

Weight-bearing cross-country running influences on the knee articular cartilage -a study using T2 MRI and muscle monitoring

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Abstract: The purpose of this study was to develop a quantitative method to acquire and analyze the transverse relaxation time (T2 relaxation) of the magnetic resonance imaging of in-vivo knee joint articular cartilage. To reveal the practical significance of this research, participants who underwent weight-bearing cross-country running were assessed by MR T2 imaging and knee functional test. As a result, temporary changes in the cartilage relaxation time at regions of interest were observed shortly post the running ($P < 0.05$), accompanying with EMG signal monitored in muscles around knee. This study shows the potentials of utilizing quantitative MRI T2 imaging technique as a non-invasive approach to detect the knee articular cartilage loading and stress, which is important for earlier prevention and intervention of cartilage lesions.

Keywords: Knee articular cartilage; Medical imaging; Cross-country running.

1. Introduction

Articular cartilage covers the tibiofemoral lubricated surfaces inside the knee. It distributes biomechanical loading onto the joint contacts, and enables bones to glide easily with minimal friction. Researchers have found that the key components of the articular cartilage are water, type II collagen, chondroitin sulfates, and proteoglycans (PGs). From microstructure point of view, the interaction of fluid and collagen matrix provides articular cartilage with viscoelastic and mechanical properties for bearing load. The overall health and function of articular cartilage depends on the appropriate amount and distribution of its key internal components, particularly PGs, water, and the collagen network [2,3,4].

Magnetic resonance imaging (MRI) can provide direct visualization and useful morphological information of the articular cartilage and soft tissues. But not all the MRI sequences are sensitive to the cartilage components, hence developing MRI methods that are able to investigate the PG concentration alteration within articular cartilage are conducive to early evaluation before severe morphological damage occurs.

Quantitative T2 MRI has shown increasingly relevance in detecting the earliest degenerative changes inside cartilage. In recent years, quantitative T2 MRI, based on the analysis of relaxation times in the transverse plane, has been adopted as a promising diagnostic reference for cartilage lesion detection. T2 relaxation, also known as the relaxation in transverse plane, can reflect the ability of free water molecules moving and exchanging energy inside the extracellular matrix within cartilage. The damage of collagen or PG in cartilage matrix can increase water content in cartilage and cause shifting of T2 relaxation times. Previous researchers found positive correlation between the cartilage water content and T2 relaxation time, and negative correlation between cartilage T2 times and PG content. In this way, T2 relaxation time has potential to serve as a characterized imaging parameter that

can reflect the knee articular cartilage biochemical components and health status upon appropriate quantification.

The computation of T2 relaxation time using quantitative MRI depends on the applied algorithms. The conventional methods of T2 relaxation time calculation are the nonlinear exponential-decay curve fitting algorithms. This study used Levenberg-Marquardt curve fitting algorithm, which is one of the widely used conventional T2 relaxation calculation algorithms.

Knee articular cartilage often bear loads in various activities. In recent years, more and more individuals participate in marathon or cross-country running, sometimes with a backpack during running. These sports could add extra loading to knee joints. Long term or frequent over-load to the knee articular cartilage are risky factors that may cause lesion or initiate the cartilage degenerative disease such as Osteoarthritis (OA). Previous studies reveal that early signs of OA include proteoglycan loss and increasing hydration of the extracellular matrix, which leads to disruption of the collagen architecture and aberrations in mechanical properties. But further study needs to be done regarding the relationship between cartilage in-vivo loading and its imaging influences.

This research adopted the spin-echo multislice-multiecho (MSME) Carr-Purcell Meiboom-Gill (CPMG) sequence, which is a useful T2 MRI sequence, to scan the tibiofemoral articular cartilage. Levenberg-Marquardt curve fitting algorithm was used for T2 relaxation time calculation and quantification. At different loading status, the T2 relaxation changing characters of tibiofemoral condyle cartilage were observed. In addition, electromyography (EMG) was used as an additional measure to observe the muscle activity around the knee.

2. Methodology

2.1. Study Participants

There were in total 20 qualified volunteers participated in

this study (N = 20). The inclusion criteria of the study participants are specified as follows: male, aged 18-40 years, 170-190 cm in height, 60-80 kg in weight, body mass index (BMI) ranging 19-23, no history of cardiopulmonary or neurological diseases, no contraindications for receiving knee MRI scan, no musculoskeletal disease or injury that hinders strenuous exercise, no acute sport injury, no obvious lower limb deformity, no flat feet. All the participants have signed the informed consent, and the study was approved by the institutional ethical reviewing board (ID# REB13-0170_REN2).

