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A Comparison of Knee Joint Biomechanics during Gait and Cartilage T2 Mapping Values in Asymptomatic Women in their Twenties and Forties

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Abstract

Objective: To investigate the difference in knee joint kinematics and kinetics during gait and T2 mapping values in a healthy female population in their twenties and forties in order to determine the knee motion changes related to early knee OA change.

Methods: Thirty healthy women, 15 in their 20s and 15 in their 40s, participated (average ages 22.1 ± 2.4 and 45.7 ± 2.5 years old, respectively). Knee joint kinematic and kinetic data during gait and T2 measurements of the medial femorotibial joint cartilage using a 3T MR system were assessed.

Results: The first peaks of knee adduction moment (KAM) in women in their 20s and 40s were not significantly different, although the first peaks of knee flexion moment in their 40s ($5.7\times10^{-2} \pm 1.7\times10^{-2}$) were significantly greater than the values in their 20s ($3.2\times10^{-2} \pm 2.6\times10^{-2}$, $P<0.05$). T2 values of the femoral superficial cartilage in the 40s (34.0 ± 1.8 msec) were significantly longer than the values in the 20s (32.2 ± 1.4 msec) ($P<0.01$). The first peak of the knee flexion moment and the T2 values in the 40s were not significantly correlated ($r = -0.21$).

Conclusion: Although T2 values at the medial superficial femoral cartilage in the 40s were longer than in the 20s, the knee flexion moment was not related to T2 values of knee joint cartilage in the 40s.

Keywords: Gait; Knee adduction moment; Knee flexion moment; T2 mapping

Introduction

Knee osteoarthritis (OA) is a common joint disease highly prevalent among aged elderly and increasing from middle age [1,2]. Patients with medial knee OA are reportedly 10 times more common than patients with lateral knee OA [3]. Women are more predisposed to knee OA than males [1], and race is also related to the prevalence rate of knee OA [4]. The female/male ratio in Japan is higher than the ratio among Caucasians in the United States [4]. The prevalence rate of knee OA among Japanese women has been reported to be 11.4% in their 40s, and the rates in the 50s, 60s and 70s are 30.3%, 57.1%, and 71.9%, respectively [1].

The external knee adduction moment (KAM) is the moment at which the tibia rotates in the adduction (varus) direction associated with the femur with the axis of the knee joint center on the frontal plane. Knee adduction moment (KAM) during gait as a surrogate measurement of the medial compression force (MCF) [5,6] has been associated with medial knee OA [7-9] reported linear regression equations with KAM and knee flexion moment (KFM) to obtain MCF using one patient with a force-measuring knee implant. The KAM and MCF impulse with area under KAM- or MCF-time curve reflecting both the magnitude and duration of knee load during gait are also important information for medial knee pathology [6,10]. Therefore, those biomechanical values are thought to associate with the onset of medial knee OA.

The prevalence of knee OA increases around three-fold among females in their 40s to 50s in Japan [1]. Hypothetically, biomechanical changes such as the increased KAM, MCF, their impulses, or KFM occur before and after the 40s. Investigation of the changes of these biomechanical values from healthy young adults to middle age (around the 40s) up to just before the onset of knee OA in Japanese women, who have a high prevalence ratio of knee OA, could provide the basis for the prevention of very early-stage knee OA.

T2 values with MR imaging can indicate cartilage water content and collagen fiber orientation as early cartilage degeneration [11-13]. However, T2 values for knee cartilage in the asymptomatic middle-aged have been sufficiently reported compared to the young and healthy. Additionally, there is no study comparing the T2 values of knee cartilage and knee biomechanical values related to knee OA in both young healthy adults and the middle-aged.

The aims of this study were to investigate 1) the differences in knee biomechanics related to medial knee OA between young (20s) and middle ages (40s), 2) the differences in T2 mapping in the medial femorotibial joint between these ages, and 3) the relationship between knee kinetics and T2 values in women in their 40s with the significant difference between both ages, which results from aims 1 and 2. Our hypotheses are: 1) KAM and KFM in 40s are greater than the moments

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in 20s; 2) T2 values at the medial side of femur and tibia cartilage in 40s are longer than the values in 20s; 3) the kinetics and T2 values are correlated.

