MEASURING 3D TIBIOFEMORAL KINEMATICS AND CONTACT USING DYNAMIC VOLUMETRIC MAGNETIC RESONANCE IMAGING

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INTRODUCTION

Dynamic magnetic resonance imaging (MRI) can characterize musculoskeletal mechanics during movement. Previously, both real-time [1] and cine phase contrast (PC) [2] sequences have been used to measure *in vivo* skeletal kinematics. However, both sequences are only able to image a single plane within reasonable scan times. While cine-PC provides 3D velocity information which can be integrated to estimate out-of-plane motion, it remains challenging to register 3D skeletal positions in space. This limits the capacity of using MRI-based measures to characterize inter-articular contact patterns. The purpose of this study was to investigate the use of dynamic volumetric MRI to measure 3D tibiofemoral kinematics. Volumetric imaging is achieved using radially under-sampled trajectories, termed vastly under-sampled isotropic projections (VIPR), to obtain isotropic resolution within a reasonable scan time. We show that this imaging technique can be coupled with a functional loading device and simultaneous knee angle measures to characterize both 3D joint motion and cartilage contact patterns.

METHODS

Ten healthy subjects (5 F; 24.6 ± 3.2 y; 65.1 ± 5.0 kg) who had no history of past knee injuries, pathologies, surgeries, or chronic pain were imaged bilaterally. High resolution static images (0.37 mm cubic voxels) of each knee were first obtained in a 3.0T MR scanner. Subject-specific bone and cartilage models of the tibia and femur were segmented from these images, and local anatomical coordinate systems were defined [3].

Subjects were then asked to perform a cyclic knee flexion-extension task at 0.5 Hz for 5 min while lying supine in the scanner, with their lower limb attached to a MR-compatible knee loading device. The device applies an inertial load to the lower leg in response to cyclic motion, resulting in peak quadriceps loading with knee flexion as seen in the load acceptance phase of gait. Knee angle was monitored in real-time using a MR-compatible rotary encoder attached to the device's rotation axis. Volumetric images (1.5 mm cubic voxels, 160x160x160 resolution) were continuously collected using a spoiled gradient (SPGR) sequence in conjunction with VIPR. The encoder data was then used to retrospectively sort the MR data into 60 equally sized bins over the 2 s knee motion cycle, from which 60 volumetric images were generated. The high resolution bone models were then co-registered to the volumetric dynamic images at each frame of the motion (Fig. 1). Co-registration was achieved using numerical optimization to determine the bone positions and orientations that minimized the sum-squared intensities of the dynamic images at the locations of the bone model vertices. Tibiofemoral joint angles (flexion-adduction-rotation order) were then determined based on the orientation of the tibia relative to the femur.

For a subset of subjects (n=3), the reconstructed knee kinematics were used to characterize cartilage contact. This was done using a proximity functions between articulating cartilage [4]. Center of contact was defined as the weighted average location of overlapping vertices.

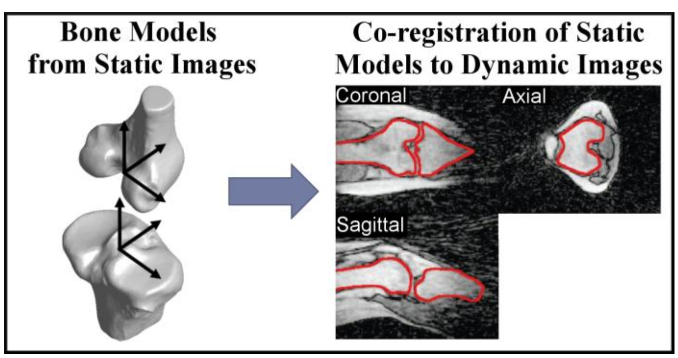

Figure 1. High resolution bone/cartilage models are co-registered with dynamic images.

RESULTS

All subjects exhibited internal tibia rotation (7.8 ± 3.5°) with knee flexion (35.8 ± 3.8°), characteristic of the screw-home mechanism. The internal tibia rotation angles were greater than those previously measured during unloaded knee motion with cine-PC [2]. This difference may be due to the quadriceps loading induced by the loading device, as the average tibia rotation trajectory agreed extremely well with kinematic measures during the load acceptance phase of gait (Fig. 2) [5]. Estimated cartilage contact patterns exhibited greater contact excursion on the lateral condyle (Fig. 3), consistent with contact measures obtained during weight-bearing knee flexion using biplane fluoroscopy [6].

