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Quantitative magnetic resonance imaging (MRI) morphological analysis of knee cartilage in healthy and anterior cruciate ligament-injured knees

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Abstract

Purpose—To analyze the morphological change in the cartilage of the knee after anterior cruciate ligament (ACL) injury by comparing with that of the intact contralateral knee.

Methods—A total of 22 participants (12 male and 10 female patients) who had unilateral ACL injury underwent MRI scan of both the injured and intact contralateral knees. Sagittal plane images were segmented using a modeling software to determine cartilage volume and cartilage thickness in each part of the knee cartilage that were compared between the ACL-injured and the intact contra-lateral knees. Furthermore, the male and female patients' data were analyzed in subgroups.

Results—The ACL-injured knees had statistically significant lower total knee cartilage volume than the intact contralateral knees ($P = 0.0020$), but had similar mean thickness of total knee cartilage (not significant: n.s.). In the male subgroup, there was no significant difference in cartilage volume and thickness between normal and ACL-injured knees. In the female subgroup, the ACL-injured knees demonstrated statistically significant difference in total knee cartilage volume ($P = 0.0004$) and thickness ($P = 0.0024$) compared with the normal knees. The percentage change in the cartilage thickness in women was significantly greater than that in men.

Conclusion—Cartilage volume was significantly smaller in the ACL-injured knees than in the contralateral intact knees in this cohort. Women tended to display greater cartilage volume and thickness change after ACL injury than men. These findings indicated that women might be more susceptible to cartilage alteration after ACL injuries.

Level of evidence—III.

Keywords

MRI; Cartilage; Knee; Anterior cruciate ligament

Introduction

Anterior cruciate ligament (ACL) injury is one of the most common sports injuries and has a direct relation with morphological and structural change in articular cartilage [1, 20]. Due to the dramatically altered articular cartilage contact and pressure distribution [16, 26], the cartilage of the tibiofemoral joint is inexorably devastated with time in the ACL-injured knee and will ultimately develop into osteoarthritis (OA). Since articular cartilage morphological change plays an important role in the pathophysiology of OA, it is interesting to know whether there are cartilage morphological changes in an ACL-injured knee before the occurrence of obvious OA.

MRI is a noninvasive powerful tool in analyzing cartilage morphology in the knee, such as the cartilage volume, area, and thickness [2, 8, 17, 25]. It provides quantitative and reliable data on cartilage morphology in healthy subjects with different age groups and different genders [5, 6, 15, 21]. Calculation of cartilage volume and thickness according to MRI data can provide important indication of the pathological mechanisms of the diseased knees, such as osteoarthritis knee [4], painful knee [7, 10], and injured knee [12]. Frobell et al. [12] investigated the knee cartilage morphological change using quantitative MRI during the first year after acute ACL injury and found that cartilage volume decreased in the trochlea femur and increased in the central medial femur following an acute ACL injury. These findings indicated that the knee cartilage might experience a morphological change after ACL injury. Furthermore, gender difference in the cartilage morphology has long been known, and women appear to have a thinner and smaller volume of cartilage in the knee than men [18]. However, it is unclear whether the knee cartilage change has a gender difference following ACL injuries.

The purpose of this study was to perform MRI scans on the ACL-injured patients and to analyze the cartilage morphology of the bilateral knee joints in the early time after ACL injury. It was hypothesized that the mean cartilage volume differed between the ACL-injured and the contralateral intact knees.

Materials and methods

Twenty-two participants with unilateral ACL injury were recruited for this study (12 men and 10 women with an average age of 35.3 years and mean body mass index (BMI) of 25.8 kg/m²). There was neither significant difference in age (35.7 ± 11.8 vs. 34.8 ± 10.5 ; *n.s.*) nor significant difference in BMI (26.0 ± 3.8 vs. 25.7 ± 2.2 ; *n.s.*) between men and women in this cohort. Furthermore, the mean time from injury was 3.4 ± 2.6 months. There was no significant difference in injury time between men and women (3.9 ± 2.4 months vs. 2.8 ± 2.9 months; *n.s.*). The ACL injury was confirmed during arthroscopy operation. The ACL-injured participants were excluded if they had any of the followings: (1) obvious knee cartilage defect in arthroscopy, (2) history of knee cartilage surgery, (3) osteoarthritis, and (4) evidence or history of injury, surgery, or disease in the contralateral knees. Collectively,

there were 13 right and 9 left ACL-injured knees, which were grouped as the ACL-injured side, whereas the contralateral intact knees served as the control side. The study was approved by the IRB of our institution, and written consents were obtained from all participants before experiment.