Methods

Subjects

Thirty healthy women participated; 15 in their 20s and 15 in their 40s. Participants were recruited from a university health science campus (20s) and local medical and care facilities staff (40s). Table 1 shows the characteristics of the subjects. Subjects were excluded from the study if any of the following were reported: a history of previous lower extremity surgery, and/or a previous injury that resulted in ligamentous laxity at the knee joint. All participants were informed as to the nature of the study, and informed consent was obtained in writing, as required by the Ethics Committee of the School of Health Sciences, Nagoya University.

3D gait analysis

Three-dimensional trajectory data were obtained using a 10-camera motion analysis system (Venus 3D; Nobby Tech, Tokyo, Japan). Trajectory data were sampled at 100 Hz and digitally recorded. Ground reaction forces were collected at a rate of 100 Hz using a force plate (AccuGait; AMTI, MA, USA), and the force plate and 3D motion analysis system were synchronized. Twenty-five reflective sphere markers (7 mm diameter) were attached to anatomical locations and marker plates were used to quantify segment motion.

All subjects wore compression shorts and T shirts. Reflective markers were placed on the lateral side of randomly selected right or left leg over the following anatomical landmarks: medial and lateral femoral epicondyles, greater trochanters, second sacrum (mid-way between the posterior superior iliac spines (PSIS), medial and lateral malleolus, tibia (superior and inferior part), calcaneus, 2^{nd} and 5^{th} metatarsal head. ASIS and acromion were attached on the bilateral sides (Figure 1A and B). In addition, non-elastic plates (ethylene vinyl acetate copolymerization) with a wand (5 markers) were placed bilaterally on the lateral surfaces of the subject's thigh and lower leg (Figure 1C). All 25 markers were attached during static calibration, after which the medial femoral epicondyle and malleolus were removed (23 markers). Data collection was done in the training room of the Health Science campus at Nagoya University.

The tasks were performed barefoot, with only the right or left leg randomly selected. Subjects were allowed to walk at a controlled speed set within ±5% of standard speed (1.36 m/s) for Japanese women according to a previous report [14]. Walking speed was confirmed by the speed of the second sacrum marker in the walking direction (X axis of the laboratory coordination) over 2 m after passing the frontal force plate line immediately after gait task. Subjects were asked to walk along a 7-m walkway, and three successful trials were recorded. Practice trials allowed subjects to become familiar with gait on the walkway.

A 4-link model with four segments of the pelvis, thigh, shank (lower leg), and foot was developed in the present study. The segment (bone position) was estimated using the global optimization by Lu and O'Connor [15]. The model was customized to the subject using marker data measured during static calibration with each subject. These marker coordinates were used to define segment-embedded reference frames for the associated body segments, following suggestions by [16]. Inertial properties of each limb segment were used from Japanese inertial characteristics [17].

	20s (n = 15) mean (SD)	40s (n = 15) mean (SD)
Age (years)	22.1 (2.4)	45.7 (2.5)
Height (cm)	157.5 (5.5)	158.8 (5.5)
Weight (kg)	54.4 (5.7)	56.5 (6.4)

Table 1: Demographic characteristics of healthy women in their 20s and 40s.

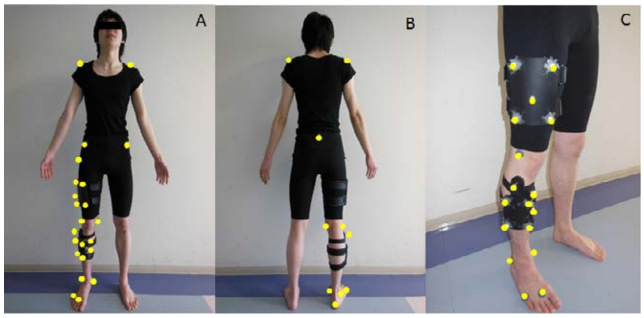

Figure 1: Markers set in static calibration (A, B). Markers on medial epicondyle and medial malleolus were removed during gait task. Marker plates of the thigh and lower leg (C).

Joint center positions were then identified and defined in the reference frames of their adjacent body segments. The hip joint center was defined using the Davis method [18] based on ASIS and PSIS. The knee and ankle joint centers were defined as the midpoint between the lateral and medial femoral epicondyle and medial and lateral malleolus, respectively. Euler angles were used to determine relative segmental motion, and joint angles were calculated based on segmental motion of the distal segment about a fixed point on the proximal segment. Three-dimensional coordinates of the key bony landmarks and joint center positions were used as the parameters for the customization of the 4-link model (Table 2).

