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Loading and knee alignment have significant influence on cartilage MRI T2 in porcine knee joints

T. Shiomi †, T. Nishii †‡*, H. Tanaka §, Y. Yamazaki ||, K. Murase ||, A. Myoui †¶, H. Yoshikawa †, N. Sugano †‡

† Department of Orthopaedic Surgery, Osaka University Medical School, Osaka, Japan
‡ Department of Orthopaedic Medical Engineering, Osaka University Medical School, Osaka, Japan
§ Department of Radiology, Osaka University Medical School, Osaka, Japan
|| Department of Medical Physics and Engineering, Osaka University Medical School, Osaka, Japan
¶ Medical Center for Translational Research, Osaka University Hospital, Osaka, Japan

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SUMMARY

Objective: Physiological magnetic resonance imaging (MRI) under loading or knee malalignment conditions has not been thoroughly investigated. We assessed the influence of static loading and knee alignment on T2 (transverse relaxation time) mapping of the knee femoral cartilage of porcine knee joints using a non-metallic pressure device.
Methods: Ten porcine knee joints were harvested *en bloc* with intact capsules and surrounding muscles and imaged using a custom-made pressure device and 3.0-T MRI system. Sagittal T2 maps were obtained (1) at knee neutral alignment without external loading (no loading), (2) under mechanical compression of 140 N (neutral loading), and (3) under the same loading conditions as in (2) with the knee at 10° varus alignment (varus loading). T2 values of deep, intermediate, and superficial zones of the medial and lateral femoral cartilages at the weight-bearing area were compared among these conditions using custom-made software. Cartilage contact pressure between the femoral and tibial cartilages, measured by a pressure-sensitive film, was correlated with cartilage T2 measurements.
Results: In the medial cartilage, mean T2 values of the deep, intermediate, and superficial zones decreased by 1.4%, 13.0%, and 6.0% under neutral loading. They further decreased by 4.3%, 19.3%, and 17.2% under varus loading compared to no loading. In the lateral cartilage, these mean T2 values decreased by 3.9%, 7.7%, and 4.2% under neutral loading, but increased by 1.6%, 9.6%, and 7.2% under varus loading. There was a significant decrease in T2 values in the intermediate zone of the medial cartilage under both neutral and varus loading, and in the superficial zone of the medial cartilage under varus loading ($P < 0.05$). Total contact pressure values under neutral loading and varus loading conditions significantly correlated with T2 values in the superficial and intermediate zones of the medial cartilages.
Conclusions: The response of T2 to change in static loading or alignment varied between the medial and lateral cartilages, and among the deep, intermediate, and superficial zones. These T2 changes were significantly related to the contact pressure measurements. Our results indicate that T2 mapping under loading allows non-invasive, biomechanical assessment of site-specific stress distribution in the cartilage.

Introduction

Knee imaging using quantitative magnetic resonance imaging (MRI) techniques such as delayed gadolinium-enhanced MRI of cartilage (dGEMRIC), transverse relaxation time (T2) mapping and T1rho showed great advancements in non-invasive assessment of the articular cartilage, particularly with regard to matrix composition and degenerative changes[1–4]. Sensitive evaluations of water, collagen, and proteoglycan content or collagen arrangement in the cartilage *in vivo* were made using the aforementioned techniques, without performing destructive retrieval analysis. Quantitative MRI revealed site-specific and age- or sex-dependent variation in normal cartilage composition and allowed early detection of osteoarthritic involvement of knee cartilages[3,5]. MRI in most of these investigations was performed without externally loading the knee with patients or volunteers lying supine on the imaging table.

The articular cartilage in the knee joint has a load-bearing function in conjunction with the interposed meniscus owing to its highly organized collagen architecture and the osmotic pressure

* Address correspondence and reprint requests to: Takashi Nishii, Department of Orthopaedic Medical Engineering, Osaka University Medical School, 2-2 Yamadaoka, Suita, Osaka 565-0871, Japan. Tel: 81-6-6879-3271; Fax: 81-6-6879-3272.
E-mail address: nishii@ort.med.osaka-u.ac.jp (T. Nishii).

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due to proteoglycan and interstitial water. While performing daily activities such as standing or walking, the articular cartilage in the knee joint is subjected to substantial external loading, which leads to cartilage deformation along with alteration in the collagen architecture or water distribution within the cartilage[6,7]. This property of the cartilage under loading differs among individuals, depending upon factors such as weight, knee alignment, ligament instability, and involvement of injury or degeneration of the cartilage and meniscus. Therefore, it is important to evaluate the articular cartilage under loading for each individual to understand the physiological and biomechanical status of the knee and to explore the disorders of stress resistance function of the cartilage that may lead to progression of osteoarthritis.

Responsiveness of the normal cartilage to compressive loading was investigated using excised cartilage plugs or exposed articular surfaces in experimental studies on MRI[8–10]. Changes in cartilage thickness and signal intensity were observed in response to an increase in loading. Among all MRI parameters, cartilage T2 mapping of cartilage is influenced by water content and collagen fiber orientation of cartilage and is indicated as a potent quantitative index for the load response of the articular cartilage[11–13]. However, few studies have investigated the load response of the articular cartilage in an intact knee joint, with preservation of the other fundamental structures such as menisci, ligaments, and capsules.

