Original Research

Real-Time Imaging of Skeletal Muscle Velocity

Deanna S. Asakawa, PhD,[1] Krishna S. Nayak, PhD,[2] Silvia S. Blemker, MS,[1] Scott L. Delp, PhD,[1,3] John M. Pauly, PhD,[2] Dwight G. Nishimura, PhD,[2] and Garry E. Gold, MD[4]*

Purpose: To test the feasibility of using real-time phase contrast (PC) magnetic resonance imaging (MRI) to track velocities (1–20 cm/second) of skeletal muscle motion.

Materials and Methods: To do this we modified a fast real-time spiral PC pulse sequence to accommodate through-plane velocity encoding in the range of –20 to +20 cm/second. We successfully imaged motion of the biceps brachii and triceps brachii muscles during elbow flexion and extension in seven unimpaired adult subjects using real-time PC MRI.

Results: The velocity data demonstrate that the biceps brachii and the triceps brachii, antagonistic muscles, move in opposite directions during elbow flexion and extension with velocity values in the muscle tissue ranging from –10 to +10 cm/second.

Conclusion: With further development, real-time PC MRI may provide a means to analyze muscle function in individuals with neurologic or movement disorders who cannot actively complete the repeated motions required for dynamic MRI techniques, such as cine PC MRI, that are more commonly used in musculoskeletal biomechanics applications.

Key Words: muscle; real time; MRI; velocity; cine PC; skeletal
J. Magn. Reson. Imaging 2003;18:734–739.

DYNAMIC IMAGING TECHNIQUES, such as cine phase contrast (PC) magnetic resonance imaging (MRI), have made it possible to study muscle, tendon, and bone motion in living human subjects (1–4). Cine PC MRI provides, for example, one anatomical image and three directions of velocity images for each time frame of the motion cycle. However, standard cine PC MRI sequences require multiple cycles of gated motion; typically 60–120 repetitions are needed to acquire composite images representing one motion cycle. The requirement of many motion cycles creates three problems. First, the quality of the images degrades dramatically if the motion cycles are not repeated accurately. Second, only low loads (less than approximately 15% of maximum voluntary contraction force) can be studied due to fatigue. Third, subjects with musculoskeletal or neurologic diseases who cannot complete a large number of repeated motions cannot be studied with cine PC MRI techniques unless the investigator moves the limb passively. This limits the use of cine PC MRI for musculoskeletal applications.

Advances in MR have allowed real-time imaging of cardiac blood flow (5–8). These real-time MRI techniques were developed to image the high velocities (on the order of 100–200 cm/second) of cardiac blood flow. Skeletal muscle velocities are typically much lower, in the range of 2–20 cm/second. Measuring low velocities with PC techniques presents a challenge for rapid imaging as larger motion encoding gradient waveforms are needed for slower tissue velocities (9,10).

The purpose of this study was to demonstrate the feasibility of using real-time PC MRI to image the slower velocities (2–20 cm/second) that are more typical of skeletal muscle motion. To accomplish this we used a fast spiral real-time PC technique to image the biceps brachii (an elbow flexor) and triceps brachii (an elbow extensor) muscles. We defined proof of feasibility as all muscle tissue within the imaging plane having reasonable direction and magnitude of velocities. We expected the muscles to move in the direction indicated by their moment arm during joint motion (e.g., elbow flexors move superiorly and elbow extensors move inferiorly during elbow flexion). To determine if the magnitudes of velocities measured with real-time PC MRI were reasonable, we compared the velocities to those measured with cine PC MRI in the same subjects.

Real-time PC MRI is a new method to analyze skeletal muscle contraction. Because this technique can image

[1]Department of Mechanical Engineering, Stanford University, Stanford, California.
[2]Department of Electrical Engineering, Stanford University, Stanford, California.
[3]Department of Bioengineering, Stanford University, Stanford, California.
[4]Department of Radiology, Stanford University, Stanford, California.
Contract grant sponsor: National Institutes of Health; Contract grant numbers: HD38962, HL-39297, T32 GM63495; Contract grant sponsor: GE Medical Systems; Contract grant sponsor: Whitaker Foundation; Contract grant sponsor: National Science Foundation; Contract grant sponsor: American Association of University Women.
Presented in a podium presentation at the 9th Annual Meeting of ISMRM, Glascow, Scotland, 2001.
*Address reprint requests to: G.G., Packard Electrical Engineering Building, Mail Code 9510, Stanford University, Stanford, CA 94305-9510. E-mail: gold@stanford.edu
Received May 15, 2003; Accepted August 21, 2003.
DOI 10.1002/jmri.10422
Published online in Wiley InterScience (www.interscience.wiley.com).

