Accuracy of Using Real-time MRI for Joint Motion Measurements: A Phantom Study

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Introduction: Accurate measurements of *in vivo* joint motion are needed to understand normal and pathological joint mechanics. Current methods of measuring joint motion include the use of skin-based reflective markers[1], bi-plane radiography[2], and cine-phase-contrast MRI[3]. Real-time MRI[4] is advantageous compared to these previous techniques for several reasons: direct bone and soft tissue motion can be measured; it is non-ionizing; and only one motion cycle is required. Real-time MRI provides a means to measure highly-loaded motion while minimizing the risk of muscle fatigue. The accuracy of measuring the position of a moving object using real-time MRI depends on the image acquisition rate, the image resolution, the SNR of the images, and image artifacts. These parameters depend strongly on the magnitude and slew rate of the available gradients, the scanner field strength, and the homogeneity of the scanner, which vary depending on the scanner design. The goals of this study are to determine the accuracy of measuring object motion of different speeds using real-time MRI and to assess the trade-offs in tracking accuracy when using a 0.5T upright, open-bore MRI scanner as compared to a closed-bore 1.5T MRI scanner.

Methods: We developed an MRI-compatible motion phantom with a known and repeatable trajectory. The phantom consists of a hollow polypropylene sphere filled with olive oil attached to a rotating wooden bar (Figure 1). The bar was connected to a 24VDC gear motor with encoder by a 2.7m long driveshaft made of filament wound epoxy tubing. This long driveshaft allowed the motor to be placed far enough from the scanner that it was not affected by the main field.

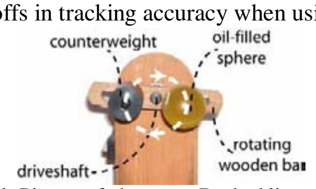

Figure 1: Picture of phantom. Dashed line represents path traced by sphere. Motor is connected to driveshaft.

	1.5T	0.5T
Field of View (cm)	20	16
Readout Length (ms)	12.2	16
Pixel Size (mm)	1.8	1.88
Frame Rate (frames/s)	11.8	6
Number of Interleaves	4	6

Table 1: Description of Real-time Sequences

The speed of rotation of the phantom was controlled through a proportional-integral-derivative motor controller, and once set, remained constant throughout the duration of the trial. The trajectory of the phantom center was a circle with radius 25.5mm (Figure 1). The position trajectory of the phantom, defined as the x-y position at each time point, was measured using standard 3D optical motion capture techniques (EVaRT, Motion Analysis Corp.).

Real-time, single-slice spiral imaging sequences designed to image large joints, such as a knee, were implemented in a 1.5T GE Excite HD MRI scanner and a 0.5T GE Signa SP open-MRI scanner (GE Healthcare) (Table 1). A 5-inch surface coil was used in both scanners.

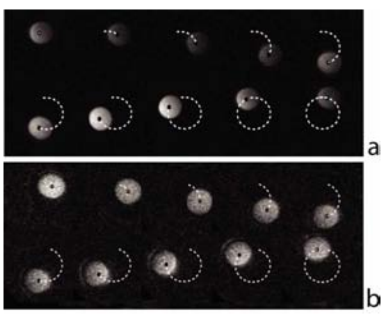

Figure 2: Real-time images of phantom in 1.5T (a) and 0.5T (b) scanners. Black dot represents centroid of sphere and dashed line represents the path traced by the centroid.

We acquired real-time MR images of the phantom rotating at up to 19 different velocities, ranging from 1 rad/s to 10 rad/s in 0.5 rad/s increments (25.5mm/s to 255mm/s). We chose the image plane to go through the center of the sphere and be oriented such that only in-plane motion occurred. The SNR of the real-time images was calculated as the ratio of the signal in the phantom divided by the standard deviation of the noise in the image. For images obtained from both scanners, the SNR was measured at 20 different locations and the mean and standard deviation were found.

We used a 2D tracking algorithm to measure the position trajectory of the phantom from the real-time images (MATLAB, The MathWorks, Inc.). The algorithm consisted of computing the area centroid of the sphere in the real-time image and recording this position for each frame of the image sequence (Figure 2).

To determine the accuracy of tracking an object using real-time MRI, the root-mean-square (RMS) error between the real-time MRI-measured position trajectory and the optically-measured trajectory was calculated for each of the phantom velocities tested.

Results: The SNR of the images from the 1.5T scanner was significantly larger than that of the 0.5T scanner ($p<0.001$). In the 1.5T scanner, the SNR was 39±6.1 and in the 0.5T scanner, the SNR was 16±2.2. In the 1.5T scanner, we tracked the phantom to within 2mm for velocities up to 153mm/s (Figure 3). In the 0.5T open-bore MRI scanner, the phantom could be tracked to within 2mm for phantom velocities up to 38mm/s and to within 3mm for phantom velocities up to 127mm/s (Figure 3). On average, the RMS errors at a given speed were 72% lower in the 1.5T scanner compared to the 0.5T scanner. Furthermore, using the 1.5T scanner, we were able to track the phantom with comparable accuracy for movements that were over three times faster than those imaged in the 0.5T scanner.

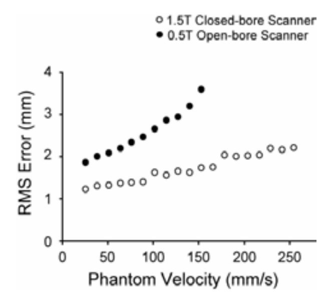

Figure 3: Plot of RMS tracking errors at different speeds of phantom motion.

Discussion: Real-time MRI addresses several limitations of current techniques to study joint movement. The results of this phantom study indicate that it is feasible to use real-time MRI to measure joint motion at physiologically relevant speeds, such as knee flexion at a rate of 50-60°/s, if 2mm accuracy is acceptable. Although using a 0.5T open-MRI scanner would result in kinematic data obtained during upright, weight-bearing tasks, these results indicate that joint motion can be measured more accurately and at faster speeds when using a 1.5T closed-bore MRI scanner.

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