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Relationship between individual forces of each quadriceps head during low-load knee extension and cartilage thickness and knee pain in women with knee osteoarthritis

Masahide Yagi [a,*], Masashi Taniguchi [a], Hiroshige Tateuchi [a], Tetsuya Hirono [a,b], Momoko Yamagata [a,b,c], Jun Umehara [a,b], Shusuke Nojiri [a], Masashi Kobayashi [d], Noriaki Ichihashi [a]

[a] Human Health Sciences, Graduate School of Medicine, Kyoto University, 53 Kawahara-cho, Shogoin, Sakyo-ku, Kyoto, 606-8507, Japan
[b] Research Fellow of Japan Society for the Promotion of Science, Kojimachi Business Center Building, 5-3-1 Kojimachi, Chiyoda-ku, Tokyo 102-0083, Japan
[c] Department of Human Development, Graduate School of Human Development and Environment, Kobe University, 3-11 Tsurukabuto, Nada-ku, Kobe, Hyogo 657-0011, Japan
[d] Kobayashi Orthopaedic Clinic, 50-35 Kuzetakada-cho, Minami-ku, Kyoto 601-8211, Japan

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ABSTRACT

Background: This study aimed to clarify the individual forces of each quadriceps head during low-load contractions and to determine the associations between individual muscle force and cartilage thickness and symptoms in female knee osteoarthritis patients.
Methods: Twenty-two women with painful knee osteoarthritis and 15 asymptomatic age-matched women (control group) participated in this cross-sectional study. Maximal knee extension strength and the cross-sectional area of each quadriceps muscle were measured. Shear modulus was calculated for each muscle during 20-Nm torque production by shear-wave elastography. Muscle force index was defined as the product of the cross-sectional area and shear modulus. Medial femur cartilage thickness was measured using an ultrasound B-mode image. Knee pain during gait was evaluated using a Numerical Rating Scale. Muscle force index, cross-sectional area, and maximal knee extension strength, which were defined as muscle functions, were compared between groups using the unpaired *t*-test. Correlation coefficients were calculated using muscle function, cartilage thickness, or pain.
Findings: Maximal strength and vastus lateralis force index were smaller in the knee osteoarthritis group than in the control group ($p < 0.001$ and $p = 0.005$, respectively). In the knee osteoarthritis group, vastus medialis and vastus lateralis force indexes were positively correlated with cartilage thickness ($r = 0.57$ and $r = 0.45$, respectively), whereas the rectus femoris force index was negatively correlated with cartilage thickness ($r = -0.45$). The vastus lateralis force index was negatively correlated with knee pain ($\rho = -0.56$).
Interpretation: Vasti force indices were positively associated with cartilage thickness; however, rectus femoris index was negatively associated in female patients with knee osteoarthritis.

1. Introduction

Knee osteoarthritis (KOA) is a common progressive disease in older adults (Yoshimura et al., 2009). Therefore, treatment is focused on not only improving symptoms but also preventing its onset and/or progress by determining its modifiable factors (Wirth et al., 2017). Many studies have focused on whether modifiable factors such as maximal muscle strength could be related to cartilage degeneration (Culvenor et al., 2019; Eckstein et al., 2015; Tuna et al., 2016) because cartilage degeneration (e.g., decreased cartilage thickness) is known as a meaningful biomarker of the onset and progress of KOA.

One cohort study investigated cartilage degeneration using magnetic resonance imaging and revealed that decreased maximal knee extension strength was not related to cartilage degeneration in the tibiofemoral joint (Culvenor et al., 2019). However, another study found a positive linear correlation between maximal knee extension strength and

* Corresponding author.
E-mail address: yagi.masahide.5s@kyoto-u.ac.jp (M. Yagi).

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cartilage thickness in the medial femur of KOA patients (Tuna et al., 2016). These inconsistent findings suggest that maximal knee extension strength is not necessarily a clinical indicator of cartilage degeneration. Because maximal muscle strength is not required during gait, which is an activity of daily living (ADL) (Hubley-Kozey et al., 2008; Tikkanen et al., 2016), it is essential to determine whether KOA patients have unique muscle function during low-load contraction, such as exerted for gait, and to explore whether muscle function could be related to cartilage thickness.

Owing to the redundancy in the musculoskeletal system, different combinations of individual muscle forces can perform a given task (Hug and Tucker, 2017). A particular combination of individual muscle forces is defined as force distribution, and the type of muscle that exerts the most force depends on the participant (Crouzier et al., 2019; Hug et al., 2015a). Furthermore, the muscle force is determined by biomechanical factors, such as muscle activity and cross-sectional area (CSA) (Hug et al., 2015b). It has been reported that the distribution of muscle activities during isometric contraction is similar to that during gait and pedaling, and their relationship is robust in each participant (Crouzier et al., 2019). The force distribution could influence the mechanical stress of the joint (Lewis et al., 2007). Increased muscle force spanning the knee increases the knee stress; in particular, increased muscle force in the rectus femoris (RF) might increase the mechanical knee stress (van Veen et al., 2019). Therefore, the individual force of each quadriceps head might be related to the cartilage thickness and/or symptoms in KOA patients. However, to the best of our knowledge, there is little evidence regarding whether the individual force of each quadriceps head during low-load knee extension could be associated with cartilage thickness or symptoms of KOA.