Image acquisition and analysis

Imaging was performed in a relaxed extended position with a 3.0-T magnetic resonance (MR) scanner (MAGNETOM Trio, Siemens, Erlangen, Germany) and a double-echo water excitation sequence. The sagittal plane images (512×512 pixels) were generated with a field view of 16×16 cm and 1 mm spacing. These sagittal images were imported into solid modeling software (Rhinoceros, version 4.0, Robert McNeel & Associates, Seattle, WA, USA), and the contours of the knee joint's bones and cartilage were manually outlined (Fig. 1). Three-dimensional (3D) geometric models of the knee joint's bones and their corresponding cartilage were constructed using these outlines (Fig. 2). The accuracy and precision of the reconstructed cartilage have been validated previously [26, 27]. The accuracy of cartilage thickness measurement using MRI-based 3D surface model of the knee joint was reported to be 0.04 mm [26]. The femur cartilage was subdivided into three parts: lateral femoral condyle (LF), medial femoral condyle (MF), and trochlea (Tr). The tibial cartilage was subdivided into two parts: lateral tibial plateau (LT) and medial tibial plateau (MT). The criterion for partitioning was according to the insertion sites of the ACL and the posterior cruciate ligament (PCL). The femoral insertion site of the ACL marked the division of the lateral femoral condyle (LF) and the trochlea (Tr). The femoral insertion site of the PCL marked the division of the medial femoral condyle (MF) and the trochlea (Tr). Similarly, the tibial insertion site of the ACL and PCL marked the division of the lateral tibial plateau (LT) and the medial tibial plateau (MT).

According to the three-dimensional surface models of the cartilage and bone, cartilage volume (CV) and subchondral bone area (sBA, cartilage covered area of subchondral bone) in each cartilage part were directly measured using Rhinoceros software. The mean cartilage thickness was defined as the ratio of cartilage volume divided by sub-chondral bone area. The percentage change in cartilage thickness was quantified with the following equation: percentage change = [(ACL-injured knee–control knee)/control knee] $\times$ 100. All measurements were taken by the same investigator.

Statistical analysis

Data analysis was performed using Statistica software (Statsoft Inc, Tulsa, OK, USA), and the data were reported as mean and standard deviation. The data were compared between the ACL-injured and contralateral control knees using paired *t* test. The percentage change in bilateral knee cartilage thickness was compared between men and women using independent two-sample *t* test. Statistical significance level was set at 0.05.

Results

Cartilage volume in normal and ACL-injured knees

As shown in Table 1, the ACL-injured side demonstrated statistically significant difference in total knee cartilage volume compared with the control side (16.1 ± 3.1 cm³ vs. 15.2 ± 3.5 cm³; $P = 0.0020$). Additionally, significant differences were also observed between the control and the ACL-injured knees for the cartilage volume in femur ($P = 0.0009$) and tibia ($P = 0.0467$). However, no difference was detected in patellar cartilage volume between the ACL-injured knees and normal knees.

In the male subgroup, there was no significant difference in cartilage volume between the control and the ACL-injured knees (Table 2). In the female subgroup, however, the ACL-injured knees demonstrated a significant difference in total knee cartilage volume compared with the control knees ($13.8 \pm 1.7 \text{ cm}^3$ vs. $12.2 \pm 1.7 \text{ cm}^3$; $P = 0.0004$) (Table 2).

