Cine Phase-Contrast Magnetic Resonance Imaging As a Tool for Quantification of Skeletal Muscle Motion

Deanna Schmidt Asakawa,[1] George P. Pappas,[1] Silvia S. Blemker,[1] John E. Drace,[3] and Scott L. Delp[1,2]

ABSTRACT

In recent years, biomechanics researchers have increasingly used dynamic magnetic resonance imaging techniques, such as cine phase contrast (cine PC), to study muscle and bone motion in vivo. Magnetic resonance imaging provides a non-invasive tool to visualize the anatomy and measure musculoskeletal tissue velocities during joint motion. Current application of cine PC magnetic resonance imaging in biomechanics includes study of knee joint kinematics, tendon strain, and skeletal muscle displacement and shortening. This paper article reviews the use of cine PC magnetic resonance imaging for quantification of skeletal muscle motion. The imaging studies presented examine the relative motion of the knee flexor and extensor muscles after orthopedic surgery and examine the uniformity of shortening within the biceps brachii muscle. The current challenges and limitations of using cine PC magnetic resonance imaging in biomechanics research are addressed as well as opportunities for future studies of skeletal muscle motion using dynamic magnetic resonance imaging.

KEYWORDS: Skeletal muscle, biomechanics, cine phase-contrast magnetic resonance imaging

Biomechanics researchers have recently begun to use dynamic magnetic resonance imaging techniques to study in vivo musculoskeletal motion.[1–4] Magnetic resonance imaging (MRI) techniques offer many advantages including the ability to perform quantitative non-invasive orthopedic research in humans. Previous knowledge of skeletal muscle geometry, mechanics, and bone motion was gained primarily from animal studies, cadaver studies, computer modeling, and motion analysis studies. Magnetic resonance imaging methods used for studying bone and muscle during motion include kinematic MRI,[5–7] cine MRI,[8,9] cine phase-contrast (cine PC) MRI,[10] and most recently real-time MRI.[11]

This review is focused on the application of cine PC MRI for the study of skeletal muscle mechanics. Cine PC MRI provides a set of anatomic images and a set of velocity images for each of three directions of tissue velocity.[12] This imaging technique provides a practical way to visualize the anatomy and measure the motion of multiple muscles, or bones, in the human body simultaneously. To date, several types of biomechanics studies have been performed using cine PC MRI including muscle

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motion in the upper and lower limb,[1,3] tendon strain,[13,14] and lower limb joint kinematics.[4,15,16]

Experimental data from dynamic MR imaging studies can be used to test assumptions about skeletal muscle contraction. Insights gained from dynamic imaging studies can improve the understanding of human skeletal muscle contraction in vivo. Also, MR imaging data can be used to test the validity of biomechanical models and to improve the accuracy of representations of muscle-tendon geometry and mechanics. Knowledge of macroscopic motion of skeletal muscle will help bridge the gaps in understanding how contraction of single muscle fibers combine to produce the observed motion of whole muscles. This review provides two examples of how cine PC MR imaging data can be used to explore skeletal muscle mechanics.

CINE PC MRI

Cine phase contrast (cine PC) MRI, a combination of cine MRI and phase-contrast MRI techniques, was developed to image the beating heart and has been adapted for use in imaging musculoskeletal tissue during joint motion.[2,10,17,18] Cine MRI synchronizes MR data acquisition to a motion cycle to enable imaging of moving tissue.[19] Cine MRI collects image data over many cycles of periodic motion and then retrospectively sorts the data into the desired number of time frames to produce a series of anatomic images.[19] Phase contrast MRI allows quantitative measurement of three-dimensional velocity over an entire imaging plane by encoding the velocity of the tissue in the phase of the MR signal.[20,21] Combining cine and phase-contrast MRI results in a technique that can quantitatively measure in vivo tissue anatomy and velocity during dynamic tasks.[12] Cine phase contrast MRI simultaneously acquires sets of images depicting the anatomy and each direction of measured tissue velocity throughout a motion cycle. The tissue velocity is encoded in the grayscale value of each pixel in the velocity images. Tissue velocities are small, on the order of 20 cm/s, for most musculoskeletal motion as compared with velocities on the order of 100 cm/s measured in studies of blood flow.