DISCUSSION

We believe this study represents the first fully dynamic volumetric MRI of skeletal motion. A key to our approach is use of radially under-sampled acquisitions which allow for isotropic images to be obtained in reasonable scan times. Subjects had to perform cyclic knee flexion-extension within a scanner for 5 min. In a separate study, we showed that the device induces repeatable loading [7] with peak knee extension moments of ~0.5 Nm/kg in flexion. This loading is at the low end of knee extension moments seen in walking, making the task no more fatiguing than a slow walk. The dynamic images we obtained are relatively low-resolution, but have sufficient contrast at the edges of the bone to resolve the position and orientation of rigid bone segments. We are now in the process of building a motion phantom to assess the absolute accuracy of kinematics measured using this imaging technique. Yet, when cartilage models were added to the bone models, realistic contact patterns were estimated based on simple proximity measures. Hence, we believe the new dynamic imaging approach could prove useful for investigating how cartilage contact changes with ligament injury and reconstructive surgery, which is important given the potential for small changes in contact to give rise to the onset of osteoarthritis.

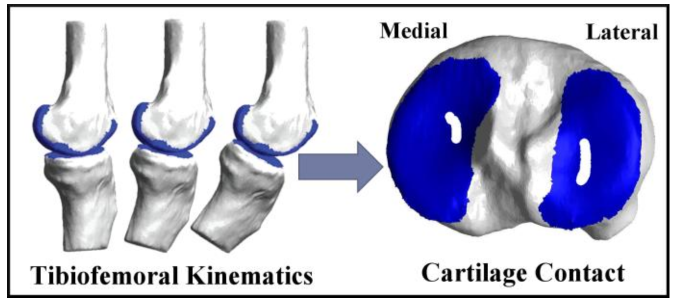

Figure 3. Cartilage models can be combined with tibiofemoral kinematics to calculate cartilage contact through the cyclic task.

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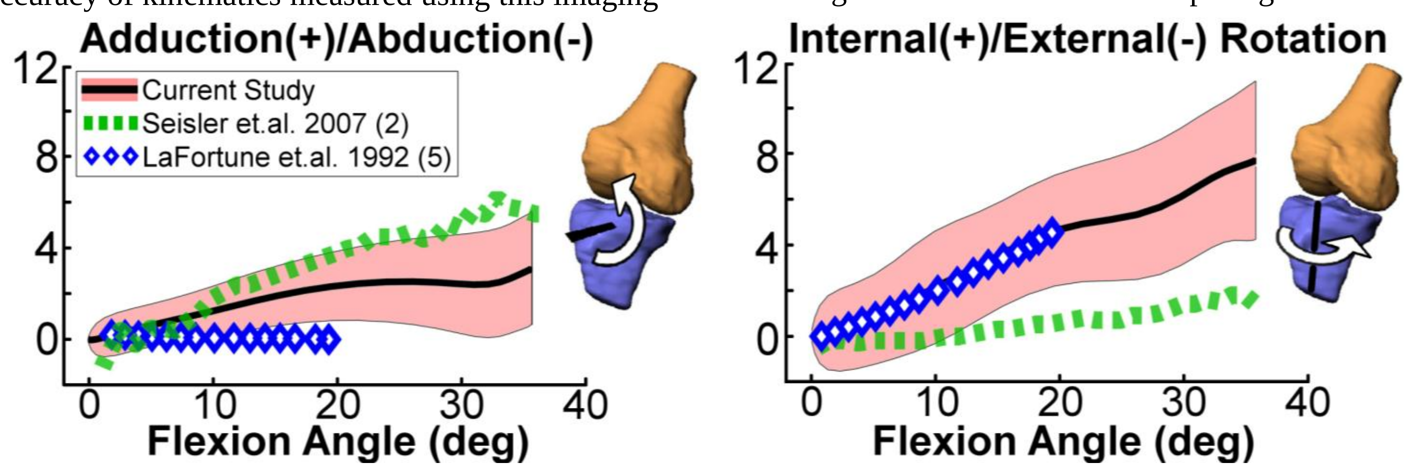

Figure 2. Tibiofemoral rotations (deg) of gait measured with intra-cortical pins (5), unloaded knee flexion measured with cine PC MRI (2) and loaded knee flexion measured with SPGR-VIPR MRI.