Table 1
Subject Description

Subject	Gender	Age (years)	Height (cm)	MVC[a] (lbs)	Arm length[b] (cm)	Arm circumference[c] (cm)	Range of motion[d] (deg)
1	F	27	152.4	29	28	29	80
2	M	41	167.6	35	29	32	50
3	M	25	167.6	39	30	32	45
4	F	33	165.1	20	31	18	85
5	F	24	160.0	30	31	27	87
6	M	28	167.6	40	30	31	90
7	M	46	180.3	45	33	34	90

[a]Maximum voluntary contraction load with 90° elbow flexion. See text for details.
[b]Arm length measured from the lateral edge of the acromium to the lateral humeral epicondyle.
[c]Arm circumference measured as the maximum with the elbow flexed in weak isometric contraction.
[d]Range of elbow flexion motion measured with a goniometer while subject was within the MR scanner during cine PC imaging. Range of motion was 5–10 degrees less for all subjects during real-time PC image acquisition.

the anatomy and muscle tissue velocities in a single cycle of motion, it may provide improvements over cine PC MRI for the study of muscle function.

MATERIALS AND METHODS

Real-time PC MRI was used to image the muscles of the dominant arm of seven unimpaired adult volunteers (Table 1). We compared velocities measured with real-time PC MRI to velocities measured with cine PC MRI in these same subjects. Cine PC MRI has been demonstrated to have submillimeter accuracy for tracking bone and muscle motion (2,4), and therefore provides a good basis of comparison for the real-time MRI velocity measurements. The Institutional Review Board of Stanford University approved the imaging protocols. Each subject was screened for MRI risk factors and provided informed consent in accordance with institutional policy.

The direction and magnitude of motion within the biceps brachii and triceps brachii were assessed. These muscles were chosen for this study because of their simple muscle geometry and because at least 45° of elbow flexion and extension was achievable within the 55-cm bore of the GE 1.5-T Signa CV/i MR scanner (GE Medical Systems, Milwaukee, WI). A flexible general-purpose radio-frequency surface coil was used to image the arm (Fig. 1). The subject's arm was aligned with the longitudinal axis of the scanner to facilitate selection of the imaging plane and to maximize through-plane motion (the direction of muscle contraction).

During real-time PC imaging subjects performed elbow flexion against the load of gravity. The arm of each subject was imaged as the subject moved the elbow from nearly full elbow extension to 45–90° of elbow flexion at a rate of 35 cycles/minute. A metronome was provided for the subjects to assist them in producing a constant rate of motion. The rate of motion was chosen to facilitate comparison to velocities measured with cine PC MRI data in these same subjects. We used an encoding velocity of 10 cm/second. Images were obtained in the axial plane; velocity was encoded along the arm in the direction of muscle contraction. We recorded several 10-second sets (approximately five motion cycles and 112 frames) of real-time images for each subject.

The fast spiral real-time PC pulse sequence used for this study was created by modifying the color flow sequence described by Nayak et al (7). Real-time MRI continuously acquires interleaved spiral PC data. Velocity maps were computed using standard PC (10). Velocity per pixel was computed from the phase difference between two images acquired with different flow encoding gradients. The real-time measurements used a water-selective spectral-spatial excitation, a 30-msec repetition time (TR), an 18-cm field of view, and a 1-cm slice thickness. We acquired images at a rate of 6 images/second, but sliding window reconstruction was used to achieve a display rate of 12 images/second (8). The velocity maps were displayed on the anatomical image using a color overlay similar to ultrasound (7).

