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A 3D MOTION PHANTOM FOR ASSESSING THE ACCURACY AND PRECISION OF DYNAMIC MAGNETIC RESONANCE MEASUREMENT OF IN VIVO KNEE KINEMATICS

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Introduction: Measurement of *in vivo* knee kinematics can provide useful insight into disease, injury, and clinical treatment. Cartilage loading patterns are of particular interest while studying the progression of osteoarthritis [1]. However, inferring cartilage contact from skeletal kinematics requires high resolution volumetric models of cartilage surfaces and accurate skeletal positions and orientations. This is a challenging requirement at the knee, which exhibits substantial translation and non-sagittal rotation during normal activities such as gait [2]. We have recently introduced a novel 3D cine magnetic resonance (MR) imaging technique to measure *in vivo* tibiofemoral kinematics [3]. The purpose of this study was to develop a MR-compatible motion phantom that can generate repeatable 3D skeletal motion suitable for quantifying the accuracy and precision of kinematics derived from dynamic MRI.

Methods: We constructed a MR-compatible motion phantom device to continuously move femoral and tibial bone segments through a known, repeatable 3D motion which mimics normal knee behavior (Fig. 1). The motion phantom is a hybrid linkage and gearing system which receives a rotary input from a stepper motor, placed outside of the MR bore and attached via 7-foot long HDPE shaft. The phantom structure and shafts are made of HDPE and acetal, and gears are made of nylon and acetal. The mechanism produces ~35° of tibial flexion and ~8° of femoral rotation through a motion cycle, which can be generated at frequencies ranging from 0.2 to 1.5 Hz (Fig. 1). Bone segments are rigidly attached to the motion phantom to enable dynamic imaging of skeletal kinematics.

Our dynamic imaging technique requires subjects to perform 150 repeat flexion-extension motion cycles for five minutes within the bore of a scanner. Hence, we assessed the repeatability of the motion phantom by using motion capture to measure the cyclic repeatability of three five-minute trials. Bone samples were attached to the phantom to ensure similar inertial loads as the MR study. Three active markers were orthogonally arranged on one surface of each bone segment. Kinematic data was measured using a three camera system at 100 Hz. Data was low-pass filtered with a 5 Hz cutoff frequency. Each trial was divided into flexion-extension cycles and the average and standard deviation of the flexion and rotation were calculated.

The phantom is now being used to assess accuracy and precision of the model-based dynamic MR imaging technique using the following methodology. An intact, matched porcine tibia and femur is harvested after sacrifice. The tibia and femur are disarticulated to allow independent mounting and motion of each segment. To ensure similar contrast as the *in* vivo case and to reduce susceptibility artefacts from tissue/air interfaces, the bone segments are embedded in an agar gel with MR relaxation parameters comparable to muscle. Embedded bone segments are then rigidly secured to femur and tibia carriers in the motion phantom. Fiduciary markers (Vitamin E pills) are secured to the bone segments to allow registration between the MR and motion capture reference frames. A 16-channel flex coil is placed over the motion volume. We then perform both static and dynamic imaging. First, a high resolution static 3D IDEAL spoiled gradient-echo image (512x512x304 cubic voxels with 0.37 mm spacing, 5:25 scan) is acquired in a clinical 3.0 T MR scanner. A stepper motor then drives the phantom at 0.5 Hz for

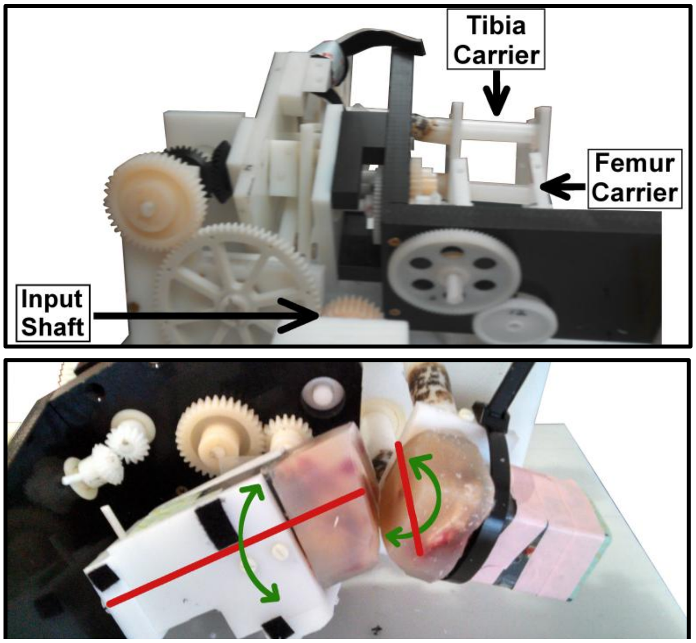

Figure 1. Motion phantom design. *(Top) A view of the motion phantom, as seen from the input shaft. A continuously rotating shaft creates tibial flexion and femoral rotation. (Bottom) The axis of rotation of the femor and tibia enclosed in agar gel.*

five minutes while spoiled gradient-echo combined with vastly undersampled isotropic projection (SPGR-VIPR) images are continuously collected on a 3.0 T MR system (1.5x1.5x1.5 mm, TR/TE= 4ms/1.4ms, flip angle = 8°, BW= 62.5 kHz, FOV= 48 cm, 75,000 unique radial lines, 60 frames). A MR-compatible rotary encoder, mounted to the phantom, allows for image reconstruction based on knee position.