Kinematic data were filtered using the low-pass Butterworth filter with a 6 Hz cut off frequency. Knee moments were calculated using inverse dynamics. The knee joint moments were normalized to body mass and leg length (the height of the trochanter marker during static calibration) [19].

Kinematic and kinetic (external moment) data from the three trials were averaged for analysis. All data were normalized to 100% of a gait cycle with 0% of the heel contact of the measured leg. The peak knee flexion moment (KFM), and the first and second peaks of knee adduction moment (KAM) during stance phase (0–60% of the gait cycle) were obtained. The first and second peaks were definite during 0–30% and 30–60% of the gait cycle [20], and entire KAM and KFM were summarized as its angular impulse. The knee flexion angle at the peak KFM was also measured, and the knee adduction angles and the lengths of the frontal plane lever arms of the first and second peaks of the KAM were obtained. The length of the lever arm was calculated as the perpendicular distance between the resultant frontal plane ground reaction force line of action and the center of the knee joint. Additionally, foot progression angles were obtained at the first and second peaks of the KAM.

The first and second peak medial compression forces (MCF) were obtained using the previously reported method [9]. The first and second peak MCF of the equation were the following: 1^{st} peak of MCF = $0.31\,M_{add} + 0.09|M_{flex}| + 0.82$, 2^{nd} peak of MCF = $0.33\,M_{add} + 0.21|M_{flex}| + 0.49$ (M_{add} and M_{flex}: the external knee adduction and flexion moment when normalized to body weight and height for the equation, respectively).

	Pelvis	Thigh	Shank	Foot
Origin	Mid-point of right and left ASIS	Hip joint center	Knee joint center	Ankle joint center
X axis	Vector using Gram-Schmidt orthonormaliza-tion with Y axis vector	Vector perpendicular to vector from lateral to medial epicondyle and Z axis	Vector perpendicular to vector from lateral to medial epicondyle and Z axis	Vector perpendicular to Y and Z axis
Y axis	Vector from right to left ASIS	Vector perpendicular to X and Z axis	Vector perpendicular to X and Z axis	Vector perpendicular to vector from 2nd metatarsal head marker to the origin and Z axis
Z axis	Vector perpendicular to X and Y axis	Vector from origin and knee joint center	Vector from origin and ankle joint center	Vector from origin in the gravity direction

Table 2: Coordinate definition of 4-link model.

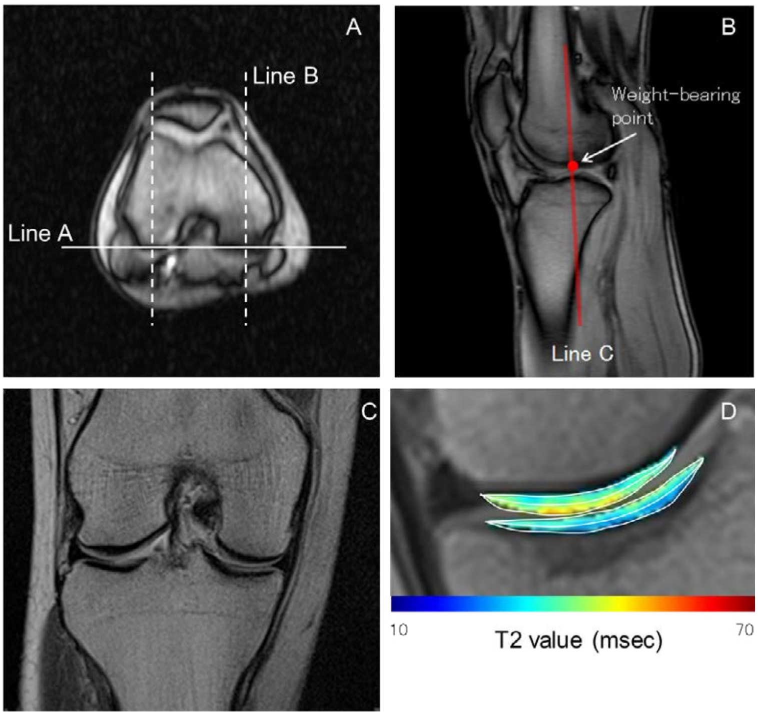

Figure 2: Procedure of the final coronal plane of the medial femoral tibia joint for T2 mapping. Axial view (A), sagittal view for determination of the weight-bearing point and parallel to the femur (B), final coronal slice (C), range of interest for half of the femur and tibia cartilages (D).

