Measuring 3D knee dynamics using center out radial ultra-short echo time trajectories with a low cost experimental setup

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Target Audience – Researchers interested in dynamic knee imaging.

Purpose – To assess whole physiological movement of structures such as the knee joint represent a clinical challenge both for an understanding of physiological function of tissues as well as to characterize functional pathologies[1]. Conventional classical methods for measuring knee dynamics use techniques that freeze the motion during acquisition by using fixed flexion angles to acquire a series of static high-resolution 3D image data[2]. Alternatively, real-time imaging techniques are applied to acquire a series of small stacks of 2D slices while flexion of the knee is performed continuously[3,4]. Although volume coverage and spatial resolution of 2D real-time techniques is limited, a recent study has reported that knee kinematics monitored by dynamic methods produce different results than those obtained with conventional classical static methods[5]. In this work, we demonstrate a method to acquire dynamic isotropic images of the whole knee during performance of a single passive knee flexion with an ultra-short echo time sequence using 3D radial center-out trajectories. In addition, a simple and low cost measurement setup for performing such slow passive knee flexion is presented.

Methods – To perform slow passive knee flexion without the need for custom fit, expensive equipment, we used an inflatable ball for kids (costs ~2 €) with a diameter of 80 cm. The diameter was chosen 20 cm larger than the MR scanner bore, so that a partly inflated ball fixates itself by pressing against the walls of the bore while simultaneously forming a supporting pocket for the leg (due to gravity). To continuously inflate the ball, an air tank with air pressure up to 10 bar was placed outside the scanner room and connected to the ball via a tube of 9 mm diameter. By controlling the air pressure, the inflation rate and thus the duration of the knee flexion could be directly controlled. The setup is schematically depicted in Figure 1.

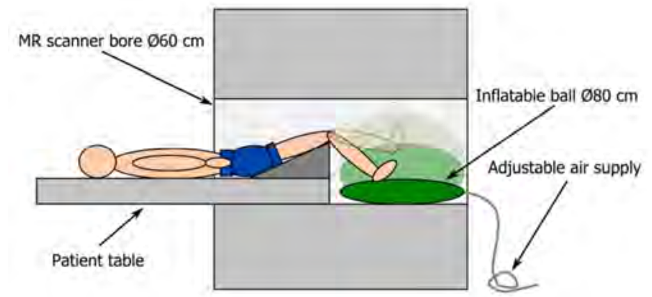

Fig. 1. Measurement setup with the volunteer positioned at the end of the patient table to enable the largest possible flexion angle in the bore. Passive knee flexion is performed by slowly pumping air into a large inflatable ball with a diameter larger than the MR scanner bore.

To acquire 3D isotropic MR data during continuous flexion, we measured 3D radial center-out trajectories (Fig. 2) that are more robust against motion artifacts than standard Cartesian coordinates. Although strong motion during acquisition will result in blurring artifacts, no other image degrading streaking or ghosting artifacts are present with this type of acquisition. To further reduce motion artifacts a very fast scan-time optimized single-echo implementation of the ultra-short time (UTE) sequence variant was used[6]. Briefly, the radial center-out readouts are acquired in concentric cone planes with variable readout gradient durations to achieve time efficient spoiling without the need of additional spoiler gradients.

To acquire data volumes of isotropic resolution of 1.25 mm³ a total of 51,664 radial readouts were required to fill k-space such that the Nyquist condition is met. With TR of 1.2 ms the acquisition time for a single 3D data set was approximately 1 minute. Overall 24 data sets were continuously acquired during the passively induced knee flexion, resulting in a total acquisition time of 24 minutes. Other acquisition parameters were: 300 µs echo time, 20 µs pulse duration, 5° flip angle and 1370 Hz/Pixel acquisition bandwidth. A 16-channel flexible Variety coil (NORAS MRI products GmbH) was used on a clinical 3T MRI system (Siemens Trio). Image reconstruction was performed offline using MATLAB and 3D gridding with iterative sampling density correction[7] on a high performance computation system (64 CPU cores, 512 GB RAM).