Cartilage thickness in the normal and ACL-injured knees

Compared with the control side, the ACL-injured side demonstrated no statistically significant difference in total knee cartilage thickness in this cohort ($2.0 \pm 0.2 \text{ mm}$ vs. $1.9 \pm 0.3 \text{ mm}$, n.s.) (Table 3). In addition, no significant difference was observed for the cartilage thickness in each part of the cartilage. In the male subgroup, there was no significant difference in cartilage thickness between the control and the ACL-injured knees (Table 4). However, in the female subgroup, the ACL-injured side demonstrated statistically significant difference in total knee cartilage thickness compared with the normal knees ($2.0 \pm 0.3 \text{ mm}$ vs. $1.8 \pm 0.3 \text{ mm}$; $P = 0.0024$). Additionally, significant differences were also observed between the normal and the ACL-injured knees in women for the cartilage thickness in patella ($P = 0.0114$), femur ($P = 0.0054$), and tibia ($P = 0.0185$) (Table 4).

Percentage change in cartilage thickness between men and women

The percentage cartilage change in women demonstrated a significant difference when compared with that in men for the total knee cartilage thickness (-8.6 ± 6.9 vs. 3.8 ± 7.5 , $P < 0.001$) (Fig. 3). Women had a decreased change in cartilage thickness, while men had an increased change in cartilage thickness. In the femoral condyle, the LF cartilage and the MF cartilage of women demonstrated a significant difference compared with those of men, respectively, whereas there was no significant difference between men and women for the percentage change in the trochlea cartilage (Fig. 4). In the tibial plateau, the LT cartilage and MT cartilage of women demonstrated a significant difference compared with those of men, respectively, (Fig. 5).

Discussion

The most important finding of the present study was that the ACL-injured knees demonstrated statistically significant difference in knee cartilage thickness compared to that of contralateral normal knees in women, and there was no statistically significant difference in cartilage thickness between the normal and the ACL-injured knees in men. In the present study, the cartilage morphology (including cartilage volume and thickness) was investigated in the ACL-injured knees and the contralateral intact knees with a mean injury time of 3.4 months. Using the three-dimensional cartilage models, the mean cartilage volume and the mean cartilage thickness were calculated for the femur, tibia, and patella. In this study, the contralateral knees were used as the control side for analyzing the cartilage morphological changes in the ACL-injured knees. We found that the ACL-injured side demonstrated statistically significant lower total knee cartilage volume compared with the control side.

Knee cartilage is an important structure in human body and plays a pivotal role in knee joint activity. It is known that cartilage morphology is influenced by many factors, such as age [15], gender [21], body mass index (BMI) [9], level of physical activity [19], osteoarthritis [4], pain [10], and ACL injury [3, 12, 13, 24]. Among these factors, ACL injury appears to be an acute factor to induce cartilage morphological changes. It has been demonstrated that the ACL resection can result in knee cartilage thinning in a rabbit model [14, 22]. Using gadolinium-enhanced MRI of cartilage, Fleming et al. [11] demonstrated that the cartilage component changed following ACL injuries when compared to the contralateral normal knees in the human body. These findings suggested that the change in the cartilage

morphology presents first in the early time following ACL injury before an obvious OA cartilage lesion occurs. Our data, in general, are consistent with these studies.

Previously, Frobell et al. [12] investigated the knee cartilage morphological change during the first year after acute ACL injury and found that cartilage volume was reduced with time in the majority of subregions of ACL-injured knee cartilage. Similarly, we observed that the mean cartilage volume was significantly reduced in the whole knee joint, the femoral condyle, and tibial plateau. These changes might be caused by the initial trauma as well as the abnormal biomechanical abrasion in the unstable knee after ACL injuries. As reported previously [16, 26], ACL deficiency alters the in vivo cartilage contact biomechanics by shifting the contact location to smaller regions of thinner cartilage, and by increasing the magnitude of the cartilage contact deformation, it is presumed that cartilage morphological alteration is accelerated in the ACL-injured knees.

In the present study, there was no statistically significant difference in total cartilage thickness of the knee between the ACL-injured side and the control side. However, it is interesting to note that there was a statistically significant difference in the cartilage thickness between the normal and the ACL-injured knees in women whereas no difference was observed in men. One possible explanation may be due to the difference in hormonal factors, which has been demonstrated to have an influence on the knee articular cartilage [28]. Additionally, it has been demonstrated that women have smaller mean cartilage thickness and cartilage volume than men in all knee cartilage parts [21]. The thinner cartilage in women might be much easier to be damaged compared to that in men. Our findings are consistent with the fact that women have a higher incidence of knee OA than men [23].

