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Loading of the knee during 3.0 T MRI is associated with significantly increased medial meniscus extrusion in mild and moderate osteoarthritis

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Abstract

Purpose—Standard knee MRI is performed under unloading (ULC) conditions and not much is known about changes of the meniscus, ligaments or cartilage under loading conditions (LC). The aim is to study the influence of loading of different knee structures at 3 Tesla (T) in subjects with osteoarthritis (OA) and normal controls.

Materials and methods—30 subjects, 10 healthy and 20 with radiographic evidence of OA (10 mild and 10 moderate) underwent 3 T MRI under ULC and LC at 50% body weight. All images were analyzed by two musculoskeletal radiologists identifying and grading cartilage, meniscal, ligamentous abnormalities. The changes between ULC and LC were assessed. For meniscus, cartilage and ligaments the changes of lesions, signal and shape were evaluated. In addition, for the meniscus changes in extrusion were examined. A multivariate regression model was used for correlations to correct the data for the impact of age, gender, BMI. A paired *T*-Test was performed to calculate the differences in meniscus extrusion.

Results—Subjects with degenerative knee abnormalities demonstrated significantly increased meniscus extrusion under LC when compared to normal subjects ($p = 0.0008–0.0027$). Subjects with knee abnormalities and higher KL scores showed significantly more changes in lesion, signal and shape of the meniscus (80% (16/20) vs. 20% (2/10); $p = 0.0025$), ligaments and cartilage during LC.

Conclusion—The study demonstrates that axial loading has an effect on articular cartilage, ligament, and meniscus morphology, which is more significant in subjects with degenerative disease and may serve as an additional diagnostic tool for disease diagnosis and assessing progression in subjects with knee OA.

Keywords

Knee MRI; 3T; Osteoarthritis; Loading; Meniscus

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1. Introduction

Failure of the knee to respond to normal weight-bearing is associated with osteoarthritis and may occur due to disorder or degeneration of articular cartilage with collagen disorganization and abnormal water content or due to degeneration of the menisci with tears. The meniscus is an important multifunctional component of the knee and has a role in load transmission, shock absorption, proprioception and joint stability. Loss of cartilage and menisci results in accelerated joint degeneration. Osteoarthritis (OA) is characterized by the progressive loss of hyaline articular cartilage, and the development of altered joint congruency, subchondral sclerosis, intraosseous cyst formation and osteophytes.

Magnetic resonance imaging (MRI) has an ever-increasing role in the diagnosis and monitoring of OA [1] and the responsiveness of normal cartilage and menisci to compressive loading using MR imaging has been evaluated. Several studies have reported a significant change of thickness and signal intensity in cartilage and menisci and also in the movement and shape of menisci under loading condition [2–9]. Clinical studies have investigated the dynamic response of cartilage thickness or volume and morphological changes of the meniscus after loading, such as knee bending and running [10–13]. However, only a small number of studies directly evaluated the knee cartilage and menisci under loading using in vivo MR imaging. Specifically, Tibesku et al. [4] reported on mensical morphological changes with loading in healthy young adults, and Vedi et al. [6] performed a similar study on young athletes. Furthermore, Boxheimer and colleagues [9] investigated mensical changes with loading in subjects with arthroscopically confirmed meniscal tears. However, none have investigated the effects of loading on tissue characteristics of the knee in subjects with primary OA making it unclear if issues such as mensical instability should be a focus of sugical management of patients with OA prior to arthroplasty. This information is critical to guide clinical decision-making in this cohort.

In order to study loading related changes of knee joint structures in vivo we have developed a loading device that applies an axial load to the knee joint during MRI at 3.0 T. The aim of this study was to determine morphological changes of knee structures such as menisci and ligaments during loading in subjects with mild and moderate OA and to compare these findings to those of healthy controls.

