Non-Invasive in vivo Measurements of Inertial Forces in Muscle using Phase Contrast Magnetic Resonance Imaging

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Target Audience: Clinicians and biomechanics researchers interested in dynamic imaging of muscle and the derivation of muscle force.

Purpose: Two-dimensional (2D) phase contrast (PC) MRI is useful for imaging muscle motion, as it allows for the acquisition of both anatomic and functional information. Previous studies on muscle velocity imaging have focused on the ability of 2D PC MRI to provide information for biomechanical models, which are in turn useful for pre-surgical planning[1]. Muscle velocities derived from PC MRI may provide a means of computing relevant biomechanical parameters, such as muscle forces. Additionally, quantification of muscle velocities and forces may provide useful diagnostic information on functional muscle deficits or focal areas of muscle hypokinesia, as in patients with neuromuscular disorders, muscle trauma, or muscle denervation.

The muscle force during motion may be thought of as a combination of active applied forces and inertial forces, which are due to the mass of the muscle itself during motion. The magnitude of inertial forces is often assumed to be negligible in biomechanical models, although this has never been demonstrated experimentally. The purpose of this study was to create and evaluate a novel tool for computing and analyzing muscle forces derived from 2D PC MRI. We hypothesized that a standard 2D PC MRI technique would provide a robust platform from which muscle forces could be derived, and we also hypothesized that this tool would measure inertial rather than applied forces.

Methods: The forearms of four healthy volunteers and lower legs of six healthy volunteers were imaged with a 2D PC MRI technique optimized for skeletal muscle motion. Images were acquired axially with through-plane velocity encoding on a 3T MR scanner; imaging parameters included: TR/TE/flip angle = 18.0 ms/7.1 ms/20°, pixel BW = 122.1 Hz, FOV = 14 cm (arm) or 26 cm (leg), slice thickness = 6 mm, 256 x 256 matrix, and velocity encoding of 10 cm/s (arm) or 40 cm/s (leg); view-sharing was employed to reconstruct to 32 time frames. During the <3min acquisition, subjects performed wrist flexion or ankle plantarflexion at 1Hz while holding a tension band for resistance; motion was coordinated with the use of a metronome. Gating for the 2D PC acquisition was performed via an ECG waveform generator matched to the metronome at 1 Hz. A fat-water separation data set (IDEAL ([Iterative Decomposition of water and fat with Echo Asymmetry and Least squares estimation][2]) was used to compute a density map at the same slice locations as the 2D PC images. Imaging parameters included: TR/TE/flip angle = 6.0 ms/3.0 ms/30°, pixel BW = 976.6 Hz, FOV = 14 cm (arm) or 26 cm (leg), slice thickness = 6 mm, and 256 x 256 matrix. Density was computed via a weighted average of the signal from the fat and water images—assuming tissue density is 1.06 g/ml and fat density is 0.9 g/ml.

A novel analysis tool was created for deriving forces in muscle by first multiplying voxel density (D) and voxel volume (V) to estimate mass (m = D*V). The mass was then multiplied by acceleration (derived from PC MRI velocity waveforms) to compute force (force = mass x acceleration) on a voxel-by-voxel basis. Mean velocities and summed forces in the forearm and lower leg flexors were computed for the peak time point of the flexion phase of the motion cycle. Velocities and forces were averaged across all subjects. Forearm experiments were repeated using tension bands of varying stiffness; velocities and forces were compared using these different tension bands.

Results and Discussion: During the peak contractile phase of a 1 Hz motion cycle, mean velocities in the flexors of the forearm (Figure 1a-c) and lower leg (Figure 1d-f) were 1.94 ± 0.97 cm/s and 5.57 ± 2.72 cm/s, respectively, as averaged across all subjects; the summed forces in the flexors of the forearm and lower leg were 1.9 x 10^{-3} ± 1.3 x 10^{-3} N and 1.1 x 10^{-2} ± 6.1x10^{-3} N, respectively, as averaged across all subjects. Forces were substantially larger in the leg as a function of the larger mass. These results also demonstrate that measured forces in muscle have a low magnitude at velocities corresponding to 1 Hz motion cycles, which indicated we are likely measuring inertial forces rather than the total force generated by the muscle contraction. Velocities and forces in the forearms did not vary significantly despite using various stiffness bands for resistance during the motion cycle. The absence of change in this experiment also supports the hypothesis that inertial, rather than applied, forces are being estimated. Furthermore, velocity-sensitive images demonstrate a range of velocities across the muscle bellies (Figure 1c,f); this distribution of velocities corresponds to variability in the rate of muscle fiber contraction within a cross-section of muscles. Such information may be useful clinically in recognizing focal areas of hypokinesia, in advancing biomechanical models that assume an entire muscle contracts with a single velocity, and for understanding kinematics.
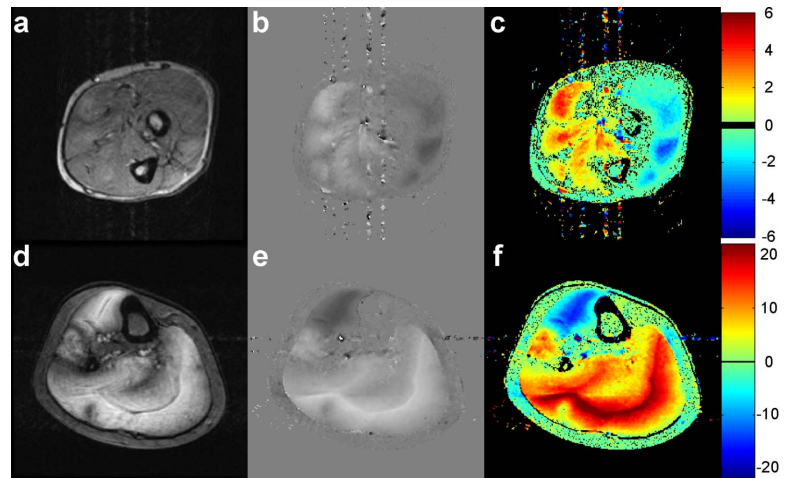
Figure 1. Cross-sectional 2D PC images of a forearm (**a-c**) and lower leg (**d-f**). Magnitude images (**a,d**), super-to-inferior velocity-encoded phase difference images with a magnitude mask (**b,e**), and color maps of the velocity-encoded phase difference images (**c,f**) are shown. Velocities in cm/s.

Conclusion: In this study 2D PC MRI provided a promising means of computing muscle velocities and forces; additionally our technique provides the first known method for quantifying inertial forces. Our analysis technique may be useful in evaluating muscle pathophysiology and further developing biomechanical models. Our results demonstrate that inertial forces are small in relation to applied forces and may be ignored in cases of low load and slow movement. However, an evaluation of inertial forces at greater movement speeds may indicate that inertial forces should be accounted for in models of human motion.

References: [1] Drace JE, Pelc NJ. Measurement of skeletal muscle motion in vivo with phase-contrast MR imaging. J Magn Reson Imaging 1994;4:157-163. [2] Reeder SB, McKenzie CA, Pineda AR, et al. Water-fat separation with IDEAL gradient-echo imaging. J Magn Reson Imaging 2007;25:644-652.