We developed a non-metallic pressure device for intact porcine knee joints that allowed MRI under variable loading or knee alignment conditions as a whole-joint model retaining the menisci, ligaments, and capsules *in situ*. The purpose of this study was to assess the load-bearing function of the femoral cartilage in association with knee alignment, using cartilage T2 as a surrogate of cartilage matrix changes.

Materials and methods

Preparation of porcine specimens and loading device

Ten fresh porcine knee joints were harvested *en bloc* with intact capsules and surrounding muscles and stored at −40°C. On the day of MRI, specimens were thawed at room temperature before the investigation. After conducting imaging and mechanical experiments, macroscopic inspection of the joint surfaces did not reveal any signs of joint disease or cartilage degeneration in the specimens used.

Knee joints were mounted in the non-metallic custom compression device, which was fitted into the head coil (eight-channel brain phased array coil, GE Healthcare, WI, USA) of an MRI scanner (Fig. 1). The femoral shaft was firmly fixed to the non-mobile base of the device by holding it between two acryl blades. The tibia was firmly fixed to the opposite side of the mobile plate such that tibial movement along the longitudinal axis and varus/valgus rotation of the knee was possible. The knee was positioned at 20° flexion, simulating the normal standing position of pigs. Under static loading conditions, axial compression force was transmitted to the knee joint *via* a sliding plate bounded by a foam material. The load was generated by a screw compression driver on one end. The viscoelastic foam material, which was made of polyolefin elastomer (Fig. 1), was compressed by 10 mm displacement and the uniaxial constitution force according to the degree of displacement was transmitted to the knee joint through an acryl plate. We used new foam material on each knee joint to avoid degeneration of the foam material. Hayashi *et al.* studied static and dynamic characteristics and stability of some kinds of elastomeric polymers by uniaxial tensile and fatigue tests in air, and demonstrated polyolefin elastomer had little stress relaxation[14]. The compression force was applied to achieve 140 N across the tibiofemoral joint, which corresponded to approximately one-third of the body weight of the specimen.

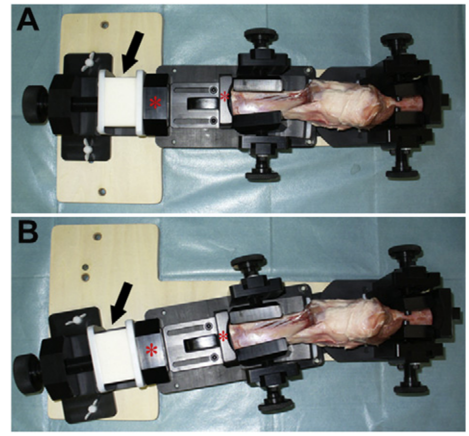

Fig. 1. Custom-made compression device along with a porcine knee joint. Axial compression force was transmitted to the knee joint *via* a sliding plate (*) bounded by a viscoelastic foam material (arrow). A: neutral position. B: 10° varus position.

Accuracy test of loading in custom compression device

In a preliminary test, loading force in the custom compression device was measured using an incompressible testing rod equipped with a load cell (TU-BR, TEAC, Japan). The accuracy of the load cell is within 0.05% rated output in non-linearity which means accuracy of linear output, and within 0.05% rated output in hysteresis which means reproducibility during loading. Compression force equivalent to 140 N was applied continuously, and real force across the testing rod was recorded from the load cell after 5, 10 and 30 min of compression to determine the time course of change in force measurements. This test was repeated five times, and the mean force measurements and the values of coefficient of variation [standard deviation/mean × 100 (%)] were 140 N and 1.5% at 5 min, 138 N and 1.5% at 10 min, and 134 N and 1.8% at 30 min. We confirmed that constant pressure was applied after 5 min–30 min of compression by the loading device.

MRI

MRI was performed using a 3.0-T MRI system (GE Healthcare). The device was placed in a head-first orientation in the center of the head coil. First, sagittal T2 maps and three-dimensional (3D) spoiled gradient-echo (SPGR) images were obtained for the lateral and medial femorotibial joints with neutral knee alignment and no external compression (no loading). Next, sagittal T2 maps and 3D SPGR images were obtained after 5 min of compression (neutral loading-1). After imaging at neutral loading-1, compression was continued for 30 min. Sagittal T2 maps and 3D SPGR images were obtained again after 30 min of compression (neutral loading-2) to examine the influence of loading duration on cartilage T2 measurements compared with neutral loading-1. Finally, sagittal T2 maps and 3D SPGR images were obtained under the same compression conditions as above with the knee at 10° varus alignment (varus loading).

T2 maps were generated using a monoexponential fit from two-dimensional (2D) multi-spin echo sequences (TR, 1500 ms; eight echoes between 10.0 ms and 80.0 ms; field of view, 10 cm; matrix, 384 × 256; slice thickness, 3 mm; signal averaging, 1; acquiring time, 6 min and 51 s). Frequency encoding was oriented in the cranial-to-caudal direction. 3D SPGR images were acquired with fat suppression (TR, 50 ms; TE, 10 ms; field of view, 10 cm; matrix, 512 × 256; slice thickness, 3 mm; signal averaging, 4; acquiring