2. Materials and methods

2.1. Subjects

The study was performed in accordance with the rules and regulations of our University Committee for Human Research and was Health Insurance Portability and Accountability Act compliant. Twenty subjects with radiographic evidence of osteoarthritis as well as 10 healthy controls were recruited. All subjects were recruited from UCSF orthopedic surgery clinics via physician referral (OA subjects) or through study flyers (controls). Inclusion criteria were female sex, age >40 years, and a body mass index of 25–35. The subjects who passed phone screening were invited to have anterior-posterior extended weight-bearing X-rays taken. On these radiographs presence or absence as well as grade of OA were documented using the Kellgren–Lawrence (KL) grading system [14,15]. Inclusion criteria for the OA participants were: self-reported pain, aching, or stiffness most days of a month during the past year in addition to a KL 2 (osteophytes and no joint space narrowing) or 3 score (osteophytes and joint space narrowing) of the study knee (readings performed by C.S. and T.L.) with the same degree of OA, less severe OA, or no OA in the contra-lateral knee. Medial joint space width (JSW) had to be larger than 2 mm, and the medial JSW smaller than the lateral JSW. Inclusion criteria for normal controls were: self-reported infrequent (or no) knee pain, aching, or stiffness during the past year and no radiographic evidence of OA on either knee (bilateral KL 0 score). General exclusion criteria were MRI contraindications including (potential) pregnancy, a history of knee surgery (including, but not limited to meniscus surgery), history of knee disease other than OA (i.e. inflammatory, crystalline, or infectious), and intra-articular steroid injection of the study knee. Once subjects met all inclusion and exclusion criteria, they were officially enrolled in the current study.

2.2. MR imaging

MRI of the study knee of each subject was acquired using a 3 T GE Excite Signa MR scanner (General Electric, Milwaukee, WI) with a transmit/receive quadrature knee coil (Clinical MR Solutions, Brookfield, WI). The imaging protocol included sagittal 2D T2-weighted fat-saturated fast spin-echo (FSE) sequences (TR/TE: 4000/48 ms, FOV: 14 cm, matrix: 384 × 192, slice thickness: 2.0 mm, echo train length: 9, bandwidth: 23.44 kHz, number of excitations (NEX): 2), coronal 2D T2-weighted fat-saturated fast spin-echo (FSE) sequences (TR/TE: 3000/10 ms, FOV: 14 cm, matrix: 384 × 192, slice thickness: 2.0 mm, echo train length: 10, bandwidth: 23.44 kHz, NEX: 2), and coronal 3D water excitation high-resolution spoiled gradient-echo (SPGR) sequences (TR/TE: 22/7.0 ms, flip angle 18, FOV: 14 cm, matrix: 512 × 512, slice thickness: 1.5 mm, bandwidth: 31.25 kHz, NEX: 1).

All imaging procedures were performed at the Department of Radiology and Biomedical Imaging of our University. All procedures were explained in detail to each subject and all subjects signed an informed consent form approved by the Committee on Human Research at our University. The study consisted of two phases: unloaded imaging, and loaded imaging at 50% body weight. All imaging was performed in the early morning to avoid the influence of weight-bearing throughout the day. Subjects arrived at the imaging center 30 min prior to their appointment time and were kept in an unloaded position (wheelchair) until their scan time. Subjects were positioned in the MR scanner in a supine position in a MR-compatible axial loading device (Fig. 1). The lower extremity to be studied was positioned in 10° of external rotation with the knee flexed to 20°, and stabilized with pillows and padding to prevent movement during scanning. At this time sagittal and coronal FSE images, as well as coronal SPGR images were acquired. Next, a load of 50% of the subjects' body weight was applied to the loading device, which transmitted the force through a pulley system using a loading footplate to the test lower extremity. The result is a 50% body weight load on the lower extremity, intended to mimic static standing conditions. Once loaded, the imaging protocol was repeated and loaded images were acquired.

2.3. MR image analysis

All MR images of the knee obtained during loading and unloading were evaluated and scored independently on picture archiving communication system (PACS) workstations (Agfa, Ridgefield Park, NJ, USA) by two musculoskeletal radiologists separately with 20 and 4 years of experience in musculoskeletal imaging; if scores were not identical consensus readings by both radiologists were performed. During the reading session ambient light was reduced and no time constraints were used.