The study aimed to clarify the individual forces of each quadriceps head during low-load contractions and the associations between muscle force and cartilage thickness and symptoms in female KOA patients. We hypothesized that among women, the RF force would be higher in the KOA group than in the age-matched asymptomatic control group and would be negatively correlated with cartilage thickness and positively correlated with pain in the KOA group.

2. Methods

2.1. Participants

We performed a cross-sectional study (level of evidence: 3) of 22 women with painful medial KOA and a control group comprising 15 asymptomatic age-matched women. The sample size in KOA was determined based on a previous study that reported a correlation between muscle size and femur cartilage thickness ($\alpha = 0.05$, power = 0.80, effect size = 0.57 ($R^2 = 0.32$)) (Hudelmaier et al., 2003), and the required sample size was 19. To avoid underpowering due to dropout, we selected $n = 22$. All participants were female and were able to live and walk independently without any assistive devices. They had no rheumatoid arthritis and neuromuscular diseases, no history of back or lower extremity surgery, and no cognitive decline to the point of not understanding the informed consent procedure. The medial KOA was diagnosed as Kellgren-Lawrence (K/L) grade ≥ 2 by one author (MK). If they had bilateral KOA, then we evaluated the side with the more severe K/L grade. If the K/L grade was the same bilaterally, then we evaluated the side with more severe pain. The control group comprised community-dwelling individuals with no history of pain lasting more than 3 months, no current pain during walking, range of motion (RoM) including more than 130° of knee flexion; we evaluated the knee that satisfied all inclusion criteria (right side, 11) (Holla et al., 2012; Vårbakken et al., 2019). Prior to this study, the procedures and goals of the study were explained to all participants, who then provided written informed consent. All procedures were approved by the Ethics Committee of the Kyoto University Graduate School and Faculty of Medicine (R1647).

2.2. Experimental procedures

The Knee Society Score (KSS) was used to evaluate knee function and symptoms. Pain during gait was assessed using the Numerical Rating Scale (NRS). Passive knee RoM was measured in flexion and extension with a goniometer. We also assessed cartilage thickness using an ultrasound machine while the participants were in the supine position. We measured muscle CSA and maximal knee extension strength. The CSA was measured with an ultrasound machine while sitting on a dynamometer (Biodex System 4; Biodex Medical Systems Inc., Shirley, NY, USA). During the low-load task, participants were asked to maintain knee extension torque at 20 Nm for 15 s using visual feedback on a display that showed the exerted torque with the dynamometer; shear modulus (G) of the quadriceps muscle was recorded during the task. Rest intervals of at least 1 min were allowed between each trial to avoid fatigue.

2.3. Measured variables

2.3.1. Cartilage thickness of the medial femur

The cartilage thickness of the medial femur was measured with the participants in the supine position and using an ultrasound machine after those participants had rested in a non-weight-bearing supine position for 15 min on a bed. The KOA patients were assessed using one ultrasound machine (Noblus, Hitachi Aloka Medical Systems, Tokyo, Japan) with a 5- to 18-MHz transducer. The cartilage thickness was measured once at the midpoint between the medial edge of the patella and the medial epicondyle with the knee fully flexed (Schmitz et al., 2017). The cartilage region measured with the knee in this position was the weight-bearing surface (Okano et al., 2016), and the degenerated cartilage of the area was associated with mechanical stress during gait (Chang et al., 2015). The distance was measured between the white band (caused by the synovia-cartilage interface) and the second white band (caused by the cartilage-bone interface) at three points on an ultrasonographic image, and the cartilage thickness was defined as the mean distance of these points (Schmitz et al., 2017) (Fig. 1). In a pilot study, the intraclass coefficient [ICC] (1,1) of the values was 0.98 and 0.96 for Aixplorer and Hitachi Aloka machine, respectively. This indicates a high within-session reproducibility for the data measured using each machine (Appendix 1). The ICC (1,1) between the data from the two ultrasound machines was 0.99.