Details on measuring tibiofemoral kinematics from dynamic MR images can be found in [3]. Briefly, bone models are segmented from static images and local coordinate systems are established using geometric and inertial properties of each segment [4]. Bone models are then registered to each dynamic image frame using numerical optimization with a objective function of the sum-squared intensities of the dynamic image at the locations of the model vertices. This drives the bone models to the low-intensity outlines of the bones in the dynamic images (Fig. 2). 3D translation and angle trajectories for the bone segments are low-pass filtered with a 5 Hz cutoff frequency and kinematics are calculated using three successive body-fixed rotations.

Motion capture will be used as the standard for comparison with the model-based MR method. Bones will remain attached to the motion phantom device following MR acquisition and the device will be transported to a motion capture laboratory. Data will be collected in similar fashion to the repeatability experiment.

Results: The average flexion range of motion of the phantom is 31.7° and an average tibial rotation range of 12.0° (Fig. 3). The motion phantom showed good repeatability across all trials with an average standard deviation of 0.7° and 0.4° for flexion and rotation, respectively. Maximum standard deviation of 1.2° for flexion and 0.7° for rotation occurred at maximal flexion for both measures.

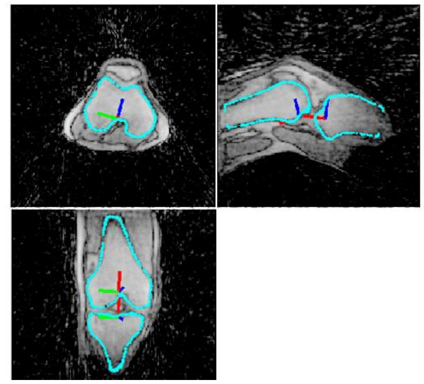

Figure 2. In vivo dynamic MR image. *Orthogonal views of a dynamic MR image with tracked tibial and femoral outlines.*

Discussion: It is imperative that a motion phantom provides conditions, such as speed, range, and repeatability of motion and imaged object geometry, similar to those in place during *in vivo* testing as the quality of the dynamic MR images is dependent on these properties. Our previous study on the knees of ten healthy subjects found an average range of motion of 37.1° and 10.6° for flexion and tibial rotation and average standard deviation of 0.8° for knee flexion angle [3]. Combined with the use of fresh porcine bones, the quality of MR image for the motion phantom should be comparable to the quality of images used in the *in vivo* study. We are now in the process of collecting the 3D image data from the motion phantom, which will be used to assess both the accuracy and precision for the dynamic MRI method for tracking 3D skeletal kinematics. We estimate that kinematic accuracies on the order 0.2 mm are needed to use the kinematic data to assess cartilage contact locations [3].

Conclusion: We have developed a multi-axis, MR-compatible motion phantom which mimics *in vivo* motion during knee flexion and extension. This instrument allows for systematic assessment of the absolute accuracy and precision of *in vivo* skeletal kinematics measured using dynamic MR techniques.

References:

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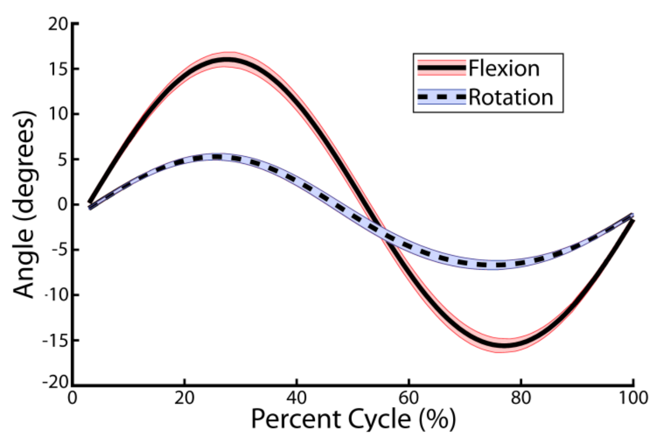

Figure 3. Repeatability of motion phantom. *Motion phantom showed good repeatability in flexion and rotation. Maximum standard deviation for both trajectories occurred at change of directions.*