The whole-organ magnetic resonance imaging score (WORMS) was used to semiquantitatively evaluate the images [16–18]. Since only a relatively small number of lesions were expected in these subjects with mild, moderate and no OA the number of anatomical compartments was reduced from 15 to 6 compartments and included the patella, trochlea, medial and lateral femur, and medial and lateral tibia. Using the semi-quantitative scoring system, the following structures were separately evaluated: cartilage, ligaments, menisci. Cartilage abnormalities were scored using an eight-point scale: 0 = normal thickness and signal; 1 = normal thickness but abnormal signal on fluid sensitive sequences; 2.0 = partial-thickness focal defect <1 cm in greatest width; 2.5 = full-thickness focal defect

<1 cm in greatest width; 3 = multiple areas of partial-thickness (Grade 2.0) defects intermixed with areas of normal thickness, or a Grade 2.0 defect wider than 1 cm but <75% of the region; 4 = diffuse (≥75% of the region) partial-thickness loss; 5 = multiple areas of full-thickness loss (grade 2.5) or a grade 2.5 lesion wider than 1 cm but <75% of the region; 6 = diffuse (≥75% of the region) full-thickness loss.

Alterations in meniscal morphology were assessed separately in six regions (medial and lateral: anterior horn, body, posterior horn) using a four-level scale (0, normal; 1, intrasubstance abnormalities; 2, non-displaced tear; 3, displaced or complex tear; 4, complete destruction/maceration). In addition meniscal extrusion was calculated in mm. The distance from the outer inferior edge of the meniscus to the outermost edge of the articular cartilage of the tibial plateau was measured for both the medial and lateral menisci [6]. A normal meniscus was defined with an extrusion less then 3 mm, an extrusion more the 3 mm was defined as abnormal. Ligaments were evaluated using a four point scale from 0 to 3 (0 = no lesion, 1 = Grade 1 sprain (signal changes around ligament), 2 = Grade 2 sprain (partial tear), 3 = Grade 3 sprain (complete tear). Based on the MR findings a knee was defined as abnormal if a WORMS value of ≥ 1 was found.

The changes between unloading and loading conditions were assessed. For meniscus, cartilage and ligaments the changes of lesions (WORMS score), changes in signal, changes in shape were studied, and in addition for meniscus, changes in extrusion were evaluated.

2.4. Statistical analysis

All statistical processing was performed with JMP software Version 7 (SAS Institute, Cary, NC). Statistical significance for differences in age, height and weight between the groups was determined using one-way analysis of variance (ANOVA). A multivariate regression model was used for correlations to correct the data for the impact of age, gender, BMI. Also a paired *T*-Test was performed to calculate the differences in meniscus extrusion in loading and unloading for subjects with and without cartilage and meniscus lesions and different KL-Scores. The level of significance was defined for all calculations as $p < 0.05$.

3. Results

3.1. Subject characteristics

There were no significant differences in age (mean age 55.67 years, $p = 0.1648$), height (1.62 m, p = 0.8512) or weight (72.94 kg, $p = 0.8329$) between subjects with different KL-scores in the statistical evaluation (Table 1).

3.2. Prevalence of focal knee abnormalities

17/30 (57%) subjects had meniscus lesions with increasing prevalence according to the KL-Scores ($p = 0.0004$). 1/10 subjects with KL 0, 7/10 subjects with KL 2 and 9/10 subjects with KL 3 had meniscus lesions. Subjects with meniscal lesions frequently had abnormalities in more than one region of the meniscus; 49 abnormalities were diagnosed in all 6 compartments. The prevalence of intrasubstance signal abnormalities was highest (24/49; 49%, WORMS 1), followed by displaced or complex tears (10/49; 20.4% WORMS 3) and non-displaced tears (8/49; 16.7% WORMS 2). 29/30 (97%) had cartilage lesions. Subjects frequently had abnormalities in more than one region of the cartilage with 81 abnormalities were recorded in all 6 compartments. Ligamentous abnormalities were found in 6/30 (20%) subjects.

3.3. Overall changes under loading

In 18/30 (60%) subjects the meniscus changed under loading (Table 2). Subjects were found to have changes of meniscus lesions according the WORMS Score (11/30; 36.7%), changes of signal (11/30; 43.4%), shape (19/30; 33.3%) and increase of meniscal extrusion (16/30; 53.33%) (Fig. 2). The ligaments changed in 7/30 (23.3%), in 2/30 (6.7%) a change of lesion grading according the WORMS score was found, in 4/30 (13.3%) signal change and in 7/30 (23.3%) change of shape (like lengthen of the ligament, thinning) were detected. The cartilage showed changes in 5/30 (16.6%) subjects under loading: in 4/30 (13.3%) subjects changes of lesions according the WORMS score were found, in 3/30 (10%) change of signal and in 4/30 (13.3%) changes in shape (like thickness in MR-images) were demonstrated.