Acquisition of cine PC data during joint motion presents several practical challenges. To acquire the image data necessary for a set of MR images representing one motion cycle, subjects must complete several cycles of joint motion. To ensure good- quality data, the joint motion needs to be highly repeatable. To address this challenge it is frequently helpful to use a device to guide the motion and to limit undesirable out-of-plane motions of the limb. When external devices are used to guide joint motion, care must be taken to avoid placing unphysiologic forces on the musculoskeletal structure of interest because doing so could alter the motion. In addition to repeatable motion, selection of the imaging plane is crucial to successful quantification of skeletal muscle motion using cine PC MRI. Although, the three-dimensional velocities can be measured with cine PC MRI, large amounts of out-of-plane motion can pose a problem when computing tissue displacements from the velocity data.[22] Selection of the imaging plane needs to be consistent among subjects to ensure comparable results. In addition, the anatomy, architecture (i.e., pennation angle and amount of tendon), and primary direction of motion of the muscle being studied should be well characterized to help with image plane selection and facilitate interpretation of the measured muscle tissue velocities in different areas of the muscle.

VALIDATION OF CINE PC MRI FOR TRACKING MUSCULOSKELTAL MOTION

Drace and Pelc first investigated the feasibility of using cine PC MRI for quantification of musculoskeletal tissue motion.[2,10,17,18] This work demonstrated that cine PC MRI tracks skeletal muscle with a root mean square error of 1 mm[2]. Similarly, a later study verified that cine PC MRI tracks trabecular bone motion with an average absolute error of less than 0.7 mm.[4] Recently, the precision of cine PC MRI with segmented phase encoding (Fast-PC) was determined to be ~1 degree for tracking knee kinematics.[16] These studies have validated the accuracy and precision of cine PC MRI for tracking musculoskeletal tissue.

SKELETAL MUSCLE TISSUE VELOCITIES MEASURED WITH CINE PC MRI

Several fundamental questions in skeletal muscle mechanics can be addressed by measuring the magnitude and direction of muscle tissue velocity with cine PC MRI. For example, muscle velocities can be characterized under both passive and active joint motion, during different load levels, and before and after orthopedic surgery. In addition, the velocity information can be used to compute the displacement of muscle tissue and, consequently, the amount of shortening within the muscle tissue during contraction.

The skeletal muscle tissue velocity (ν) measured using cine PC MR techniques are dependent on the motion of the whole muscle as primarily determined by the joint angular velocity (ω), the distance between the muscle tissue being measured and the myotendinous junction (ℓ), and the muscle moment arm (ma). It is generally assumed that the tendon is inextensible, the maximum velocity of muscle tissue is highest at the myotendinous junction closest to the joint that is moving, and that the velocity decreases linearly along the length of the muscle. That is,

$$v = ma * \omega (1 - \ell / \ell mt),$$

where ℓmt is the length of the muscle-tendon.

MUSCLE MOTION AFTER TENDON TRANSFER SURGERY

The direction of muscle tissue velocity measured with cine PC MRI can be used to test whether a muscle acts to flex or extend a joint (Fig. 1). Further, the relative magnitude of the velocity of muscles that act about a joint gives insight into the relative magnitude of each muscle's moment arm. This information about a muscle's motion can be useful when studying surgically altered muscle. For example, rectus femoris transfer surgery is commonly performed in persons with cerebral palsy to increase knee motion during walking.[23] This surgery is intended to convert the rectus femoris muscle from a knee extensor to a knee flexor. However, not all patients demonstrate improved knee flexion after surgery, and the in vivo function of the muscle after transfer is unknown.[24] Asakawa et al.[1] used cine PC MRI to test whether the tendon transfer surgery converted the muscle from a knee extensor to a knee flexor. To do this, the velocity of the quadriceps muscles (knee extensors) and the hamstrings muscles (knee flexors) were measured during knee flexion and extension in unimpaired subjects and in subjects with cerebral palsy who had undergone surgical transfer of the rectus femoris muscle.

Methods

A 1.5-Tesla GE scanner (GE Medical Systems, Milwaukee, WI) was used to acquire the cine PC MR images. The knee flexors (hamstrings) and knee extensors (rectus femoris and vastus intermedius) of 10 control subjects and 10 limbs of persons with cerebral palsy who had undergone a rectus femoris transfer surgery were imaged. The subjects were positioned supine on the table of the scanner, with the thigh supported to minimize movement during a knee extension and flexion task (Fig. 2). Dual radiofrequency coils were held on supports placed on either side of the limb being imaged. The subjects were able to flex and extend the knee through ~40 degrees of knee motion. The MR scanner was triggered by motion of the foot at the beginning of each knee motion cycle, using an optical transducer placed on the scanner table. A device was attached to the subject's ankle to allow the investigator the ability to pas-

