Dynamic Imaging of 3d Knee Kinematics using PC-VIPR

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Introduction: Surgical ACL reconstruction is successful at restoring knee function following injury. However, long-term outcomes remain problematic with 60 to 90% of patients developing osteoarthritis (OA) at 10 to 20 year follow-up [4]. The etiology of this early onset of OA is not well understood. One hypothesis is that surgery may fail to restore normal joint kinematics, thereby inducing abnormal cartilage loading patterns [1]. Static MRI can be used to track changes in cartilage morphology, but is not well suited for assessing kinematics or cartilage contact. Cartesian cine phase contrast (cine-PC) imaging has been used to measure skeletal kinematics during motion tasks performed within a scanner [3]. However, time constraints typically limit cine-PC imaging to a single plane, making it challenging to assess 3D cartilage contact. Cine-phase contrast isotropic-voxel radial projection imaging (PC-VIPR) can potentially overcome this limitation by rapidly acquiring 4D velocity data within a volume [2]. In this study, we investigated the potential to use a cine-PC-VIPR sequence to measure 3D tibio-femoral kinematics and to assess cartilage contact during movement.

Methods: We present data for one normal volunteer, who provided informed consent in accordance with an IRB approved protocol. The volunteer was positioned onto a MRI compatible device that induced loads on the knee (Fig. 1) similar to that seen in walking [5]. The volunteer was asked to flex and extend their knee at 30 cycles per minute in synch with an auditory metronome. Image data was acquired on a clinical 3T scanner (Discovery 750, GE Healthcare, Waukesha, WI) using a single channel flexible coil positioned around the knee. Knee flexion angle was simultaneously measured using a MRI compatible encoder (Micrononor; Newbury Park, CA) mounted on the device. A 160x160x160 3D PC-VIPR imaging sequence [2] was used to acquire 3D velocity data with a 1.5 x 1.5 x 1.5 mm^3 spatial resolution and 33.3 ms temporal resolution. Additional imaging parameters included TR=6.8ms, TE=3.3ms, flip angle=10, velocity encoding=40cm/s, and imaging time of 5:36. Velocity images were reconstructed into 60 time-based images of the full flexion-extension cycle. Encoder angle data was used in a post-hoc fashion to gate the cycles. We separately acquired 3D SPGR IDEAL static images (FOV=22x18x12cm^3, 1mm isotropic resolution) of the subject's knee for segmentation.

PC-VIPR data were post-processed to characterize 3D tibia and femur kinematics throughout the motion cycle. To do this, anatomical landmarks were identified in the first PC-VIPR magnitude image. Landmarks were used to define anatomical reference frames in the tibia and femur. Spherical volumes of interest (VOI) within the femur and tibia bone segments were then established. Numerical integration of the velocity data within each VOI was performed to compute the rigid bone segment motion that optimally agreed with the measured voxel velocities [5]. The static images were separately segmented to generate bone and cartilage volumetric models. Anatomical reference frames were similarly established in these models. Segmented models were then driven with the 3D kinematic data (Fig. 2) to visualize tibio-femoral motion and areas of contact (Fig. 3).

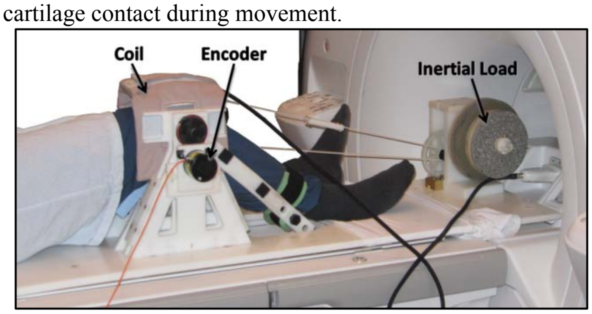

Fig. 1 An MRI compatible device imposed inertial loads on the quadriceps while the subject cyclically flexed and extended their knee. An encoder was used to monitor knee angle for gating the 3D PC-VIPR images and to assess subject repeatability.

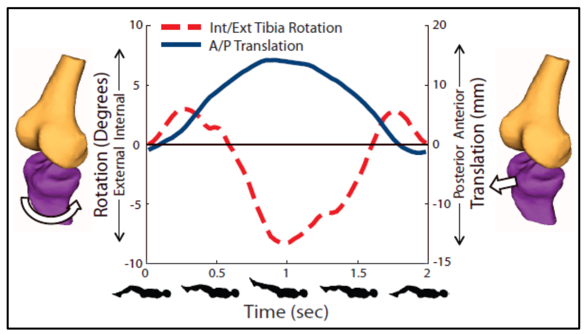

Fig. 2 External tibia rotation and anterior (A/P) tibia translation are observed with knee extension.

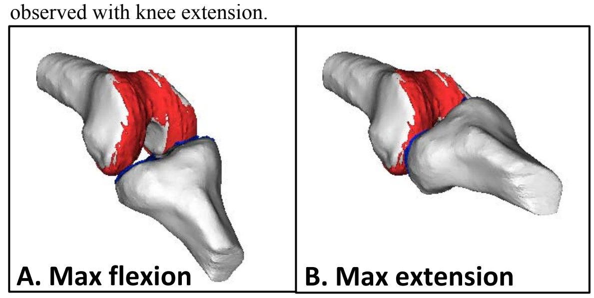

Fig. 3 3D kinematics computed from PV-VIPR images are coupled with segmented bone and cartilage models to visualize tibio-femoral motion and contact throughout a flexion-extension cycle.

Results: Knee flexion-extension motion of 37 deg was achieved in the scanner. Secondary knee motions were consistent with normative values described in the literature [4]. Specifically, ~12 degrees of external tibia rotation was seen with extension reflecting the screw-home mechanism of the knee. Anterior-posterior translation of ~14 mm reflects the femoral rollback that is guided by intact cruciate ligaments. When coupled with a high resolution model of the bone segments, good agreement was seen between the bone position and orientation with that discernable on the PC-VIPR magnitude images.

Conclusions: This study demonstrates the tremendous potential of using PC-VIPR to assess functional *in vivo* knee mechanics. The advantage over current approaches [3] is the acquisition of velocity data over an imaging volume, allowing for direct registration of motion data with high resolution static images. This capability can potentially enable one to visualize 3D cartilage contact areas throughout dynamic motion. The imaging technique is both fast and safe, meaning that 3D knee joint motion could be assessed serially to ascertain changes in knee soft tissue mechanics after injury, surgical reconstruction and rehabilitation. Further developments will include implementing a proximity function to assess cartilage contact areas, and including segmented soft tissues in the model to assess ligament stretch. Imaging of subjects before and after ACL reconstructive surgery will be performed to assess whether abnormal knee mechanics exist prior to evidence of cartilage degeneration and onset of osteoarthritis.

References: [1] Chaudhari, et al. JACSM 2008; **40**: 215-22. [2] Gu, et al. AJNR 2005; **26**: 743-749. [3] Sheehan, et al. JMRI 2003; **17**: 206-213. [4] Tashman, et al. OTSM 2008; **16**: 116-18. [5] Westphal, et al.; 2009 ASB Proceedings, Penn State, PA.