3.4. Changes under loading in subjects with different KL-Scores

Subjects were divided into a group with KL 0 and with KL 2–3 scores. Differences in meniscus, ligaments and cartilage diagnosed with MRI were analyzed in these subgroups as outlined in Table 2. Subjects with KL 2 and 3 scores had significantly more changes of the meniscus (80% (16/20)) than normal subjects (20% (2/10)) ($p = 0.0025$). Loading induced changes of meniscal extrusion were more severe in subjects with KL2 and 3 scores (70% (14/20) vs. 20% (2/10), $p = 0.0056$). Significant differences were also found for ligaments (35% (7/20) vs. 0%, $p = 0.003$). As for cartilage only subjects with KL scores 2–3 showed changes in cartilage morphology (25% (5/20) vs. 0%, $p = 0.0215$).

3.5. Subjects with meniscus lesions

Subjects were also divided according to meniscus abnormalities (Table 3). Subjects with meniscus lesions WORMS ≥ 2 had significantly more changes of the signal intensity (58.82% (10/17) vs. 23.08% (3/13), $p = 0.0205$), shape (52.94% (9/17) vs. 7.69% (1/13), $p = 0.0001$) and extrusion (70.59% (12/17) vs. 30.77% (4/13), $p = 0.0014$) of the meniscus under loading conditions. The ligaments showed significantly more changes (35.29% (6/17) vs. 7.69% (1/13), $p = 0.0246$) in subjects with meniscus abnormalities (WORMS ≥ 2). Only subjects with meniscus lesions showed changes of the cartilage in lesion, signal and shape.

3.6. Subjects with cartilage lesions

Dividing the subjects into two groups with and without femorotibial cartilage lesions (WORMS ≥ 2) significantly more subjects had changes in lesions, signal and shape of meniscus and cartilage during loading. The ligaments did not show changes between the groups (Table 4).

3.7. Extrusion of meniscus

Between unloading and loading only the medial meniscus demonstrated a significant extrusion for all subjects (1.23 ± 1.56 mm vs. 1.92 ± 2.25 mm, $p = 0.0003$) (Table 5, *p*Fig. 2*************). The subjects were divided into groups with and without meniscus lesions with and without cartilage lesions and with and without OA in the radiograph according the KL-Score. A significant change of meniscal extrusion under loading was only found in individuals with meniscus, cartilage and radiographic abnormalities (Worms ≥ 2, KL ≥ 2) (= 0.0008–0.0027). Subjects without pathology did not show a significant change in extrusion under loading.

4. Discussion

The results of this study show that subjects with knee abnormalities related to OA have significantly increased meniscal extrusion under loading conditions compared to normal subjects. We could also demonstrate that subjects with knee abnormalities and higher KL

Scores showed significantly more changes of lesions, signal and shape in meniscus, ligaments and cartilage under loading conditions.

Our results agree with previous studies in which changes of meniscus and cartilage under loading conditions were described [4–6,8,9,19]. However, in addition we also studied the effect of knee joint degeneration under direct loading conditions at 3 T comparing subjects with osteoarthritis based on the KL-score with healthy volunteers.

Load between the femur and tibia generates a compressive force on the meniscus which, with its wedge-shaped cross-section, results in an outwardly directed radial vector [6]. Tibesku et al. [4] evaluated the meniscal movement and deformation in vivo under load bearing conditions. They examined 15 healthy knees and found out, that the inner and outer distance increased with load. The inner distance increased more than the outer, resulting in a compression of the periphery. Vedi et al. [6] also examined the meniscal movement in vivo using a vertical open magnet MR scanner in normal knees under load in 16 young footballers. These authors compared erect weight-bearing regions with sitting non-weight-bearing regions. In the current study, patients had the same, supine, knee position during loading and unloading conditions. In contrast to our results, their most significant differences between weight-bearing and non-weight-bearing were the movement and vertical height of the anterior horn of the lateral meniscus, but these investigators focused mainly on sagittal images.