Impulse of MCF was obtained with the following equation: $0.63\ M_{add} + 0.16|M_{flex}| + 0.10$.

MR Imaging

A 3.0T MRI system (Magnetom Verio; Siemens, Erlangen, Germany) with a body matrix coil above the knee and spine matrix coil under the knee was used for all measurements. The subject was positioned supine with the measured knee aligned with the extension. Multi echo sequence with spin echo sequence was used for T2 mapping, and the image parameters were as follows: repetition time = 1500 ms, echo time = 13, 26, 39, 52, 65, 78, 91 and 104 ms, field of view = 150 × 150 mm, slice thickness 3.0 mm, matrix 256 × 256, band width 233 Hz/pixel.

The coronal plane [21,22] is excellent for evaluating articular cartilage along the central weight-bearing surfaces of the femur and tibia. The present study used the medial femoral condyle and tibia on the coronal plane to compare the KAM and MCF during gait. For the coronal plane procedure, the axial image was obtained first (Figure 2A), and line A was set for positioning the posterior ends of both femoral condyles. Line B was set perpendicular to Line A. The sagittal plane acquisition (Figure 2B) was obtained on the plane of Line B (Figure 2A). Line C (coronal acquisition) was determined through the center weight-bearing surface of the femur and tibia (red dot: Figure 2B) parallel to the long axis of the femoral diaphysis. Finally, the coronal acquisition was obtained and T2 mapping was used (Figure 2C).

T2 values were calculated on a pixel-by-pixel basis, and then averaged over the region of interest (ROI). Image evaluation to determine artifact-free areas of cartilage was performed by one tester. The mean T2 values for the whole cartilages of the medial femoral condyle and medial tibia were calculated, and half of the superficial cartilages of the femur and tibia were also calculated (Figure 2D).

Knee extensor strength and frontal knee joint alignment

Isometric knee extension strength was tested twice using a hand-held dynamometer (MicroFET2; Hoggan Health, Salt Lake City, UT, USA). The maximum isometric muscle strength was measured while the participant was sitting on a chair without a backrest and with the knee flexed to 90 degrees. A testing pad was attached to the front lower leg of the participant and strapped to the leg of the chair. The participant was instructed to push the pad with maximal strength.

Three trials were conducted, and the peak force of the higher score was recorded. The peak force was normalized by the lever arm (the length from epicondyle to the dynamometer pad on the distal tibia) and body weight (Nm/kg). Final analysis was conducted on one leg with measured 3D gait analysis and T2 values.

Static knee alignments (Femorotibial angle: knee adduction angle) were calculated during static calibration using 3D motion analysis of the standing position in each subject.

Statistical analysis

Differences in knee biomechanics during gait, other physical assessments of the knee joints and T2 values in the 20s and 40s group were analyzed using the unpaired *t* test. Effect size (ES: Cohen's d) was also performed in all comparisons. The practical difference was set for both conditions of P<0.05 and above 0.50 ES in this study.

The results of biomechanical data and the T2 values with practical differences between both groups were analyzed using the Pearson's correlation in the 40s group. The significance level of Pearson's correlation was also set at P<0.05. All statistical analyses were performed with SPSS, Version 16.0 (IBM Japan, Chuo Ward, Tokyo, Japan).

Results

The characteristics of the subjects are shown in Table 1. There were no significant differences in the characteristics. Table 3 shows the differences in kinematic and kinetic data and knee extensor strength between the 20s and 40s groups. The peak KFM and KFM impulse in the 40s group was greater than the counterpart values in the 20s group (P<0.05, above 0.5 of both ES). KAM and KFM curves of the time series during the stance phase (0-60% of the gait cycle) were shown in (Figure 3), and there were no other significant differences in gait variables.

Table 3 shows the difference of the T2 values in the medial femur and tibia between the 20s and 40s groups. The T2 values at the surface parts of the femur in the 40s group were practically longer than the values in the 20s group (P<0.01, ES = 1.13).

As the analysis for the third aim, the relationships between the KFM, KFM impulse and T2 values in the femur surface were not significantly correlated in the 40s group (r=-0.07, and -0.23, respectively).

Table 4 shows the relationship KFM, KFM impulse and knee flexion angle and knee extensor strength between both groups. There were significant negative correlations between increase of the KFM and knee flexion angle and decrease of the strength only in the 40s.