Because large flow encoding gradients are needed to achieve a 10 cm/second velocity encoding, two additional modifications were made to the pulse sequence used for cardiac real-time PC. Both modifications were

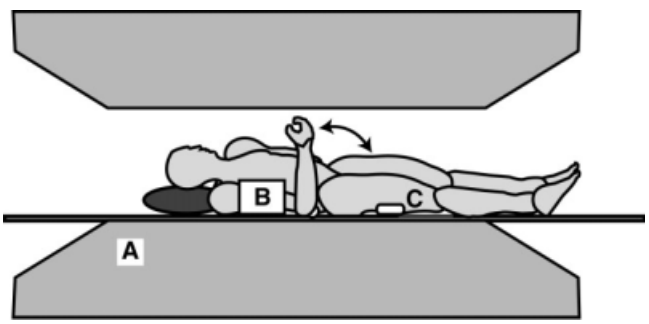

Figure 1. Experimental setup. The subjects were positioned on their side on the table of a 1.5-T GE Signa CV/i MR scanner (**A**) with a flexible radio-frequency surface coil around their dominant arm (**B**). This positioning and radio-frequency coil were used for both the real-time PC and cine PC image data acquisition. The subjects flexed and extended the elbow through at least a 45° range of motion at a rate of 35 cycles/minute against the load of gravity. For cine PC MRI, an optical transducer (**C**) was used to signal the beginning of each motion cycle.

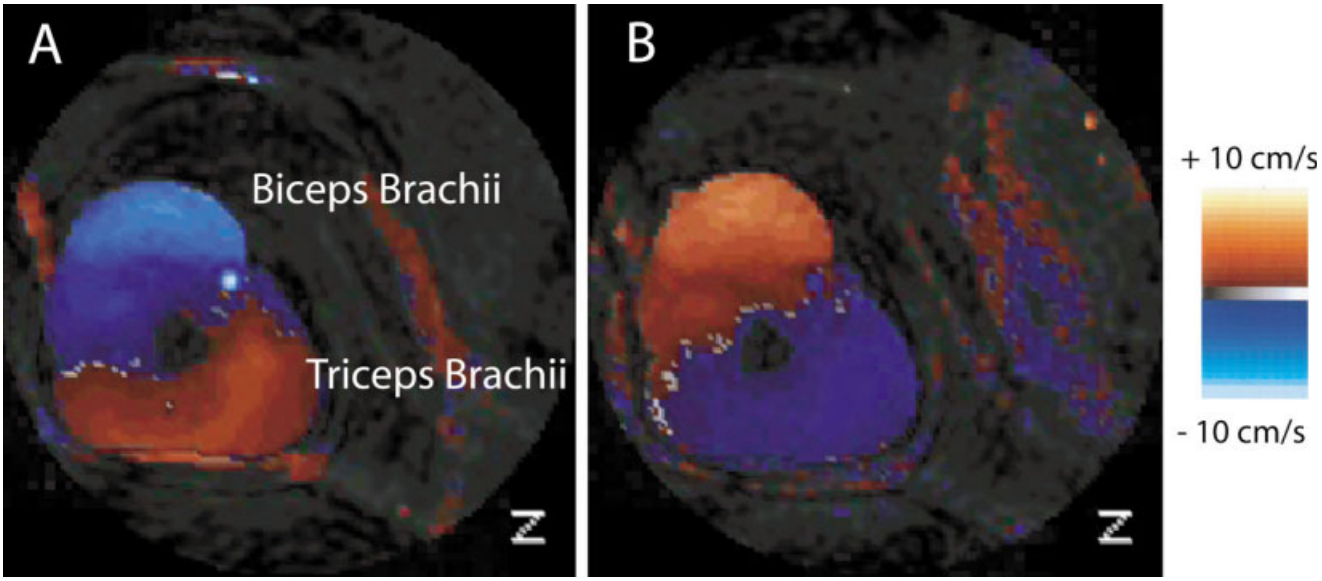

Figure 2. Muscle tissue velocities acquired in real time in the biceps brachii and triceps brachii during elbow flexion and extension against gravity. Field of view is 18 cm. Velocity maps, superimposed on the gray-scale image in red and blue, show the muscles working in opposite directions. The velocity data clearly demonstrate that these antagonistic muscles are moving in opposite directions during the elbow flexion (**A**) and that the velocities are reversed in elbow extension (**B**).