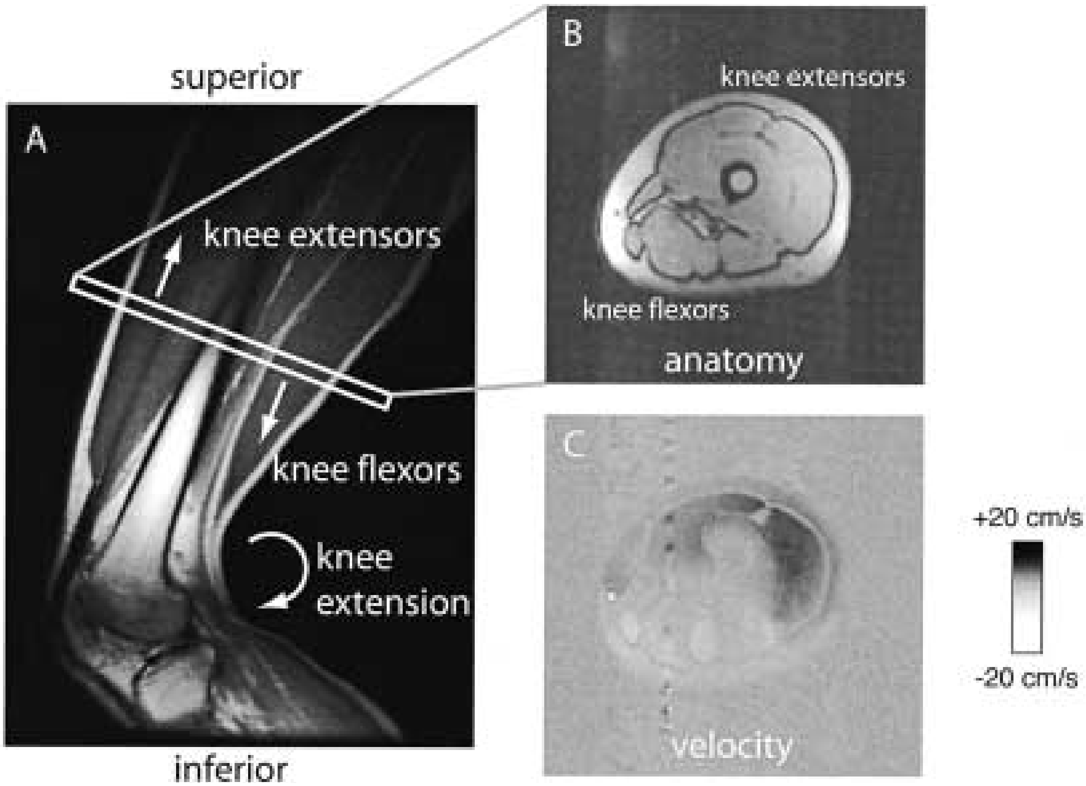

Figure 1 The direction of muscle tissue velocity measured with cine phase-contrast magnetic resonance imaging shows whether a muscle acts to flex or extend a joint. For example, the knee extensors move superiorly and the knee flexors move in the opposite direction, inferiorly, during knee extension as depicted on the sagittal plane anatomy image (A). The grayscale velocity values in one frame of the axial plane cine phase-contrast magnetic resonance images confirm that the knee extensors (black) and flexors (white) move in opposite directions in a control subject during knee extension (C).

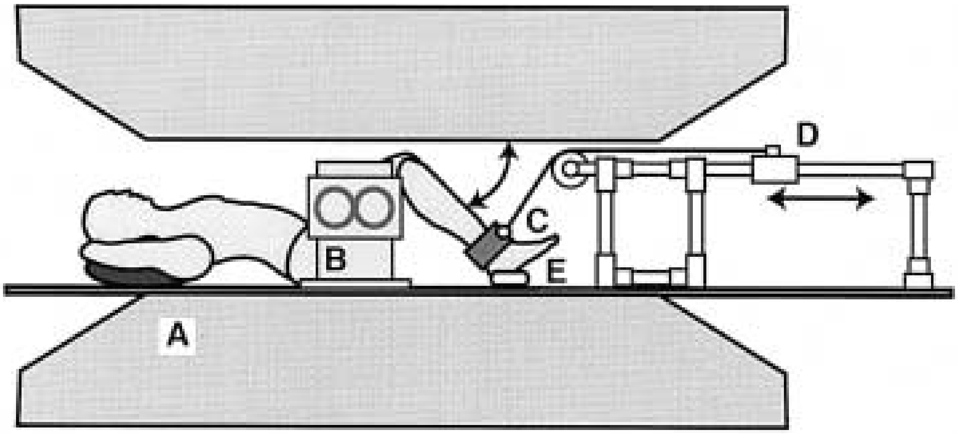

Figure 2 Experimental set up for imaging the thigh muscles during knee motion. The subject was positioned supine in the MRI magnetic resonance imaging scanner (A). Dual general-purpose radiofrequency coils (B) were held on vertical supports on either side of the limb being imaged. The subject's ankle was placed in a cuff (C) attached to ropes that passed over a pulley and attached to the handle of a slider mechanism (D). The subject's knee was moved through extension and flexion during cine phase-contrast PC MR magnetic resonance image acquisition, using the slider handle on the motion device. An optical transducer (E) placed near the foot triggered the beginning of each motion cycle. Figure adapted from Asakawa et al.[1]

sively move the knee through extension and flexion (Fig. 2).