Discussion

In the present study, peak KFM and the impulse in the 40s group were greater than the moment and impulse in the 20s group, and the KAM between both groups did not differ. Previous reports [8,23,24] indicated that KFM and knee flexion angle [24] in patients with early-stage knee OA [8] and elderly (average age: 69.0 years old) [23] were lower than the KFM and the angle in the asymptomatic participants or young control adults (average age: 21.6 years old) [8] named the phenomenon during the stance phase with decreased KFM and knee flexion angle in patients with knee OA the "quadriceps avoidance gait." In fact, it was a weakness of quadriceps strength. Generally, the knee flexion angle is related to lever arm length on the sagittal plane for KFM. Therefore, Pearson's correlation between peak KFM, KFM impulse, knee flexion angle at peak KFM and knee extensor strength was calculated in both the 20s and 40s groups as a sub-analysis.

Table 4 shows the results of all correlations. Although knee extensor strength was not significantly different between the 20s and 40s (Table 3), the peak KFM and knee extensor strength were negatively correlated significantly in only the 40s group (r=-0.61, P<0.05). Peak KFM and knee flexion angle, and knee flexion angle and knee extensor strength were significantly correlated in the 40s group, respectively (r=0.70, r=-0.67, P<0.01). On the other hand, there were no significant correlations among the three values of KFM, knee flexion angle and knee extensor strength in the 20s group. From the results, knee extensor strength might start to influence gait biomechanics in the sagittal plane (increased peak KFM and KFM impulse) from the 40s, even in the absence of knee extensor weakness. However, the relationships between the increase of KFM and knee extensor strength are counterintuitive, and the present study could not verify the relation, which must be left to future investigation.

For the MR assessment of the medial femoro-tibial joint cartilage, T2 values of the femoral surface of the cartilage in the 40s group were practically longer than the T2 values in the 20s group. Cartilage water content and collagen fiber orientation assessed by T2 mapping of the superficial femur may have degenerated already in the 40s compared to the 20s in healthy individuals.

The T2 values of the medial femoral surface were not correlated with the peak KFM in the 40s group. Peak KFM with the knee kinetic change during gait from the 20s to 40s was not associated with T2 values of medial superficial femur in the 40s with asymptomatic subjects. There are no reports about the relationships of KFM and cartilage assessment values using MR imaging in patients with knee OA and asymptomatic subjects, but there are a few reports with KAM (frontal kinetics) and cartilage evaluation. Although the subjects were patients with knee OA, [23] reported that a high KAM impulse at the baseline significantly

	20s	40s	P	ES
KAM (1st)	0.05 (0.02)	0.06 (0.02)	.26	0.42
KAM (2nd)	0.04 (0.02)	0.04 (0.02)	.75	0.12
KFM (peak)	0.04 (0.02)	0.07 (0.02)	**.001**	**1.43**
Knee adduction angle (at 1st KAM)	-0.1 (3.0)	0.2 (3.7)	.81	0.09
Knee adduction angle (at 2nd KAM)	-0.1 (2.7)	0.3 (2.7)	.73	0.13
Knee flexion angle (peak)	18.9 (4.7)	22.0 (4.1)	.07	0.70
Lever arm (at 1st KAM) (m)	0.03 (0.01)	0.03 (0.01)	.35	0.34
Lever arm (at 2nd KAM) (m)	0.03 (0.01)	0.03 (0.01)	.74	0.12
Foot progression angle (at 1st KAM)	3.7 (5.1)	2.0 (5.6)	.41	0.30
Foot progression angle (at 2nd KAM)	3.5 (6.3)	1.9 (7.7)	.54	0.23
KAM impulse	1.5 (0.7)	1.7(0.7)	.40	0.32
KFM impulse	0.7 (0.3)	0.9 (0.3)	**.02**	**0.93**
MCF (1st)	1.8 (0.3)	2.0 (0.2)	.09	0.64
MCF (2nd)	1.5 (0.4)	1.5 (0.3)	.66	0.17
MCF impulse	63.2 (22.0)	70.3 (19.8)	.36	0.34
T2 values of medial femur	28.7 (1.2)	29.9 (2.9)	.13	0.57
T2 values of medial tibia	30.8 (2.1)	31.5 (1.9)	.33	0.36
T2 values of medial femural surface	32.2 (1.4)	34.0 (1.8)	**.005**	**1.13**
T2 values of the medial tibial surface	33.8 (1.7)	34.9 (1.6)	.09	0.64
Femorotibial angle	179.1 (2.2)	179.5 (1.9)	.59	0.20
Knee extension muscle strength (Nm/kg)	1.5 (0.3)	1.5 (0.5)	.74	0.13

Bold shows both P<0.05 with the significant level and >0.5 of the effect size. KAM: Knee Adduction Moment; KFM: Knee Flexion Moment; MCF: Medial Compression Force; ES: Effect Size; Units: angle (°), T2 value (msec); mean (standard deviation).