There are two limitations that should be noted in the current study. First was that only twenty-two cases were investigated in this study, which appears to be small. Further investigations need to be performed in a larger sample size when more patients' data are available. Secondly, our study recruited only a subset of the ACL-injured patients with rather short injury time. There might be different results in the patients with long injury time. Although the side (left–right) differences in knee joint cartilage might exist in human [8], the use of cartilage morphological parameters of the contralateral limb has been advocated as a proper approach to estimate cartilage alteration in patients with unilateral disease. As such, it should be cautious to apply the results to the general ACL-injured population.

Conclusions

The mean cartilage volume of the ACL-injured knees was smaller than that of the contralateral intact knees in the present study. Additionally, the mean cartilage thickness of the ACL-injured knees exhibited significantly thinner compared with that of the contralateral normal knees in women, whereas no significant difference was found in men. The cartilage loss of the ACL-injured knee might account for the development of osteoarthritis. These findings support that the cartilage in women may be more susceptible to ACL injury than men. Collectively, this study provides clinically valuable information regarding cartilage morphology of the knee joint and could help to understand cartilage degeneration after ACL injury.

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Fig. 1.
The outlines of the knee cartilage on a magnetic resonance image

Fig. 2.
Three-dimensional model of each cartilage part in knee joint. *LF* lateral femoral condyle, *MF* medial femoral condyle, *Tr* trochlea, *LT* lateral tibial, *MT* medial tibial

Fig. 3.
Mean percentage changes in the thickness of the knee cartilage between men and women after ACL injury

Fig. 4. Mean percentage changes in the cartilage thickness of femoral condyle between men and women after ACL injury. *LF* lateral femoral condyle, *MF* medial femoral condyle, *Tr* trochlea

Fig. 5. Mean percentage changes in the cartilage thickness of tibial plateau between men and women after ACL injury. *LT* lateral tibial, *MT* medial tibial

Table 1Mean cartilage volume of the knee cartilage in all subjects (average $\pm$ SD, $n = 22$)

Cartilage plate		Normal (cm ³)	ACL-injured (cm ³)	P value
Knee	Total	16.1 $\pm$ 3.1	15.2 $\pm$ 3.5	0.0020
	Patellar	3.1 $\pm$ 0.5	3.1 $\pm$ 0.7	n.s.
Femur	Total	9.3 $\pm$ 2.1	8.7 $\pm$ 2.3	0.0009
	LF	4.4 $\pm$ 1.4	3.9 $\pm$ 1.3	0.0031
	MF	3.3 $\pm$ 0.7	3.2 $\pm$ 0.8	n.s.
	Tr	1.6 $\pm$ 0.4	1.6 $\pm$ 0.5	n.s.
Tibia	Total	3.6 $\pm$ 0.6	3.5 $\pm$ 0.8	0.0467
	LT	2.3 $\pm$ 0.5	2.1 $\pm$ 0.6	0.0198
	MT	1.4 $\pm$ 0.3	1.3 $\pm$ 0.4	n.s.

LF lateral femoral condyle, *MF* medial femoral condyle, *Tr* trochlea, *LT* lateral tibial, *MT* medial tibial

Table 2

Mean cartilage volume of the knee cartilage in the male subgroup (average $\pm$ SD, $n = 12$) and female subgroup (average $\pm$ SD, $n = 10$)