Cine PC MR images were acquired in an oblique sagittal plane and axial plane with a 36 × 27-cm field of view. The images were acquired with a 17-milliseconds repetition time, a 30-degree flip angle, and a 1-cm slice thickness. We acquired 24 time frames of cine PC image data. Velocities were encoded in three directions. The oblique sagittal plane images were carefully prescribed to maximize the in-plane motion of the quadriceps and hamstrings muscles during knee motion. Maximizing in-plane motion facilitates tracking of muscle tissue by integrating the velocity data using a closed-form Fourier integration method.[22] Software was used to specify the locations of regions of interest, generally 1-cm squares, within the muscle tissue and then compute the displacement of the muscle tissue within each region of interest from the three directions of velocity data.[22] The axial plane images were prescribed such that the velocities of the rectus femoris and neighboring muscles were perpendicular the image plane (e.g., Fig. 1).

Findings

Cine PC MR images demonstrate that the rectus femoris and vastus intermedius, two of the muscles comprising the quadriceps, have different relative displacements during knee extension and flexion in the control subjects (Fig. 3). For the 10 unimpaired subjects, the rectus femoris displaced on average 31% more than the vastus intermedius (e.g., Fig. 4). This indicates that the rectus femoris has a greater knee flexion moment arm than the vastus intermedius in control subjects. In contrast, the rectus femoris displaced less than the vastus intermedius (by 2% to 77%) in subjects who had the rectus femoris transferred to a knee flexor muscle (e.g., Fig. 4). The decreased velocity of the rectus femoris as compared with the vastus intermedius was visible in velocity images of the rectus femoris transfer subjects (Fig. 5, compare cf. Fig. 1C). This study showed that the rectus femoris muscle did not move in the direction of the knee flexors after surgery, even though its distal tendon was attached to a knee flexor. These results suggest that factors other than muscle path geometry, such as scarring of the muscle, may influence muscle motion and function after surgery.[1] This example demonstrates that cine PC MRI is a valuable tool for investigating muscle motion in subjects after orthopedic surgery.

MUSCLE CONTRACTION MECHANICS

There is a paucity of data existing that characterize in vivo shortening of muscles in humans. Skeletal muscle has a hierarchical structure, and it is often assumed that shortening of a single muscle fiber scales to produce uniform contraction at the level of the muscle. Characterization of muscle tissue shortening using cine PC MRI provides important data to improve our understanding of contraction mechanics at the whole whole-muscle level. Pappas et al.[3] used cine PC MRI to test the assumption that skeletal muscle shortens uniformly in the direction of the muscle fascicles during low-load contractions. In this study, displacement of tissue within the biceps brachii muscle was measured during elbow flexion.

Methods

Subjects were positioned on their side within a 1.5-Tesla MRI scanner (GE Medical Systems, Milwaukee, WI), and cine PC MR images of the biceps brachii were ac-

Figure 3 Four time frames from a cine phase-contrast movie of the thigh for one control subject are shown during knee extension and flexion. The positions of the white boxes relative to their positions in the first frame indicate motion of tissue regions within the rectus femoris (RF) and vastus intermedius (VI) muscles during knee joint motion.

quired (Fig. 6). The subject's hand was placed in a glove that was attached to the handle of a plastic motion device. The motion device maintained the subject's forearm in 60 degrees of supination, guided the elbow flexion and extension motion, and ensured that the subject's arm remained stationary within a cylindrical extremity coil during imaging. Each of the 12 healthy adult subjects performed repeated elbow flexion and extension during two different loading conditions: passive (minimal load) and 15% maximum voluntary contraction (MVC). Maximum voluntary contraction force was measured prior to MR scanning using a spring gauge with the subject standing and the elbow flexed 90 degrees. All elbow flexion/extension tasks were performed at a rate of 35 cycles/minute. Maintenance of this rate was facilitated with the use of a metronome. Subjects completed ~65 to 75 repetitions during the 2-minute cine PC image acquisition. Two calibrated elastic cords attached to the motion device provided the desired elbow flexion load. For the passive condition, the subject was instructed to maintain his or her arm in a completely relaxed state while his or her elbow was flexed and extended by the investigator, using a pole attached to the motion apparatus.