Table 3: Difference in knee biomechanics and T2 values between the 20s and 40s.

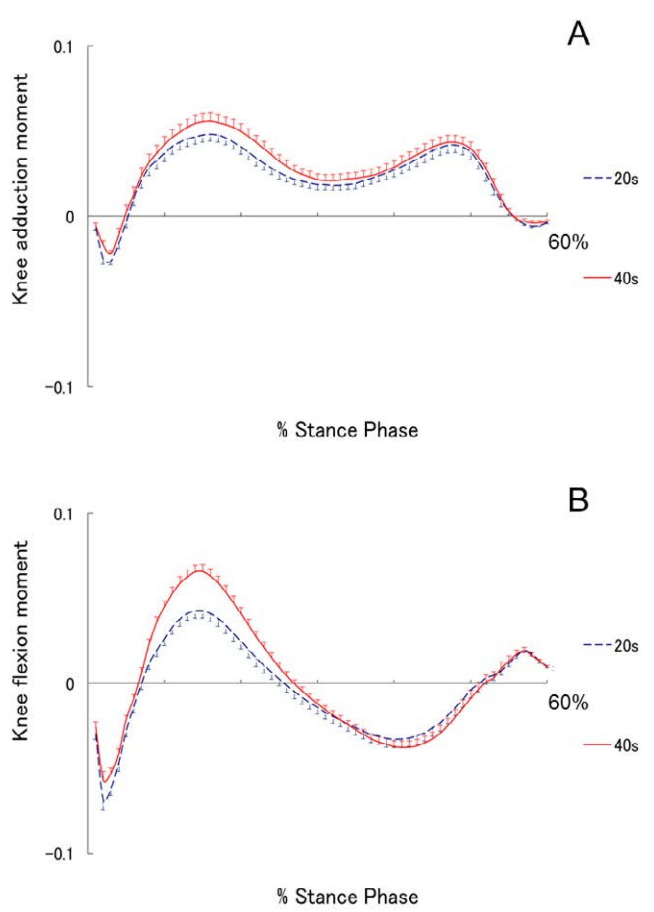

Figure 3: Knee adduction moment (A) and knee flexion moment (B) of the time series data during stance phase.

		Knee flexion moment (peak)	Knee flexion moment impulse	Knee flexion angle (peak)
Knee extension muscle strength	20s	-0.20	-0.15	0.07
	40s	-0.61*	-0.37	-0.67**

* P<0.05, **P<0.01

Table 4: Relationship between biomechanical data on the sagittal plane and knee extension muscle strength between the 20s and 40s.

correlated with greater loss of medial tibial cartilage volume in patients with knee OA [24] found that greater KAM was observed in patients with medial meniscus tear compared to KAM with a lateral tear. Most participants of the previous studies compared for knee kinetics and cartilage evaluations by MR imaging had knee OA. Only [25] observed in healthy women without knee OA (average age: 61.0 ± 5.3 years) a relationship between knee biomechanics and cartilage assessment by MR imaging; moreover, KAM and medial cartilage volume measured by MR imaging were not found to be related. The relationships between KAM and MR measurements for knee cartilage are controversial in previous reports, and it is difficult to conclude that our findings of an increase of KFM in 40s compared to 20s are associated with early change of knee OA.

There are several limitations in the present study. First, the number of participants was relatively small, and a cross-sectional methodology was used. A longitudinal study to investigate the practical difference in the peak KFM between the 20s and 40s is needed to determine the factor-disease relationship. The cartilage assessment only used T2 values, whereas it might require several aspects used in previous reports such as cartilage volume, and T1ρ.

In conclusion, the peak KFM during gait among women in their 40s was greater than in those in their 20s, but not greater than KAM and MCF. The peak KFM was negatively correlated with knee extensor strength among the 40s group. T2 values of the surface of the femoral cartilage in the 40s group were higher than the values in the 20s group. However, the T2 values related with early knee OA change and peak KFM were not correlated in the 40s group.

Acknowledgements

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