2.3.2. Muscle cross-sectional area

Participants sat on a dynamometer (Biodex System 4; Biodex Medical Systems, Inc.) with their bodies fixed. The dynamometer axis was aligned to their targeted knee axis. The knee was then fixed at 45° flexion. The CSA of the vastus medialis (VM), RF, and vastus lateralis (VL) were measured using an ultrasound machine (Aixplorer version 12.2.0; SuperSonic Imagine, Aix-en-Provence, France) with a 4- to 15-MHz linear transducer (Fig. 2a–c). Table 1 shows the measurement sites of each muscle, referring to previous studies (Maden-Wilkinson et al., 2013; Taniguchi et al., 2015). CSA were calculated using Osirix MD (version 9.0; OsiriX, Geneva, Switzerland). We detected the deep fascia surrounding the muscle using B-mode imaging before we measured the panoramic mode. We analyzed the panoramic images using B-mode images as a reference. The CSA of each muscle was measured twice and further analyzed using mean values. The ICC (1,1) were 0.98, 0.96, and 0.98 for VM, RF, and VL, respectively. In a pilot study with 10 healthy subjects, we measured the CSA of the three muscles using panoramic images and T1-weighted magnetic resonance images to confirm the validity of this measurement. The result indicated that ICC (1,1) between the CSA from MRI and US was high (VM = 0.90, RF = 0.95, VL = 0.93).

2.3.3. Maximal knee extension strength

Isometric knee extension torque was measured twice using the

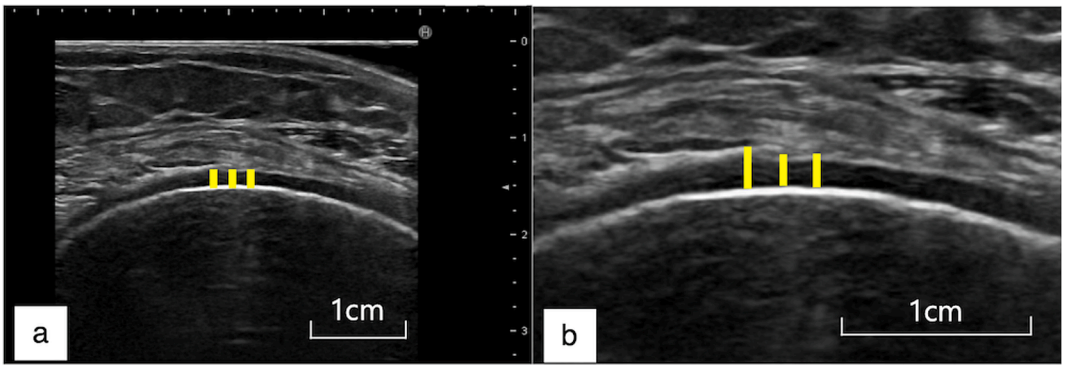

Fig. 1. Medial femur cartilage image. Fig. 1a and b show an ultrasound image of the medial femur cartilage and a closer view of the cartilage. The distance between the synovial-cartilage interface (including white band) and the cartilage-bone interface corresponds to cartilage thickness. The distance is indicated by the yellow bar. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