Boxheimer et al. [8] examined asymptomatic volunteers wit a 0.5 T open configuration MR-System. They obtained coronal and sagittal images with the knee supine in neutral, supine in 90° flexion with external and internal rotation, as well as in upright weight-bearing position. They showed, meniscal movement was most prominent in the anterior horn of the medial meniscus with the knee in the supine position in 90° flexion with external rotation. In accordance to our results, meniscal protrusion was more frequently present in the medial meniscus and averaged less than 3 mm in normal volunteers. In another study Boxheimer et al. [9] examined patients with meniscal tears with this setting. Between the different knee positions, meniscal displacement of 3 mm or more was noted in 42% of menisci with tears. Displaced menisci most commonly had complex, radial, or longitudinal tear configurations. Our results also showed significantly higher meniscus extrusion when the meniscus had tears (WORMS 2–4).

Mastrokalos et al. performed an in vivo study and examined fifteen knees of healthy young volunteers [19]. They analyzed the changes of the internal and external meniscal interhorn distance of the medial and lateral meniscus (minimum and maximum distance between anterior and posterior horn) under loading and with and without flexion. They concluded that loading increases the internal and external meniscal interhorn distance. This correlates to our findings of significant extrusion of the medial meniscus under loading.

All of these 4 investigators used low field MR scanners with a field strength varying between 0.18 and 0.5 T. Our study is the first study which used higher field strengths (3 T) under controlled loading conditions allowing enhanced anatomical visualization of the knee joint structures, in particular the cartilage. This may also in part explain the higher number of loading associated changes for cartilage and menisci shown in this study. Previous in vivo and in vitro studies have demonstrated superior visualization of cartilage, ligaments and meniscus and other small structures at 3 T vs. 1.5 T [20–24]. Wong et al. demonstrated [20] an increase in sensitivity and diagnostic performance observed at 3 T for cartilage lesion detection of the knee in vivo and Masi et al. [24] demonstrated improved diagnostic performance at 3 T vs. 1.5 T MRI for cartilage lesions in a porcine model.

Investigators also assessed the dynamic response of cartilage thickness or volume, as well as changes of the meniscus after loading, with repeated knee bending and running [10–13]. Eckstein et al. [11] studied the in vivo deformation behavior of patellar and femorotibial cartilage for different types of physiological activities. They examined 12 volunteers after physical activity such as running (5 min), knee bends (90 s) and cycling (10 min) and 10 volunteers after knee bends on one feet, static compression (2 min static loading of one leg with 200% body weight) and high impact loading (10 jumps from a chair (40 cm) onto one leg) resulting in deformation of femoro-tibial cartilage. It was reported that patellar cartilage deformation showed a dose dependent response more intense loading leading to greater in vivo surface to surface strains. In the femoro-tibial joint little deformation was observed except during high impact activities, highly significant changes were seen in the medial and lateral tibia after jumps. Figs. 3 and 4

Kessler et al. [12] examined 48 male athletes before and after running (51,020 km) with MRI. Tibial, patellar and meniscal volumes showed significant reductions after running. In another study [13], they examined 20 knees of male athletes before and after a 20 km run and after a recovery period of 1 h. The subjects showed a volume reduction of the tibial cartilage of 5.1% and 8.2% of meniscus volume after the run. This study also showed that not all cartilage and meniscus volume changes induced by the 20-km run were fully restored after a 1 h rest period. It was noted that the recovery of the medial meniscus lagged behind the other structures.

In addition to assessing cartilage pathology, thickness and volume, recent studies have shown the potential of MR imaging parameters to reflect changes in the biochemical composition of cartilage under loading [10,25]. T2 relaxation time mapping is currently most frequently used to study cartilage biochemical composition: it is sensitive to a wide range of water interactions in tissue and in particular depends on the content, orientation and anisotropy of collagen [26,27]. Mosher et al. [10] examined knee cartilage T2 values of seven subjects before and immediately after 30 min of running. There was a statistically significant decrease in T2 of the superficial 40% of weight-bearing femoral cartilage after exercise. These investigators assumed that cartilage compression might result in greater anisotropy of superficial collagen fibers. In our study we only examined the morphological changes under loading. Changes of the meniscus and cartilage matrix due to loading may add additional information in better understanding the evolution of osteoarthritis and need further investigation.

In conclusion our study demonstrated a relationship between OA and loading related changes of meniscus, cartilage and ligaments in individuals with OA compared with healthy subjects. Patients with radiographic and MR signs of OA had significantly increased meniscal extrusion under loading conditions compared to normal subjects and significantly more loading induced changes of signal and shape of the menisci, ligaments and cartilage as well as changes in pre-existing lesions. These findings suggest that in vivo loading may be a valuable tool to evaluate tissue degeneration in the evolution of OA.