aimed at reducing the effects of concomitant gradients (11). First, we used symmetric velocity encoding, rather than asymmetric velocity encoding. Asymmetric velocity encoding is used to reduce motion artifact in the magnitude images in cardiac real-time PC studies; however, asymmetric velocity encoding resulted in a constant velocity offset due to the long velocity encoding gradients needed for the low skeletal muscle velocities. Therefore, we changed the sequence to use symmetric velocity encoding and calculated the phase difference from two velocity encoded images. Secondly, we found that the real-time PC sequence required a 2-msec delay before beginning the readout gradient to ensure that data acquisition did not occur during eddy current transients from the large flow encoding gradients.

We acquired cine-PC MR images of each subject in a 60-cm bore of a GE 1.5-T Signa CV/i MR scanner (GE Medical Systems, Milwaukee, WI) in a separate imaging session from the real-time PC imaging. Cine PC images were acquired while flexing and extending the elbow against the load of gravity. All cine PC MR images were acquired with a 17-msec repetition time (TR), 30° flip angle, 256 × 128 matrix, and 1-cm slice thickness. An 18 × 18 cm field of view was used for the axial cine PC images. The elbow flexion motion was performed at the rate of 35 cycles/minute with a metronome. Velocities were encoded in three perpendicular directions with a maximum encoding velocity of 20 cm/second. The order and timing of gated two-dimensional Fourier transform PC acquisitions were chosen to avoid velocity underestimation (12) and used product sequences.

MATLAB (The Mathworks, Inc., Natick, MA) software was used to assess the velocities from the gray-scale values of the pixels within the muscle tissue at each frame in the motion cycle for both the real-time PC and cine PC velocity data. A 1 × 1 cm region was prescribed in the center of the biceps cross section on the axial plane velocity images. The average and standard deviation of tissue velocities for the pixels within each region were computed for each time frame. The velocity values from the two different imaging techniques, real-time PC and cine PC, were compared at equivalent intervals throughout the complete elbow flexion-extension motion cycle. We compared the peak tissue velocity measured during elbow flexion using real-time PC MRI to the peak tissue velocity during elbow flexion measuring using cine PC MRI. We also computed real-time PC velocity error throughout a elbow flexion-extension motion cycle as the difference between the real-time PC measured velocity value and the cine PC MRI measured velocity value at each sampled interval. We compared two representative cycles of real-time PC data to the cine PC data for each subject.

RESULTS

We successfully encoded velocities in the biceps brachii and triceps brachii muscle tissue in all subjects using real-time MRI (e.g., Fig. 2). Velocities were encoded throughout the extent of muscle tissue in the imaging plane. The velocity images clearly illustrate the direction of muscle motion; biceps brachii moved superiorly and triceps brachii moved inferiorly with elbow flexion.

Real-time PC MRI measurements of maximum velocity within the biceps brachii ranged among subjects from 2.2–8.5 cm/second during elbow flexion against the load of gravity (Table 2). Maximum velocities measured using cine PC MRI ranged among subjects from 2.1–10.7 cm/second. Subjects with a small range of elbow motion (e.g., subjects 2 and 3) had lower peak biceps brachii velocity than subjects with a larger range of motion. Real-time PC velocity data were collected for at least four cycles of elbow flexion and extension for