Cine PC MR images were acquired in an oblique sagittal plane with a 28 × 14-cm field of view. One magnitude and three velocity images were acquired per time frame with a 17-milliseconds repetition time, 30-degree flip angle, 35-cm/sec maximum encoding velocity, 256 × 128-pixel matrix, and 1-cm slice thickness. Cine PC image data were interpolated into 24 time

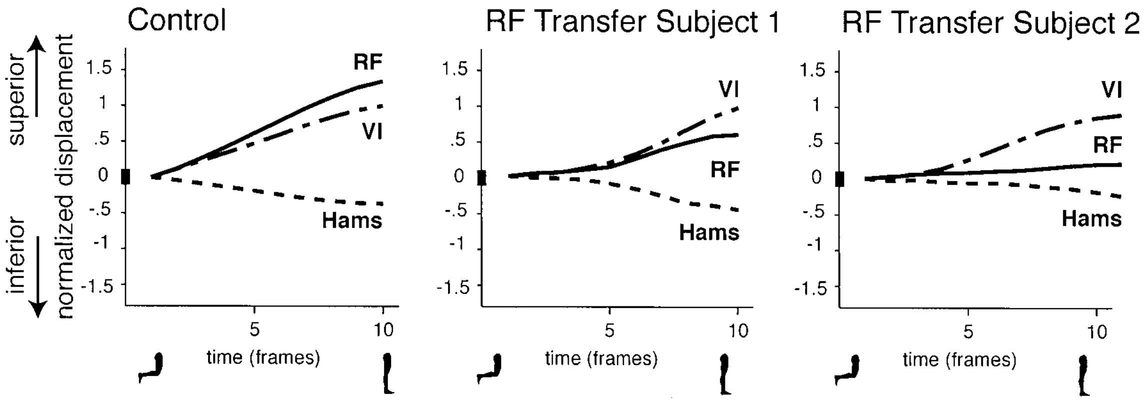

Figure 4 Displacements of regions of interest with the rectus femoris (RF), vastus intermedius (VI), and hamstrings (Hams) muscles for one control subject and two subjects after rectus femoris transfer plotted for 12 time frames of passive knee extension. Displacements were normalized by peak displacement of the VI muscle. Positive (and negative) values indicate superior (and inferior) motion of the muscles with knee extension, respectively. After surgical transfer to a knee flexor, the rectus femoris displaced in the direction of the knee extensors (VI), but in contrast to the control subjects, the rectus femoris displaced less than the vastus intermedius muscle. Figure adapted from Asakawa et al.[1]

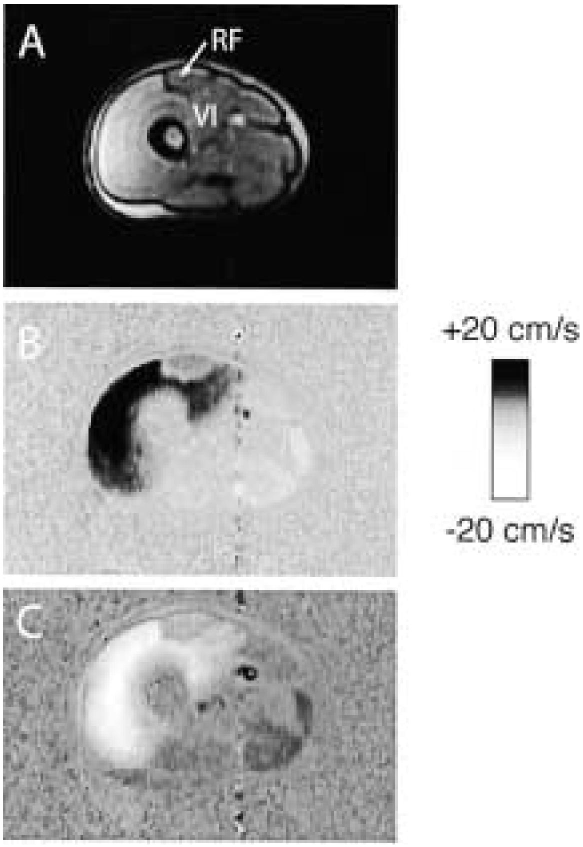

Figure 5 Axial plane anatomy (A) and velocity images during knee extension (B) and flexion (C) showing the rectus femoris (RF) and vastus intermedius (VI) in a subject after rectus femoris transfer surgery. The velocity of the tissue is indicated by the grayscale value of the pixels within the velocity image. It is visually appreciable that the transferred rectus femoris muscle has a lower velocity than the vasti muscles after transfer to one of the hamstrings.

frames. Software was used to graphically prescribe 1 × 1-cm (9 × 9-pixel) regions of interest within the biceps brachii tissue seen on the magnitude image.[22] Square regions were prescribed longitudinally along the centerline of the muscles, along the anterior border of the muscle, and transversely across the mid-axial plane of the muscle. The displacements of these regions were tracked throughout elbow flexion, using the velocity image data.[22] The amount of shortening along the longitudinally and anterior placed regions was calculated by the change in length between regions. The displacements of the transversely placed regions were normalized by the displacement of one region of interest placed at the distal end of the muscle near the biceps tendon.

