Knee MRI with in situ mechanical loading using prospective motion correction

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Introduction Magnetic resonance imaging (MRI) can be used to probe the structural and biochemical changes in articular cartilage associated with osteoarthritis. Cartilage thickness as well as T_2 and $T_{1\rho}$ relaxation times have been shown to serve as diagnostic markers for chondromalacia of the knee joint, providing insight into the degree of cartilage damage and dysfunction [1]. Since chondromalacia is associated with altered mechanical properties of the cartilage, the response of these tissue parameters to mechanical loading is of particular interest. However, in situ loading of the knee impairs the stability of the experimental MR setup and therefore gives rise to considerable motion artifacts in the acquired MR images. These artifacts are particularly severe for imaging of the patellofemoral joint, which can only be loaded in a flexed posture. While knee MRI with in situ loading of the tibiofemoral compartment has already been proposed [2], in vivo MRI studies of the patellofemoral joint have not been performed with in situ mechanical loading to date. Recently, MRI with real-time prospective motion correction has been proposed, using a moiré phase tracking (MPT) system consisting of a single in-bore camera and a tracking marker with a multilayer structure for accurate orientation measurement [3-5]. Using prospective motion correction, MRI of the tibiofemoral as well as the patellofemoral joint with in situ mechanical loading is demonstrated in this work.

Methods: All experiments were performed on a Magnetom Trio 3T system (Siemens Healthcare, Germany). Knee loading was realized with a home-built MR-compatible loading jig. Prospective motion correction was performed with a MPT system (Metria Innovation Inc., Milwaukee, US) [4]. The tibiofemoral joint was loaded with a small knee flexion angle of 10-20°, while a birdcage extremity coil was used for signal reception (setup 1, Figs. 1a,b). The tracking marker was attached to the shin close to the tuberositas tibiae. For imaging of the patellofemoral joint the knee was positioned with a large flexion angle of approximately 60° to ensure strong loading. The tracking marker was attached to the knee cap and images were acquired with a 11 cm loop coil (setup 2, Figs. 1c,d). Imaging was performed with a spoiled 3D gradient-echo sequence using selective water excitation. In some experiments, the signal from the posterior part of the knee was erased with a coronal presaturation slab. The 3D measurement volume as well as the presaturation slab were updated every TR right before excitation. Inter-scan position locking corrected for motion between scans. All corrections could be realized without a scan time penalty. Acquiring images with and without mechanical loading using setup 2, load-induced cartilage compression of the patellofemoral joint was quantified in six healthy subjects.

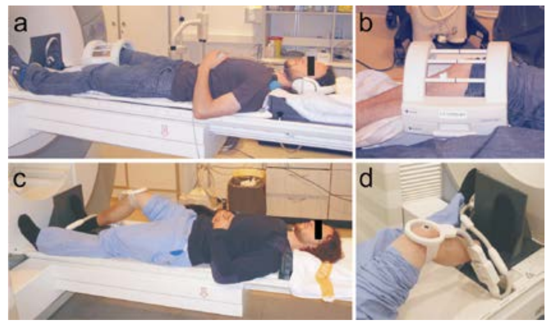

Fig. 1: Experimental setup with a loading jig for imaging of the tibiofemoral joint (a, b, setup 1) and the patellofemoral joint (c, d, setup 2).

Results: Figure 2 shows sagittal images of the tibiofemoral joint acquired with loading setup 1 without and with prospective motion correction, respectively. Images without major artifacts could be obtained with motion correction (Fig. 2b) while considerable ghosting and blurring of the cartilage contours is visible in the uncorrected image (Fig. 2a). In Fig. 3 transverse images of the patellofemoral joint acquired with loading setup 2 are presented. Signal from the dorsal knee structures was ersased with a coronal presaturation slab. The quality of the uncorrected images (Fig. 3a) is strongly affected by motion while with prospective motion correction an image quality similar to measurements without loading could be obtained (Fig. 3b). Since the foot plate of the loading jig slightly yielded under the strong force applied by the subject, the knee position changed quite a bit with the onset of loading. Position locking in the motion-corrected scans ensured that the imaging volume as well as the presaturation slab were corrected and therefore kept the position they had during protocol setup. High-resolution motion-corrected transverse images of the patellofemoral joint acquired with setup 2 are shown in Fig. 4. Comparing the images acquired without loading (a) and with loading (b) demonstrates load-induced cartilage compression at the lateral facet (white arrow). A substantial cartilage thickness decrease was detected in five out of six healthy subjects measured with this technique [6].

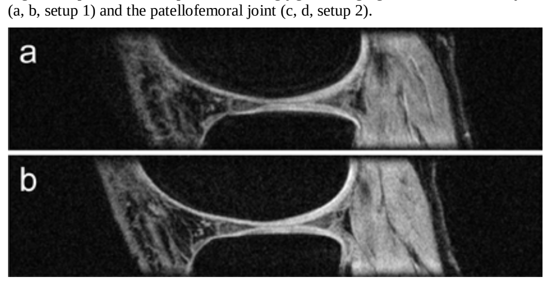

Fig. 2: Sagittal images of the tibiofemoral joint with mechanical loading: a) without motion correction, b) with motion correction.

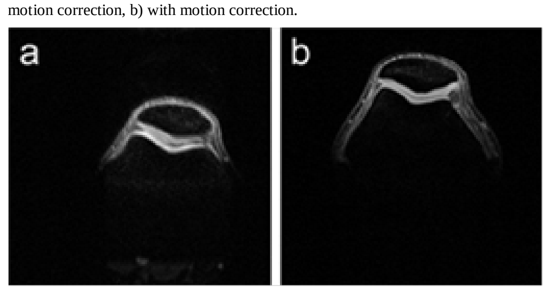

Fig. 3: Transverse images of the patellofemoral joint acquired with dorsal presaturation: a) without motion correction, b) with motion correction.

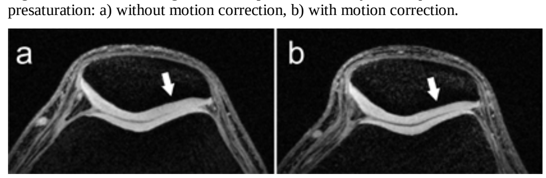

Fig. 4: High-resolution transverse images of the patellofemoral joint acquired with motion correction: a) without mechanical loading, b) with mechanical loading. The white arrows indicate the region where cartilage thickness is decreased through load-induced compression.

Discussion: It is evident that for MRI of the patellofemoral knee compartment the rigid-body approximation is fulfilled well enough for prospective motion correction with a tracking marker attached to the knee cap, enabling a considerable improvement of image quality through suppression of major motion artifacts. For imaging of the tibiofemoral joint the marker should be attached to the shin to achieve a more direct coupling. However, this method may fail for obese subjects with thicker subcutaneous fat tissue at the shin. Furthermore, marker visibility is an issue when a birdcage coil is used for signal reception. With the proposed method, mechanical properties of the knee cartilage can be studied in vivo with meaningful in situ loading paradigms. A 3D gradient-echo sequence, as applied in this work, can be used for assessing cartilage deformation under loading. It should be noted that the motion correction methodology can also be readily implemented with any other sequence. Another promising application would be a turbo spin echo measurement for the investigation of T_2 relaxation changes due to altered water concentrations in the loaded cartilage, thus probing the integrity of the chondral proteoglycan-collagen matrix.

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