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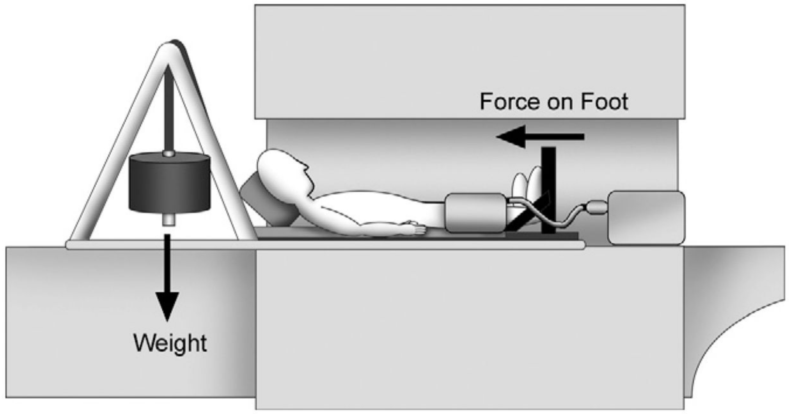

Fig. 1.
MRI-compatible axial loading device. The patient is placed in a supine position within the scanner bore. Hanging weights are supported by a loading frame, and a series of pulleys transfers the resulting force to a foot loading plate.

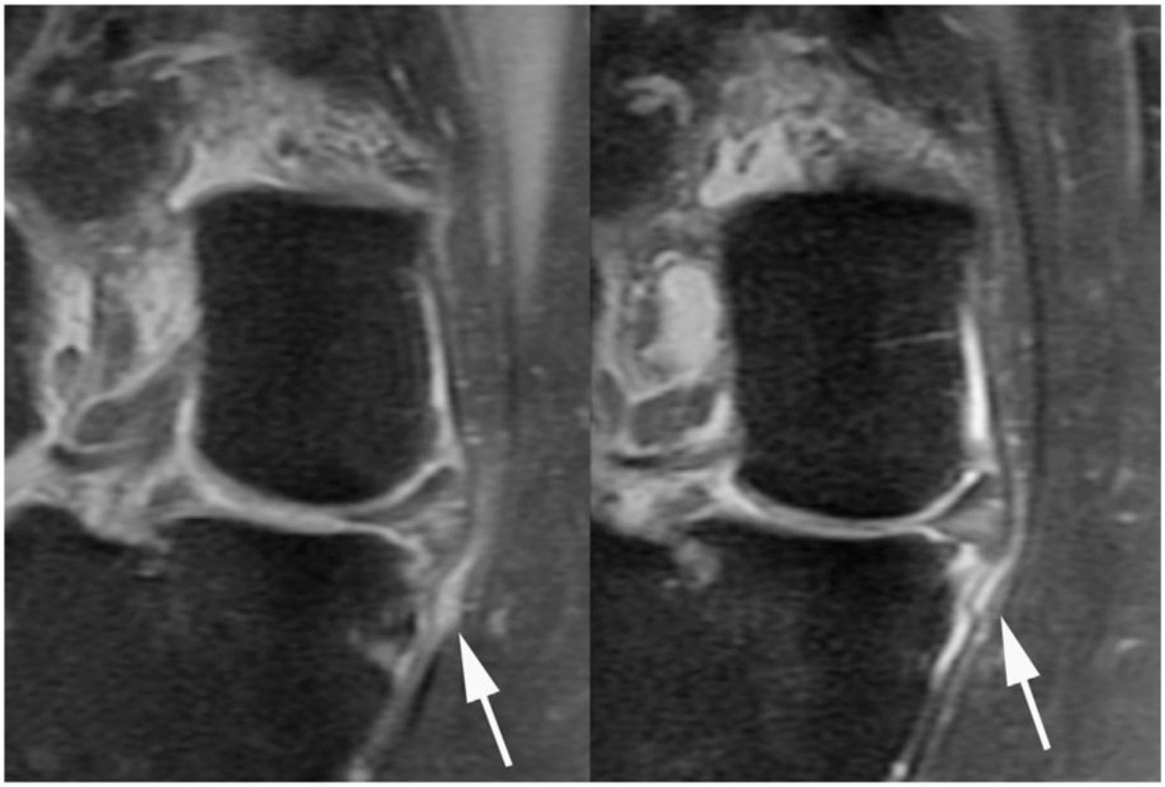

Fig. 2.
Representative MR images show the medial meniscus body before (a) and under loading conditions (b). Under loading there is an increasing extrusion of the meniscus and changes in shape.

