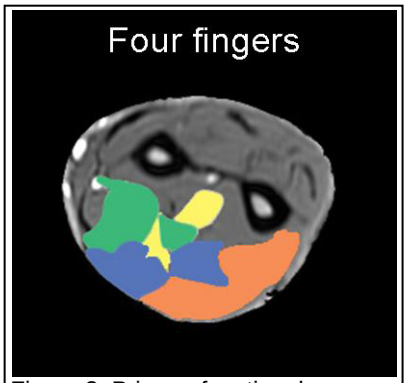

Figure 3: Primary functional compartments of the flexor muscles (yellow: index; green: middle; blue : ring and orange: little finger)

References:(1)Bhadra et al. J Hand Surg 24 :700-703,1999. (2) Fleckenstein et al., J Appl Physiol 72 :1974-1977,1992. (3) Bickerton et al., Muscle and Nerve 20 : 1041-1043, 1997. (4) Muthupillai et al., *Science* 269: 1854-1857, 1995. (5) Yin et al., Clin Gastroenterol Hepatol 5:1207-1213, 2007. (6) Reily et al., J Neuro Physiol 90:2560-2570, 2003. (7) Li et al., Motor Control 8: 1-15,2004.