Table 2
Biceps Brachii Velocities

Subject	Cine PC peak velocity (cm/second)	Real-time PC peak velocity (cm/second)	Real-time PC average (SD) peak velocity[a] (cm/second)	Difference peaks[b] (%)	Error real-time PC cycle 1 vs. cine-PC		Error real-time PC cycle 2 vs. cine-PC	
					Mean (range) (cm/second)	Mean as % of peak cine PC	Mean (range) (cm/second)	Mean as % of peak cine PC
1	6.1	4.4	3.9 (.4)	28	1.3 (0.0–2.7)	22	1.2 (0.1–3.0)	19
2	3.0	3.2	2.8 (.3)	5	0.8 (0.0–1.4)	26	0.6 (0.2–1.1)	21
3	2.1	2.2	2.2 (.4)	4	0.3 (0.0–1.0)	15	0.3 (0.0–1.0)	13
4	6.8	7.3	7.2 (.6)	8	2.0 (0.3–5.2)	30	2.4 (0.5–4.9)	36
5	6.3	5.6	4.9 (.5)	11	1.0 (0.2–2.4)	17	1.3 (0.0–4.8)	21
6	10.7	8.5	8.3 (.3)	20	3.1 (0.0–6.3)	29	3.1 (0.5–7.1)	29
7	7.2	6.1	5.5 (.4)	15	1.5 (0.0–2.4)	21	1.8 (0.6–3.1)	25

[a]Average of the peak velocity from four cycles of real-time PC data
[b]Percent difference computed as (cine PC peak velocity-real time PC peak velocity)/cine PC peak velocity

each subject (e.g., Fig. 3). There was some difference in peak velocity values among the different cycles; the standard deviation of peak real-time velocity values was less than 0.6 cm/second for all subjects (Table 2). Comparison of peak muscle tissue velocities showed that real-time PC MRI measurements were at most 28% (≈2 cm/second) different than the peak velocities measured with cine PC MRI (Table 2).

The velocities in a region of interest within the biceps brachii measured with real-time PC throughout two different elbow motion cycles were compared to the cine PC MRI data for each subject (Fig. 4). The mean error values varied among the subjects with values between 0.3 and 3.1 cm/second (Table 2). The mean error measurement was at most 36% of the peak cine PC velocity.

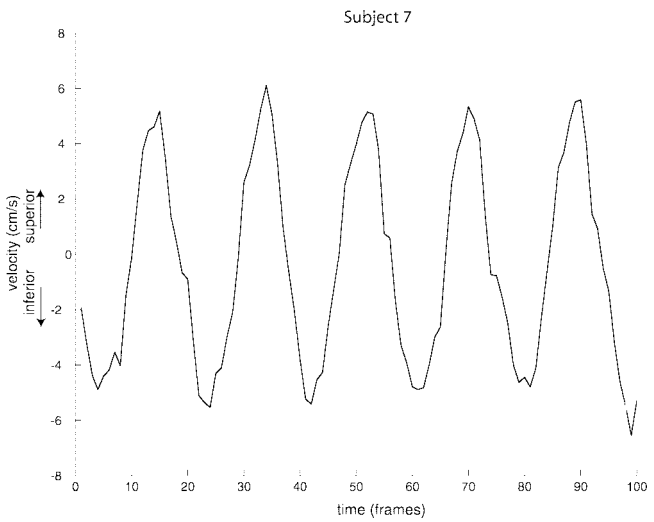

Figure 3. Biceps brachii velocities measured with real-time PC MRI for subject 7 for several cycles of elbow flexion and extension. The average velocity within a region of muscle tissue is plotted for several cycles of elbow flexion and extension. Positive values of velocity indicate superior motion of the biceps brachii during elbow flexion. Negative values of velocity indicate inferior motion of the biceps brachii during elbow extension.

DISCUSSION

This study indicates that real-time PC MRI is a feasible means to acquire in vivo skeletal muscle tissue velocity data during joint motion. The direction of muscle tissue motion during elbow flexion and extension was consistent among all subjects. Muscle velocity data for these subjects demonstrate that preliminary measurements made using the real-time PC imaging technique agree reasonably well with cine PC MR measured velocities with greatly reduced scan times.

Some current limitations of real-time PC MRI warrant mentioning. Certain disadvantages arise due to tradeoffs that are made to achieve such rapid imaging of motion. For example, anatomy images, because they are acquired with spiral k-space trajectories, do not have resolution comparable to images obtained using cine MRI. Also, real-time PC MRI currently encodes velocity in one direction relative to the imaging plane. Resolving velocities in all three directions is possible with real-time PC, but would double the time to acquire each frame of image data. However, in the cine PC data, motion not in the direction of muscle contraction was minimal (<0.5 cm/second) for this elbow flexion-extension task.