Cartilage	Male subgroup		Female subgroup	
	Normal (cm ³)	ACL-injured (cm ³)	Normal (cm ³)	ACL-injured (cm ³)
Knee	18.0 $\pm$ 2.5	17.7 $\pm$ 2.5	13.8 $\pm$ 1.7	12.2 $\pm$ 1.7
Patellar	3.4 $\pm$ 0.5	3.5 $\pm$ 0.6	2.8 $\pm$ 0.4	2.6 $\pm$ 0.5
Femur	10.7 $\pm$ 1.8	10.3 $\pm$ 1.7	7.7 $\pm$ 1.1	6.7 $\pm$ 0.9
LF	5.1 $\pm$ 1.5	4.8 $\pm$ 1.1	3.5 $\pm$ 0.6	2.9 $\pm$ 0.6
MF	3.7 $\pm$ 0.6	3.6 $\pm$ 0.7	2.8 $\pm$ 0.4	2.7 $\pm$ 0.6
Tr	1.9 $\pm$ 0.3	1.9 $\pm$ 0.4	1.3 $\pm$ 0.3	1.1 $\pm$ 0.3
Tibia	3.9 $\pm$ 0.5	3.9 $\pm$ 0.6	3.2 $\pm$ 0.5	2.9 $\pm$ 0.6
LT	2.5 $\pm$ 0.4	2.4 $\pm$ 0.5	2.0 $\pm$ 0.4	1.8 $\pm$ 0.4
MT	1.5 $\pm$ 0.3	1.5 $\pm$ 0.3	1.2 $\pm$ 0.2	1.1 $\pm$ 0.3

LF lateral femoral condyle, MF medial femoral condyle, Tr trochlea, LT lateral tibial, MT medial tibial

Table 3Mean cartilage thickness of the knee cartilage in all subjects (average $\pm$ SD, $n = 22$)

Cartilage plate		Normal (mm)	ACL-injured (mm)	P value
Knee	Total	2.0 $\pm$ 0.2	1.9 $\pm$ 0.3	n.s.
Patellar	Total	2.5 $\pm$ 0.3	2.5 $\pm$ 0.4	n.s.
Femur	Total	1.8 $\pm$ 0.2	1.8 $\pm$ 0.3	n.s.
	LF	1.7 $\pm$ 0.3	1.7 $\pm$ 0.3	n.s.
	MF	1.8 $\pm$ 0.3	1.7 $\pm$ 0.3	n.s.
	Tr	2.2 $\pm$ 0.5	2.1 $\pm$ 0.4	n.s.
Tibia	Total	2.0 $\pm$ 0.3	2.0 $\pm$ 0.3	n.s.
	LT	2.3 $\pm$ 0.3	2.2 $\pm$ 0.3	n.s.
	MT	1.7 $\pm$ 0.3	1.7 $\pm$ 0.3	n.s.

LF lateral femoral condyle, *MF* medial femoral condyle, *Tr* trochlea, *LT* lateral tibial, *MT* medial tibial

Table 4

Mean cartilage thickness of the knee cartilage in the male subgroup (average $\pm$ SD, $n = 12$) and female subgroup (average $\pm$ SD, $n = 10$)

Cartilage	Male subgroup		Female subgroup	
	Normal (mm)	ACL-injured (mm)	Normal (mm)	ACL-injured (mm)
Knee				
Total	1.9 $\pm$ 0.2	2.0 $\pm$ 0.2	2.0 $\pm$ 0.3	1.8 $\pm$ 0.3
Patellar				
Total	2.5 $\pm$ 0.3	2.5 $\pm$ 0.4	2.6 $\pm$ 0.3	2.4 $\pm$ 0.4
Femur				
Total	1.8 $\pm$ 0.2	1.9 $\pm$ 0.3	1.8 $\pm$ 0.3	1.6 $\pm$ 0.3
LF	1.7 $\pm$ 0.3	1.8 $\pm$ 0.3	1.7 $\pm$ 0.3	1.5 $\pm$ 0.3
MF	1.8 $\pm$ 0.3	1.8 $\pm$ 0.3	1.8 $\pm$ 0.3	1.6 $\pm$ 0.3
Tr	2.3 $\pm$ 0.5	2.3 $\pm$ 0.4	2.2 $\pm$ 0.4	2.0 $\pm$ 0.5
Tibia				
Total	2.0 $\pm$ 0.2	2.0 $\pm$ 0.2	2.0 $\pm$ 0.3	1.9 $\pm$ 0.3
LT	2.2 $\pm$ 0.2	2.3 $\pm$ 0.2	2.3 $\pm$ 0.3	2.2 $\pm$ 0.4
MT	1.7 $\pm$ 0.2	1.8 $\pm$ 0.2	1.7 $\pm$ 0.3	1.6 $\pm$ 0.3

LF lateral femoral condyle, MF medial femoral condyle, Tr trochlea, LT lateral tibial, MT medial tibial