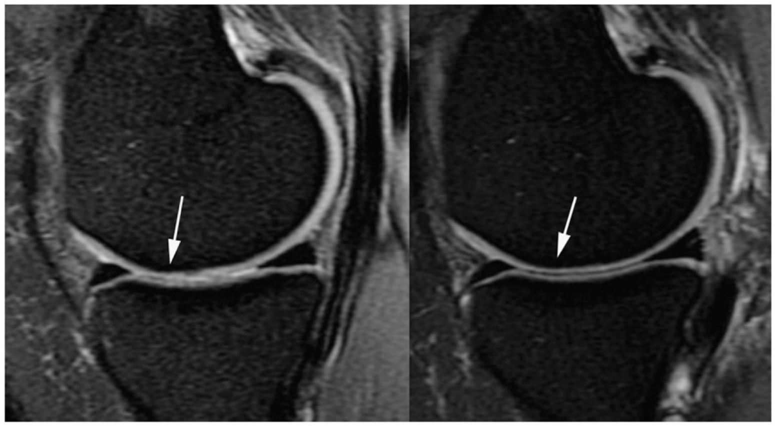

Fig. 3.

Representative MR images show the medial femoral and tibial cartilage before (a) and during loading conditions (b). There is a change of the cartilage lesion grading. A questionable superficial, partial thickness cartilage lesion at the femoral condyle in (a) is not demonstrated under loading conditions (b).

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Fig. 4.
Representative MR images show the posterior crucial ligament before (a) and during loading conditions (b). There is a change in shape of the ligament under loading with the PCL being more extended.

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Table 1

Subject characteristics (age, height and weight) for each group. No statistically significant differences were found in these parameters between individuals with and without OA.

	All		KL0		KL2		KL3		
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**AN OVA**
Age	55.67	5.63	52.9	6.51	57.1	6.15	57	3.02	0.1648
Height (m)	1.62	0.08	1.61	0.07	1.62	0.07	1.63	0.10	0.8512
Weight (kg)	72.94	8.22	72.44	6.76	72.14	10.70	74.26	7.39	0.8329

Table 2

Changes under loading for meniscus, ligaments and cartilage in all subjects and in subjects with different KL-Scores. Subjects with higher KL Scores showed significantly more changes of lesion and shape in meniscus, ligaments and cartilage, changes of signal in the ligaments and more changes in meniscus extrusion under loading conditions.

	All		KL-Score				Statistical analysis (p)
			KL 0		KL2-3		
	Number	Percent	Number	Percent	Number	Percent	Multiregression model (likelihood ratio)
Subjects	30	100	10	100	20	100	
Changes under loading							
Meniscus							
Change any	18	60	2	20	16	80	0.0025 *
Change lesion	11	36.67	1	10	10	50	0.0320 *
Change signal	13	43.33	2	20	11	55	0.1014
Change shape	10	33.33	0	0	10	50	0.0012 *
Change extrusion	16	53.33	2	20	14	70	0.0056 *
Ligaments							
Change any	7	23.33	0	0	7	35	0.0030 *
Change lesion	2	6.67	0	0	2	10	0.1072
Change signal	4	13.33	0	0	4	20	0.0488 *
Change shape	7	23.33	0	0	7	35	0.0030 *
Cartilage							
Change any	5	16.67	0	0	5	25	0.0215 *
Change lesion	4	13.33	0	0	4	20	0.0383 *
Change signal	3	10	0	0	3	15	0.1254
Change shape	4	13.33	0	0	4	20	0.0383 *

* Correction for age, weight and height.

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Table 3

Changes under loading for meniscus, ligaments and cartilage in all subjects and in subjects with and without meniscus abnormalities. Subjects with meniscus abnormalities WORMS ≥ 2 Scores showed significantly more changes of signal and shape in meniscus and cartilage, changes of the lesions in cartilage, changes of shape of the ligaments and more changes in meniscus extrusion under loading conditions.