2.2. Exercise Methods

A 3.0 Telsa MRI scanner (GE Discovery 750) and a 16-channel phased-array knee coil were used for this research. The subjects underwent an initial MRI scan before the cross-country running to establish the referencing data to be compared with the data after running.

On the running day, the subjects completed a 5 km cross-country running with a weight of 20kg in the backpack. Similar as marathon matches, electrolytes drinks and snacks supplies were provided along the route. The running completion time was 30-45 minutes, and the endpoint was set near to the radiology department. Once the subjects had completed running, they rested 5 minutes for sweat removal and changing clothes. Then they received an MRI scan, with imaging details the same as the initial referencing MRI scan.

2.3. Imaging sequences and MRI Parameters

Spin echo multislice multiecho Carr-Purcell Meiboom-Gill (CPMG) sequence was adopted for T2 imaging of the tibiofemoral condyle cartilage. The sequence key parameters are as following: in the sagittal plate, there were 24 scanning slices across the knee joint, each slice had 8 echoes (TE= 15, 45, 75,..., 210, and 240 ms). Slice Thickness (ST): 3mm, Between Slice Spacing (SS): 3 mm, Flip Angle (FA) :90 degree, Repetition Time (TR) :3.17s. The high resolution Steady-State Free Precession (SSFP) sequence was also applied for knee joint mapping. The SSFP sequence has fully balanced gradients with constructive interference in steady state, which provides both high contrast images of cartilage and joint fluid with high signal-to-noise ratio. The SSFP scan sequences key parameters : Slice Thickness (ST): 1mm; Between Slice Spacing (SS): 0.5mm; Field Of View (FOV): 24×24cm; Matrix: 512×512 pixels; Number of Slices (NS): 200; Echo Time (TE): 2.016ms; Repetition Time (TR): 5.946ms; Flip Angle (FA): 60°.

2.4. T2 Relaxation Calculation Methods

Quantitative T2 mappings of subjects' right knee tibiofemoral condyles were generated from the images acquired with the CPMG sequence, using a published open-source software named MRmap . The three-parameter Levenberg-Marquardt curve fitting algorithms for T2 relaxation times calculation were used as shown below.

The 3-parameter Levenberg-Marquardt curve fitting algorithm with correction:

$$y = A \exp(-TE/T2) + B \quad (1)$$

(A is the signal when t = 0, and B is a constant, take B =10 ms, TE is the echo times of the CPMG sequence).

The tibiofemoral condyle cartilage was segmented into the lateral femur, medial femur, lateral tibia and medial tibia

compartments. As shown in Fig.1, three ROIs, anterior, middle and posterior, were selected for both the femur and tibia in the medial condyle cartilage.

Once the T2 relaxation times have been calculated based on the CPMG sequence imaging data, the cartilage regions were plotted using color-scale, then the colored cartilage mapping is covering the corresponding position on the SSFP images, so that the high- quality bony structure and colored T2 mapping were merged into one image with advantages from both sequences.

2.5. Statistical Methods

Based on the running status, the subjects were labeled as before-running and post-running groups. Paired t-test was used to compare the mean values of T2 relaxation times at different ROIs. The level of significance is 0.05, and we consider the differences is significant if the P-value is smaller than 0.05.

2.6. Electromyography

Prior to MR testing on a separate day, electromyography (EMG) testing was conducted to observe the muscle activities status. Subjects wore shorts and were asked not to apply lotion to their legs. Subjects stood and performed an isometric squat and a calf raise to allow the tester to identify and mark the muscle bellies of the vastus medialis, vastus lateralis, rectus femoris, biceps femoris, semitendinosis, medial gastrocnemius, and lateral gastrocnemius. The areas were dry shaven to remove hair, and then swabbed with rubbing alcohol to fully clean the skin surface. When the surface was dry, silver/silver chloride electrodes were placed over the midline of the muscle belly. EMG was collected in a position that mimicked the subject's position during jogging. Maximum voluntary contraction (MVC) signals were collected for the quadriceps, hamstring, and gastrocnemius muscle groups. During the test, verbal encouragement was given to promote MVC exertion. For the quadriceps test, the tester applied pressure to the distal end of the tibia while the subject lay supine. The subject resisted the posterior force, activating the quadriceps to try attempt to extend the leg. Data were sampled at 1200 Hz. The DC offset was removed, and the data were full wave rectified. A low pass 4th order Butterworth filter with a cut-off frequency of 50 Hz was used to filter the data in both directions. The cut-off frequency was chosen based on a power spectrum analysis using a Fast Fourier transform.