Findings

Analysis of the images showed that longitudinal shortening was approximately uniform along the length of the anterior boundary of the biceps brachii muscle and averaged 21% for the 15% MVC loading condition[3] (Fig. 7). However, shortening was highly non-uniform along the centerline of the muscle during active elbow flexion (Fig. 7). Centerline shortening was significantly ($P < 0.001$) lower in the distal region of the muscle (3.7% for 15% MVC) as compared with the midportion of the muscle (28.2% for 15% MVC).

Non-uniform muscle motion was also measured along the mid-axial plane of the biceps brachii during elbow flexion[25] (Fig. 8). For all loading conditions, transversely distributed regions of interest displaced in a non-uniform fashion (Fig. 8B). The muscle tissue displacement averaged for the 12 subjects was significantly greater (P

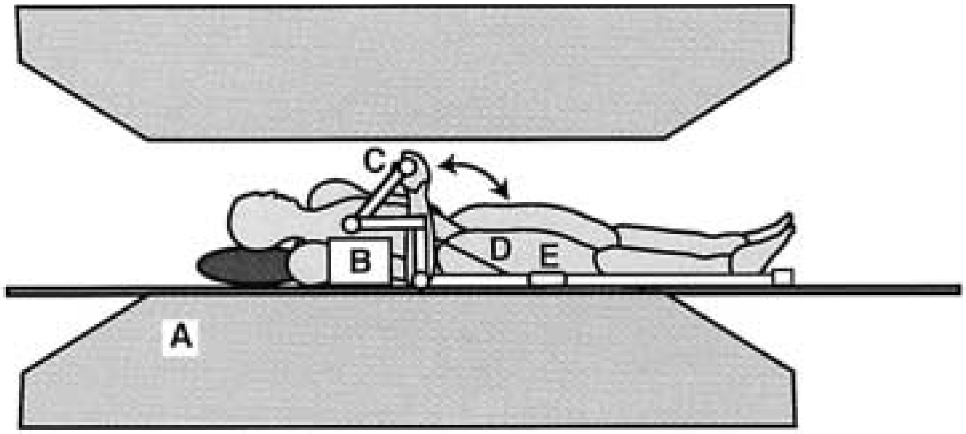

Figure 6 Experimental setup for imaging the arm muscles during elbow motion. The subject was positioned on their side in the magnetic resonance imaging scanner (A). A cylindrical radiofrequency coil (B) was placed around the subject's arm. An elbow flexion motion device (C) was aligned with the center of rotation of the subject's elbow, as approximated by the lateral humeral epicondyle. An adjustable nylon strap (D) limited the subject's elbow motion to 90 degrees. An optical transducer (E) placed near the hand triggered the beginning of each motion cycle when the elbow was extended.

