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, loading of the patellofemoral compartment requires knee flexion, which impairs the stability of the experimental MR setup and therefore gives rise to considerable motion artifacts in the acquired MR images, especially since this flexed position has to be kept for several minutes during the scan. 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 an external optical tracking system consisting of a camera and a retro-grate reflector [3,4]. Since only rigid-body motion can be corrected with this method, it has so far been restricted to brain MRI. It is shown in this work that for small involuntary knee motion during a MR examination the patellofemoral compartment fulfills the rigid-body condition when the knee is tracked via a marker attached to the patella. Using prospective motion correction, MRI of the patellofemoral joint with in situ mechanical loading is demonstrated.

Materials and Methods: The experiments were performed on a Magnetom Trio 3T system (Siemens Healthcare, Germany), using an 11 cm loop coil for signal reception. Knee loading was realized with a home-built MR-compatible loading jig (Fig. 1a). Prospective motion correction was performed with a tracking system consisting of a single camera mounted inside the scanner bore and a tracking marker with a multilayer structure, which generates moiré patterns for accurate orientation measurement (an earlier version is reported in [4]). This tracking marker was glued to the knee cap of the subject (Fig. 1b). Communication with the tracking system was implemented directly on the real-time control unit of the scanner as previously proposed by Zaitsev et al. [5]. Imaging of the patellofemoral joint was performed with a spoiled 3D gradient-echo sequence using selective water excitation (TE = 9.8 ms, TR = 26 ms, in-plane resolution of transverse images: 0.6 mm, scan duration = 2:30 min). 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.

Fig. 1: Experimental setup with a loading jig (a) and a tracking marker attached to the knee cap (b).

Results: Figure 2 shows the results of the MRI experiments. Even the scans without knee loading benefitted from motion correction, as can be seen from the reduction of artifacts in Fig. 2f compared to Fig. 2b. The quality of the uncorrected images acquired with knee loading is strongly affected by motion (Fig. 2c,d), but with prospective motion correction an image quality similar to the measurements without loading can be obtained (Fig. 2g,h). In the measurements without a coronal presaturation slab, pulsation artifacts from the popliteal artery impair the image quality. These artifacts are usually removed with a proximal transverse presaturation slab, but a coronal slab has the advantage of crushing all signal from the posterior part of the knee, which does not fulfill the rigid-body approximation with respect to the knee cap. 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 from the unloaded to the loaded setup (Fig. 2c,d). Position locking ensured that the imaging volume did not change in between motion-corrected scans (Fig. 2g,h). However, there is still a slight slice mismatch between the unloaded and loaded setup, which is due to the decreaed flexion angle of the knee in the loaded setup, which in turn is associated with slight skin motion with respect to the patella. This mismatch could be reduced with a more rigid loading jig.

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. The inter-scan alignment is an additional benefit which facilitates scan planning and image assessment (Fig.2, bottom). A loop coil of appropriate size as used in this work yields a sufficient SNR for the patellofemoral joint and ensures marker visibility at all times. Strong knee loading always gives rise to involuntary motion, which has hampered MRI studies with in situ mechanical loading to date. Therefore the mechanical properties of the patellofemoral cartilage have so far only been investigated in either ex vivo or post-exercise in vivo MRI studies. With the proposed method, mechanical properties of the patellofemoral 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. The results obtained in this proof-of-concept work suggest a decrease of cartilage thickness in the loaded compared to the unloaded setup (Fig. 2). Proper assessment of cartilage deformation would require 3D data segmentation, which will be addressed in future work. 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.

References:

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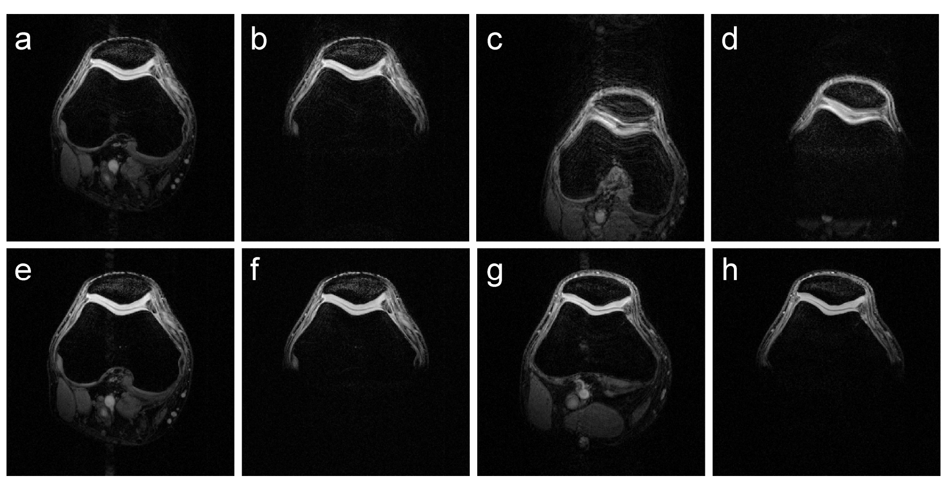

Fig. 2: Transverse images from the experiments without (a-d) and with (e-h) motion correction. Measurements were performed without (a,b,e,f) and with (c,d,g,h) knee loading as well as without (a,c,e,g) and with (b,d,f,h) a presaturation slab.