3. Results and Discussion

3.1. The T2 relaxation times of ROIs and the visualization

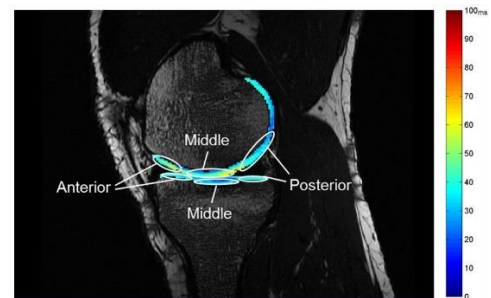


Figure 1. The MRI T2 relaxation mapping (using colored scale to display the T2 relaxation time values), with the schematic diagram of ROIs in sagittal plate.

In order to better analyze the imaging influences caused by the dynamic cross-country running, cartilage ROIs (anterior, middle, posterior) were selected on the lateral and medial femur condyles/ tibia compartments (as shown in Figure.1). Obviously, not each ROI was frequently loaded during running, and the contacted zones depend on the knee range of motion. From biomechanical point of view, the cartilage in middle ROIs was frequently loaded during cross-country running, and the loading may higher than normal because the participants were running with a backpack weighting 20kg. The cartilage in middle ROIs bears all these loading during running, as well as the friction and shearing stress caused by knee flexion and extension. We noticed that at the articular cartilage regions where loading & shearing stress are more densely applied, the T2 relaxation time are more inhomogeneous. Moreover, at middle ROIs of tibia cartilage, where the femur cartilage condyles directly contact and transit body weight, the T2 relaxation time tends to be lower than other positions.

Moreover, we found that, after the weight-bearing cross-country running, the articular cartilage of femur and tibia showed a temporary decreased T2 relaxation time. This phenomenon is statistically significant ($P < 0.05$) at the medial & lateral femur cartilage of middle ROIs, and the medial middle tibia cartilage of middle ROI. Previous research found the static loading can lead to a decreased T2 relaxation time, now we find that similar phenomenon exists when cartilage is dynamic loaded by cross-country running. This temporary decreased T2 relaxation time could because that the free water molecules were pushed out during loading, and lead to a temporary shift of the proteoglycan concentration.

For muscle monitoring, maximum voluntary contraction (MVC) signals were collected for the quadriceps, hamstring, and gastrocnemius muscle groups. The average signal over the load ramp up and sustained loading was also assessed. Data was compared for a given muscle at each load level ($\alpha = 0.05$) with a paired, one-sided t test. At all load levels, the EMG signal as a % of MVC was significantly less than 5%, with the exception of the GM at the ramp down to 0 N (descending) where no significant difference was detected (ie: neither significantly greater or less than 5%). For all subjects, muscle guarding was not sustained over the trial at any load level.

Table 1. The T2 Relaxation Times of Knee Tibiofemoral Condyle Cartilage ROIs (before running, using Mean \pm SD format)

Position	Anterior	Middle	Posterior
Lateral Femur	37.9 \pm 5.7	47.1 \pm 5.4	43.0 \pm 3.5
Medial Femur	41.3 \pm 6.0	46.0 \pm 6.3	37.2 \pm 5.3
Lateral Tibia	36.8 \pm 6.4	35.7 \pm 4.2	40.8 \pm 4.7
Medial Tibia	45.2 \pm 7.3	38.7 \pm 6.8	38.4 \pm 5.2

Table 2. The T2 Relaxation Times of Knee Tibiofemoral Condyle Cartilage ROIs (after running, using Mean \pm SD format)

Position	Anterior	Middle	Posterior
Lateral Femur	35.2 \pm 5.8	*41.6 \pm 5.6	42.3 \pm 4.4
Medial Femur	38.7 \pm 5.2	*39.2 \pm 6.1	36.6 \pm 6.5
Lateral Tibia	34.5 \pm 6.8	33.2 \pm 5.3	38.9 \pm 4.3
Medial Tibia	43.3 \pm 4.2	*34.7 \pm 5.9	35.7 \pm 5.4

*Means the T2 relaxation time mean value is significantly decreased, $p < 0.05$.

4. Conclusion

This research has academic significance for MRI methodological developing, and provides valuable image characters about the biochemical changes within knee articular cartilage. Also, it to study the potential influences caused by weight-bearing cross-country running, which is a novel view angle to link sports and medical imaging. The findings have the potential to serve as imaging biomarkers of early OA and evaluating indicator of cartilage degeneration. Combined with clinical functional knee testing, this work may be beneficial to OA progression prediction and longitudinal assessment.

The MRI T2 relaxation is sensitive to the dynamic loading during weight-bearing cross-country running. Temporary decreased T2 relaxation times were observed ($P < 0.05$) at cartilage regions where most loading and stress were applied. For muscle monitoring, EMG signals were collected for the quadriceps, hamstring, and gastrocnemius muscle groups. The average ECM signal didn't show significant evidence of muscle guarding after completion of the cross-country running.

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