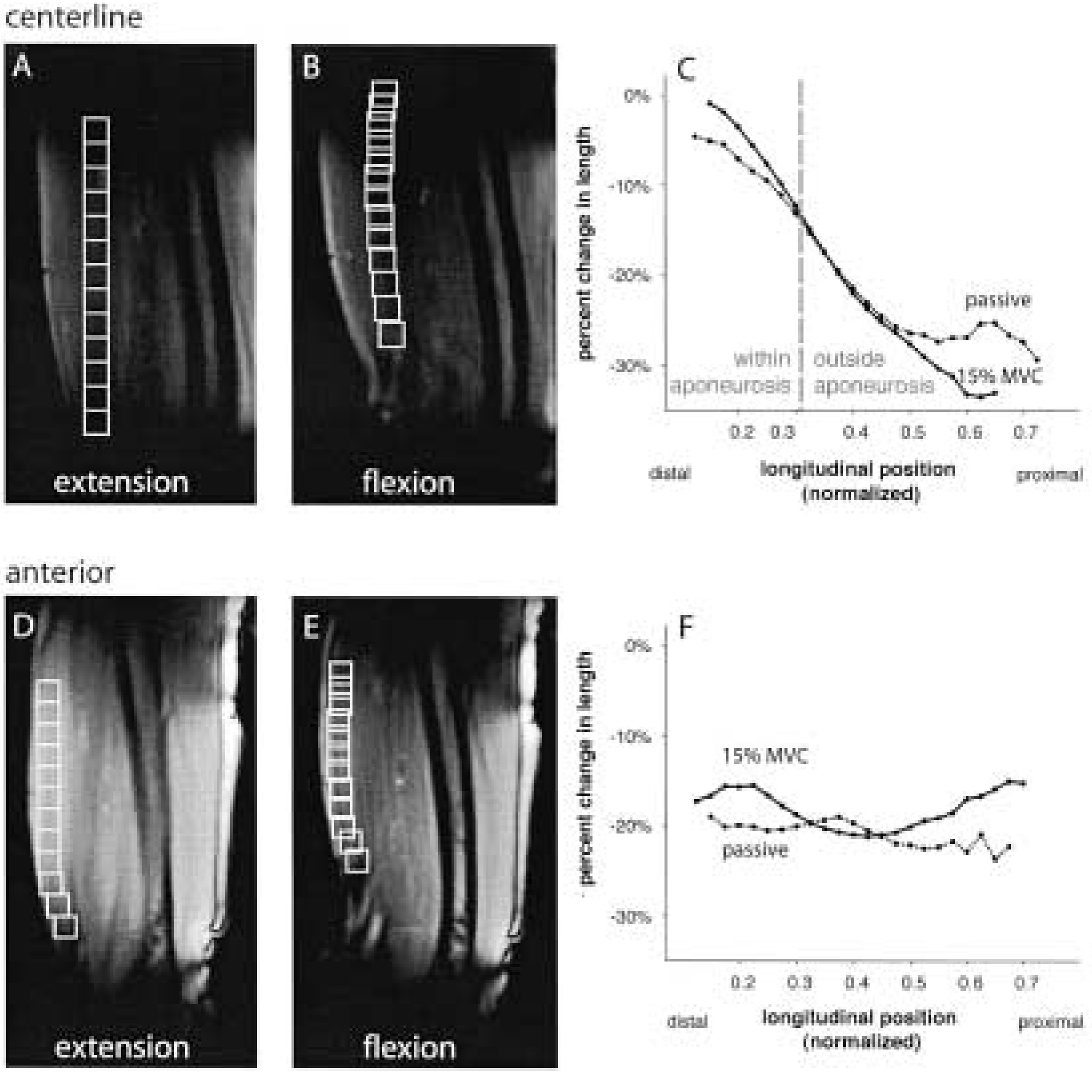

Figure 7 Displacement of tissue regions (white boxes) along the centerline and anterior of the biceps brachii is graphically displayed on cine PC magnitude images during elbow extension (A, D) and flexion (B, E) for one subject. The regions are prescribed graphically during full extension of the elbow (time frame 1) and tracked to the position at maximal elbow flexion using the velocity data. Percentage change in length averaged for the 12 subjects is plotted as a function of distance from the distal tendon, normalized by the length of the biceps brachii long head muscle belly (C, F) for both the passive and 15% maximum voluntary contraction load levels. Negative values of percent length change indicate muscle shortening with elbow flexion. Mean shortening along the centerline of the biceps is non-uniform (C); greater shortening is observed along the proximal regions of the centerline as compared with the distal end.

< 0.001) in the central portion of the muscle as compared with the superficial (anterior) and deep (posterior) periphery. Displacement of anterior tissue regions was also significantly greater than displacement of posterior tissue regions for elbow flexion against a 15% MVC load. Normalized displacement of the regions of interest was significantly greater in the active flexion case (15% MVC) as compared with passive flexion of the inactive biceps. Mean displacement of the midpoint of the biceps (at the center of the midline) was 69%, and 79% of the displacement of a region of interest placed distally just proximal to the biceps tendon for the passive and 15% MVC loading conditions, respectively.

This study demonstrated that muscle shortening is not uniform throughout the biceps brachii muscle during elbow flexion.[3] The observation that midplane displacement at the anterior periphery approaches half the magnitude of distal tendon displacement is consistent with more uniform shortening along anterior fascicles than is exhibited at the centerline.[3,25] The observed centerline displacement is likely related to the presence of a central distal aponeurosis within the biceps brachii. The presence of aponeurosis, as well as the architectural arrangement of fascicles within the biceps brachii, may contribute to the non-uniform displacement observed during elbow flexion.[3] In conclusion, common assump-