	All		**Meniscus abnormalities**				
			WORMS ≤ 1		**WORMS ≥ 2**		**Statistical analysis (*p*)**
	Number	**Percent**	**Number**	**Percent**	**Number**	**Percent**	**Multiregression model (likelihood ratio)**
Subjects	30	100	13	100	17	100	
Changes under loading							
Meniscus							
Change any	18	60.00	4	30.77	14	82.35	0.0007*
Change lesion	11	36.67	3	23.08	8	47.06	0.0626
Change signal	13	43.33	3	23.08	10	58.82	0.0205*
Change shape	10	33.33	1	7.69	9	52.94	0.0001*
Change extrusion	16	53.33	4	30.77	12	70.59	0.0014*
Ligaments							
Change any	7	23.33	1	7.69	6	35.29	0.0246*
Change lesion	2	6.67	1	7.69	1	5.88	0.7093
Change signal	4	13.33	1	7.69	3	17.65	0.5079
Change shape	7	23.33	1	7.69	6	35.29	0.0246*
Cartilage							
Change any	5	16.67	0	0.00	5	29.41	0.0109*
Change lesion	4	13.33	0	0.00	4	23.53	0.0177*
Change signal	3	10.00	0	0.00	3	17.65	0.0107*
Change shape	4	13.33	0	0.00	4	23.53	0.0177*

* Correction for age, weight and height.

Table 4

Changes under loading for meniscus, ligaments and cartilage in all subjects and in subjects with and without cartilage abnormalities at the femorotibial compartments. Subjects with tibiofemoral cartilage abnormalities (WORMS ≥ 2) showed significantly more changes of lesion, signal and shape in meniscus and cartilage and more changes in meniscus extrusion under loading conditions.

	All		Femorotibial cartilage abnormalities				
			WORMS ≤ 1		WORMS ≥ 2		Statistical analysis (*p*)
	Number	Percent	Number	Percent	Number	Percent	Multiregression model (likelihood ratio)
Subjects	30	100	14	100	16	100	
Changes under loading							
Meniscus							
Change any	18	60.00	4	28.57	14	87.50	0.0003*
Change lesion	11	36.67	2	14.29	9	56.25	0.0117*
Change signal	13	43.33	2	14.29	11	68.75	0.0019*
Change shape	10	33.33	2	14.29	8	50.00	0.0084*
Change extrusion	16	53.33	4	28.57	12	75.00	0.0024*
Ligaments							
Change any	7	23.33	2	14.29	5	31.25	0.1728
Change Lesion	2	6.67	2	14.29	0	0.00	0.0557
Change signal	4	13.33	2	14.29	2	12.50	0.8024
Change shape	7	23.33	2	14.29	5	31.25	0.1728
Cartilage							
Change any	5	16.67	0	0.00	5	31.25	0.0045*
Change lesion	4	13.33	0	0.00	4	25.00	0.0056*
Change signal	3	10.00	0	0.00	3	18.75	0.0412*
Change shape	4	13.33	0	0.00	4	25.00	0.0056*

*Correction for age, weight and height.

Table 5

Between unloading and loading only the medial meniscus demonstrated a significant extrusion in all subjects. The meniscus extrusion changed more significantly under loading in subjects with higher KL-Scores, meniscus or cartilage abnormalities abnormalities (KL ≥ 2, Worms ≥ 2). Subjects without pathology did not show significant extrusion under loading.

Extrusion medial meniscus in subjects (m	**Unloading**		**Loading**		**Statistical analysis (*p*)**
	Mean	**SD**	**Mean**	**SD**	**Paired *T* test**
All	1.23	1.56	1.92	2.25	0.0003*
With KL 0	0.2	0.42	0.5	1.08	0.1934
With KL 2–3	1.75	1.67	2.63	2.36	0.0008*
With meniscus WORMS ≤ 1	0.31	0.63	0.62	1.19	0.1039
With meniscus WORMS ≥ 2	1.94	1.7	2.92	2.38	0.0012*
With cartilage WORMS ≤ 1 femorotibial	0.68	1.2	1.07	1.77	0.0512
With cartilage WORMS ≥ 2 femorotibial	1.72	1.71	2.66	2.41	0.0027*