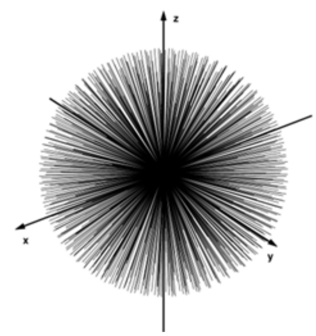

Fig 2. 3D radial center-out sampling scheme.

Results – A knee flexion angle of 40° was achieved within the MR scanner bore of 60 cm diameter with total acquisition of 24 minutes. Even though the 3D radial center-out data were continuously acquired, the reconstructed images showed good sharpness with no major motion or blurring artefacts (Fig. 3). Since TE was 300 µs, an UTE tissue contrast was produced including high contrast between muscle and fat and also yielding signal in tissues such as ligaments and compact bone. Since the knee flexion was acquired with isotropic 3D resolution, volume reconstruction and arbitrarily oriented slices could be obtained from the acquired data (Fig. 4).

Discussion & Conclusion – Although the presented setup does currently not enable repetitive, periodic passive knee movements, slow single flexions can be easily realized with adjustable speed directly controlled by the airflow. Since the single knee flexion is acquired as a 4D data set with isotropic spatial resolution, one measurement is sufficient to extract the dynamics from arbitrarily oriented or even curved slices. In this work, we have demonstrated the feasibility of our approach and presented first results. Future work regarding analysis of the 4D (x-y-z-t) UTE data sets may include 3D bone and patella segmentation, extraction of bone rotation information or ligament deformation analysis. The imaging sequence and image reconstruction could be both further improved by applying acceleration techniques like 3D radial GRAPPA[8] and compressed sensing[9] to reduce acquisition time or increase spatial resolution.

References – [1] Boeth H, et al., Am J Sports Med, 2013 [2] von Eisenhart-Rothe R, et al., BMC Musculoskeletal Disorders, 2012 [3] Sheehan FT, et al., Journal of Biomechanics, 1998 [4] Lin CC, et al., Medical Physics, 2013 [5] d'Entremont AG, et al., Magn Reson Med, 2013 [6] Herrmann K-H, et al., ISMRM 22, 2014 #4267 [7] Zwart NR, et al., Magn Reson Med, 2012 [8] Weight KL, et al., J Magn Reson Imaging, 2014 [9] Lustig M, et al., Magn Reson Med, 2007

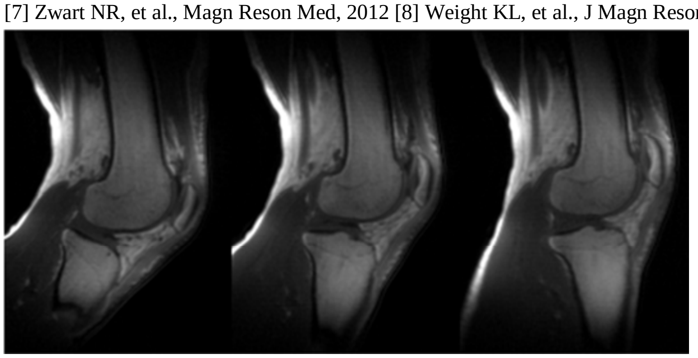

Fig 3. From left to right: Corresponding sagittal slices from data sets 1, 12 and 21 showing good image sharpness and resolution with an UTE tissue contrast, including signal in ligaments.

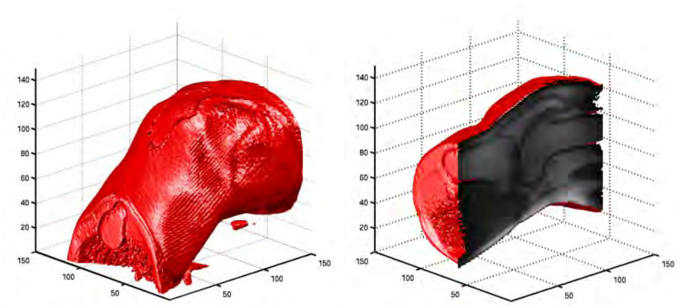

Fig. 4. Surface renderings of the entire 3D data set for two cases, demonstrating coverage of the whole knee.