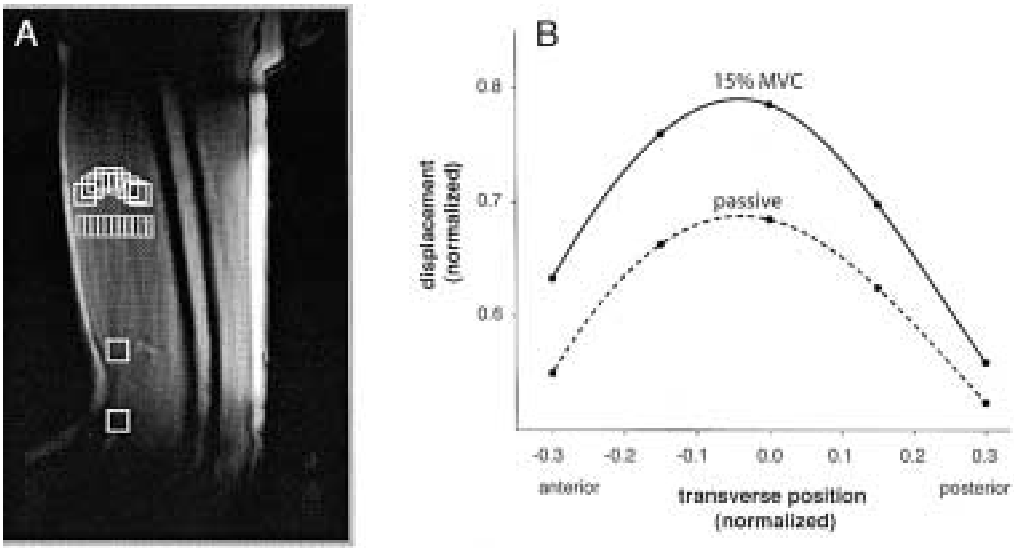

Figure 8 Displacement of the tracked muscle tissue regions in the biceps brachii are shown on the cine PC magnitude image (A). Transversely placed boxes indicate the position of the regions of interest in the mid-biceps when the elbow was fully extended (gray) and fully flexed (white). Mean displacements of transverse regions for the 12 subjects are plotted at full elbow flexion under passive and 15% maximum voluntary contraction loading conditions (B). Transverse position is relative to the biceps midpoint and is normalized by anterior-posterior muscle thickness in the mid-axial plane. Displacement values are normalized by the displacement of the most distal centerline region of interest, just proximal to the biceps tendon, which estimates the overall shortening of the biceps during elbow flexion. Distal region of interest displacement was 3.31 ± 0.47 cm and 3.50 ± 0.50 cm over the full range of motion for passive and 15% maximum voluntary contraction elbow flexion, respectively.

tions made about muscles for biomechanical analysis, such as uniform contraction, may be inappropriate for many muscles because of their complex muscle-tendon architectures.

SUMMARY AND FUTURE DIRECTIONS

The two studies presented are examples of the many possible questions that can be addressed using cine PC MRI techniques to quantify musculoskeletal tissue velocity in vivo. In vivo measurements are needed to test assumptions made in mathematical models of the musculoskeletal system. For example, it is commonly assumed that muscles transmit force only to their own tendons. The first example reviewed here showed that the rectus femoris displaced in the direction of the knee extensors, not the knee flexors, in the rectus femoris transfer subjects, even though the distal tendon is attached to a knee flexor. This suggests that force generated by the rectus femoris is transmitted not only to its distal tendon but may also be transmitted laterally to the surrounding vasti, presumably due to adhesive scar tissue that develops between the rectus femoris and vasti after surgery. It is also frequently assumed that muscle fascicles shorten uniformly. In the second example, we found that shortening along the centerline of the biceps brachii was nonuniform. This demonstrates that the assumption that muscle fascicles shorten uniformly along their length is not always valid. These results emphasize the need to make in vivo measurements of muscle motion to test assumptions about muscle contraction, improve the accuracy of muscle models, and further our understanding of muscle function.

Cine PC MRI presents some experimental challenges for the study of skeletal muscle motion. Specifically, the cine MR technique requires multiple cycles of repeated motion. If the motion cycles are not repeated accurately, the image quality degrades, and the resulting velocity images may be compromised. For this reason, devices that guide motion and limit unwanted movement are needed to ensure good-quality data. The requirement of repeated motions can be difficult for subjects, especially those with musculoskeletal or neuromuscular disorders or individuals who have had recent injury or orthopedic surgery. Finally, the size of the standard magnetic resonance scanner bore can restrict the range of joint motion available. The range of joint motion needed to extract meaningful results needs to be considered when designing a dynamic MR imaging research study.

Future directions in the use of dynamic MR techniques to study biomechanics may include application of real-time MR imaging techniques[26,27] to image muscle and bone motion. The ability to capture musculoskeletal motion in real- time addresses several of the current limitations of cine PC MRI. Recently, the use of a real-time MRI technique for capture of joint motion was demonstrated by Quick and colleagues.[11] Combination of real-time MR imaging with phase contrast[28] will make acquisition of musculoskeletal tissue velocities possible with shorter scan times and without the requirement of repeatable motion cycles. Real-time MRI with phase contrast ability may further expand the application of dynamic MR imaging techniques to study populations of subjects with musculoskeletal injury, pathology, or movement disorders who cannot actively complete the number of motion cycles needed for cine PC MRI. Cine PC MRI, and other dynamic MR imaging techniques, provide the opportunity for biomechanics researchers to quantify in vivo skeletal muscle motion and to test the current understanding of skeletal muscle mechanics.

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