When using spiral PC, because the k-space origin is sampled every TR, the effect of low temporal resolution is similar to averaging the velocity over the acquisition window (13). Low temporal resolution can be interpreted therefore as a low-pass filtering of the velocity waveform. The acquisition window was minimized given hardware constraints and spatial resolution requirements. Also, due to the large velocity encoding gradients, this sequence is susceptible to velocity error induced by concomitant gradients. Additional compensation could be performed to reduce these effects (11). The eddy current compensation on our MR scanner was calibrated before data collection for this study began.

Real-time PC MRI measures magnitude and direction of skeletal muscle motion that are comparable to cine PC MRI while offering several advantages over cine PC MRI. This technique can acquire muscle motion data very quickly, and the velocities are not a result of motion averaged over multiple motion cycles. This technique, therefore, could be used to rapidly assess muscle

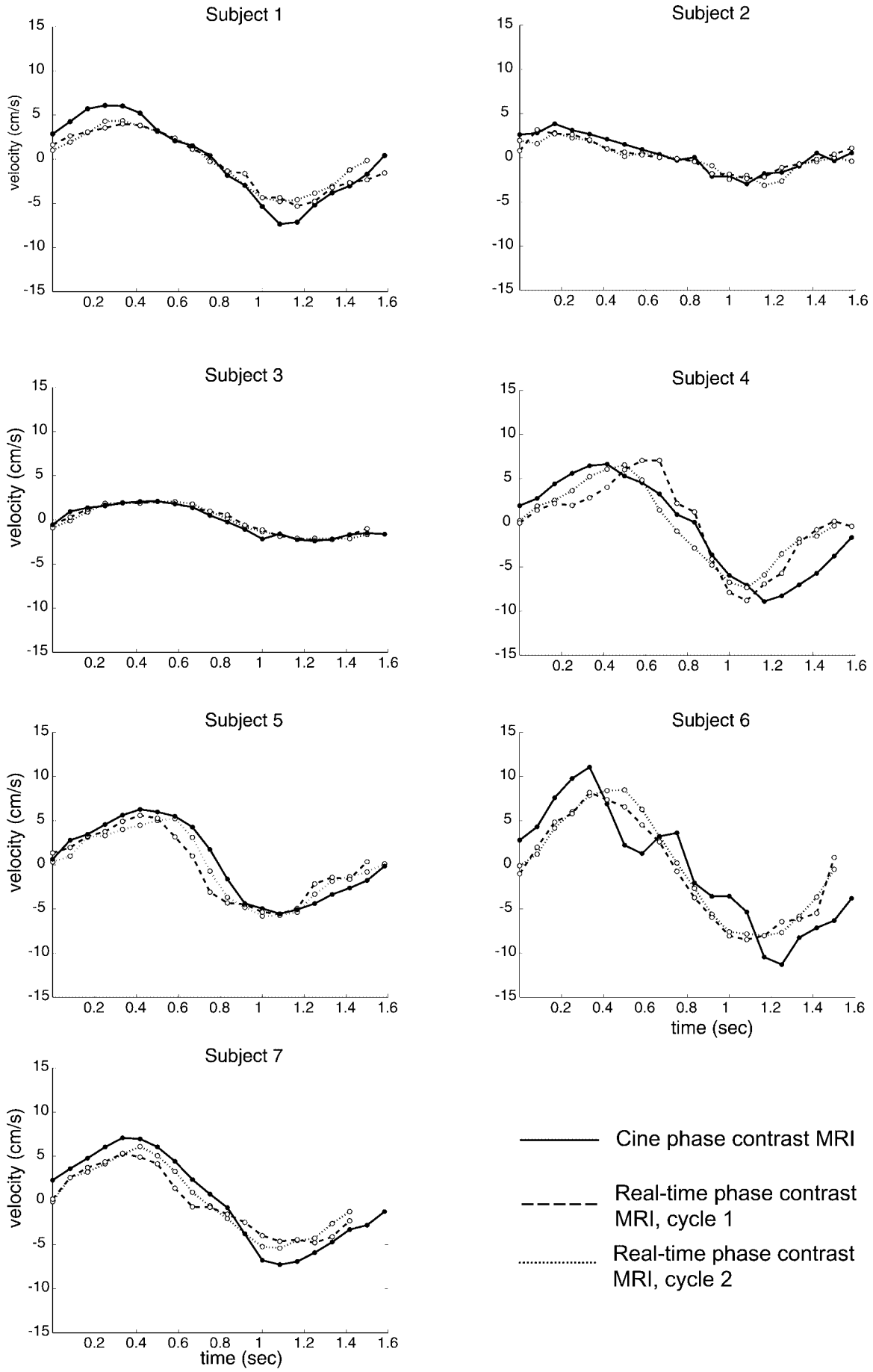

Figure 4. Comparison of real-time PC and cine PC MRI velocity measurements in the biceps brachii muscle for all subjects during elbow flexion and extension. The velocities measured in the biceps brachii muscle with real-time PC MRI (dotted and dashed lines) for two different elbow flexion-extension cycles were compared to cine PC MRI muscle tissue velocity measurements (solid line) for each subject. Positive (negative) values indicate superior motion of the biceps brachii during elbow flexion (extension).

tissue velocities within contracting muscles in several imaging planes or different locations within the muscle. Real-time PC MRI enables the study of muscle contraction under high load levels, cycle-to-cycle differences in muscle tissue velocity, and muscle motion in subjects who have difficulty producing repeatable motion. Ultimately, real-time PC MRI may provide an effective means to analyze muscle function in individuals with movement disorders, such as cerebral palsy, who cannot actively complete the repeated motions required for cine PC MRI.

ACKNOWLEDGMENTS

We thank the Diagnostic Radiology Center, Palo Alto, CA, and the VA Health Care System, Palo Alto, CA.

REFERENCES

1. Asakawa DS, Blemker SS, Gold GE, Delp SL. In vivo motion of the rectus femoris muscle after tendon transfer surgery. J Biomech 2002;35:1029–1037.
2. Drace JE, Pelc NJ. Measurement of skeletal muscle motion in vivo with phase-contrast MR imaging. J Magn Reson Imaging 1994;4: 157–163.
3. Pappas GP, Asakawa DS, Delp SL, Zajac FE, Drace JE. Nonuniform shortening in the biceps brachii during elbow flexion. J Appl Physiol 2002;92:2381–2389.
4. Sheehan FT, Zajac FE, Drace JE. Using cine phase contrast magnetic resonance imaging to non-invasively study in vivo knee dynamics. J Biomech 1998;31:21–26.
5. Holsinger AE, Wright RC, Riederer SJ, Farzaneh F, Grimm RC, Maier JK. Real-time interactive magnetic resonance imaging. Magn Reson Med 1990;14:547–553.
6. Kerr AB, Pauly JM, Hu BS, et al. Real-time interactive MRI on a conventional scanner. Magn Reson Med 1997;38:355–367.
7. Nayak KS, Pauly JM, Kerr AB, Hu BS, Nishimura DG. Real-time color flow MRI. Magn Reson Med 2000;43:251–258.
8. Riederer SJ, Tasciyan T, Farzaneh F, Lee JN, Wright RC, Herfkens RJ. MR fluoroscopy: technical feasibility. Magn Reson Med 1988;8: 1–15.
9. Moran PR. A flow velocity zeugmatographic interlace for NMR imaging in humans. Magn Reson Imaging 1982;1:197–203.
10. Pelc NJ, Herfkens RJ, Shimakawa A, Enzmann DR. Phase contrast cine magnetic resonance imaging. Magn Reson Q 1991;7:229–254.
11. Bernstein MA, Zhou XJ, Polzin JA, et al. Concomitant gradient terms in phase contrast MR: analysis and correction. Magn Reson Med 1998;39:300–308.
12. Frayne R, Rutt BK. Frequency response of prospectively gated phase-contrast MR velocity measurements. J Magn Reson Imaging 1995;5:65–73.
13. Park JB, Olcott EW, Nishimura DG. Rapid measurement of time-averaged blood flow using ungated spiral phase-contrast. Magn Reson Med 2003;49:322–328.