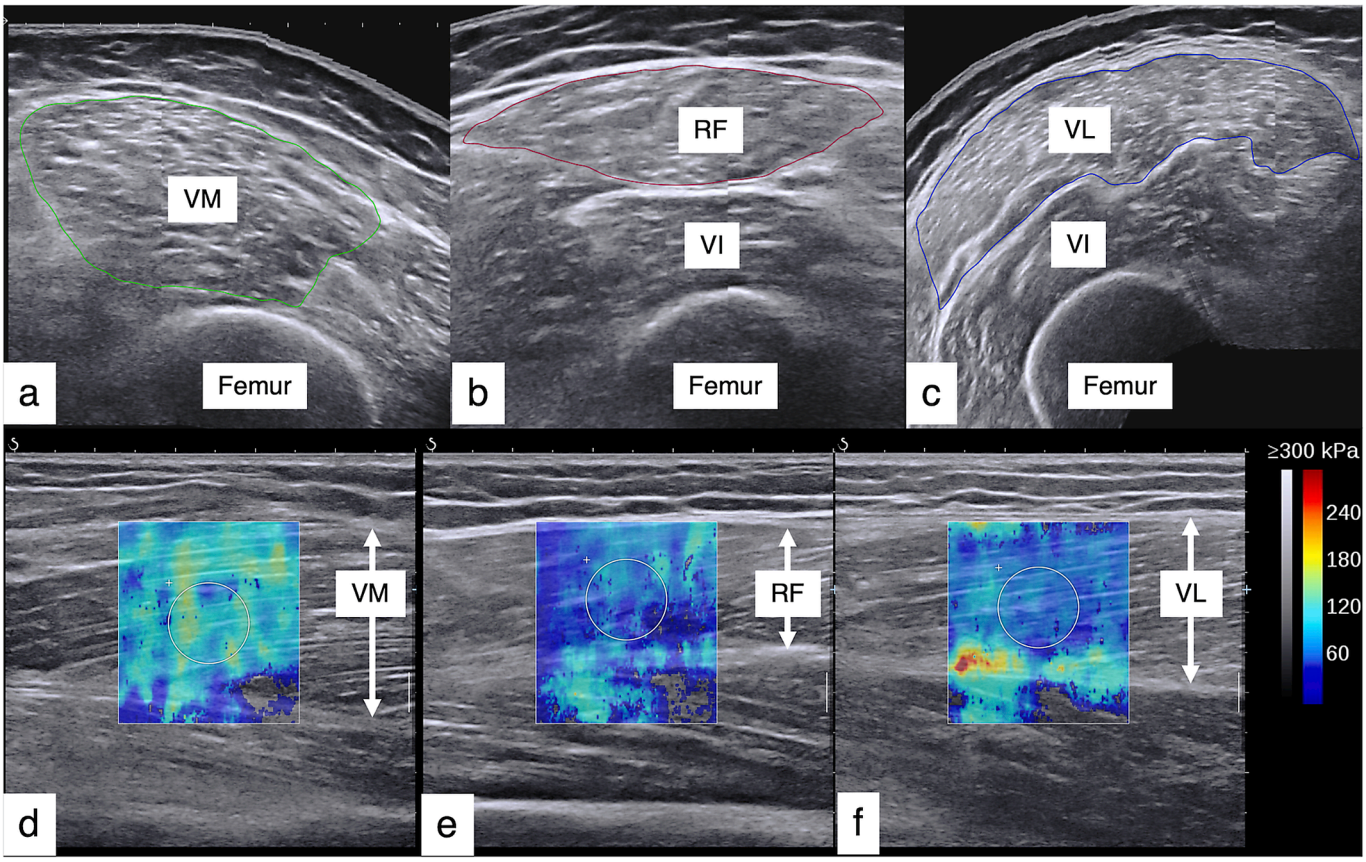

Fig. 2. Example shear wave velocity and muscle size images. CSA was measured as the area surrounded by the fascia on the Panoramic mode image [a–c]. The circle on the elastography images indicates the region of interest for the assessment of shear wave velocity[d–f]. VM; vastus medialis, RF; rectus femoris, VL; vastus lateralis, VI; vastus intermedius.

Table 1
The measured location of each muscle.

Muscle	Measured site
Vastus medialis	The distal 30% point along the thigh-length from the greater trochanter to the lateral epicondyle of the femur
Rectus femoris	The midpoint point along the thigh-length from the anterior superior iliac spine to the proximal patellar border
Vastus lateralis	The midpoint point along the thigh-length from the greater trochanter to the lateral epicondyle of the femur

dynamometer in the same position as that used for CSA measurements. Based on a previous study, we defined 45° flexion as the knee angle (Krishnan and Theuerkauf, 2015). Peak knee extension torque was measured during each maximal voluntary contraction (MVC) for 5 s, and the larger peak torque was defined as MVC torque. Then, MVC torque was normalized by body weight. The ratio of 20 Nm to MVC torque was calculated for each participant as the test torque.

2.3.4. *Muscle force index*

The G of the VM, RF, and VL were measured using an ultrasound shear wave elastography machine (Aixplorer version 12.2.0; SuperSonic Imagine) with a 4- to 15 MHz linear probe (SL15-4; SuperSonic Imagine)

(Fig. 2d–f). Shear wave elastography was set to the following parameters: mode, musculoskeletal; opt, penetration mode; and shear wave velocity scale, 0–16.3 m/s. The measurement site was the same as that used for the CSA measurement of each muscle.

After we detected the transverse section of each muscle using an ultrasound image during each low-load trial, the transducer was held parallel to the longitudinal axis of the RF and the muscle fibers of the VM and VL for approximately 3 s for stable color mapping. Then, the propagation speed was recorded for 10 s in the SWE mode at 1.3 Hz. G was calculated from the propagation speed (V) using the following equation:

$$G\ (kPa) = \rho V^2$$

where ρ is the muscle mass density, which was presumed to be 1000 kg/m^3.

The region of interest (ROI) (2.5 cm × 2.0 cm) was set over the muscle in each ultrasound image. A circle with a radius of 1.0 cm was centered on the ROI. If an artifact, void area, or non-muscle tissue was observed at the center of the ROI, then we moved the ROI slightly toward the center of the muscle belly. The G was calculated for approximately 6 s at the center of the measured section, and the average was calculated within the circle. Two trials were performed to calculate the G of each muscle, and the average value of both trials was used for further analyses.

G shows an inter-individual variability during the same joint torque (Nm), and the variability in G may be a limiting factor for comparison between individuals. Muscle size is associated with the variability in G (Dresner et al., 2001). In addition, a previous study suggested that the product of muscle size and G might be used as an indicator of muscle force (Hug et al., 2015b). Our previous study based on the above-mentioned background showed that the muscle size-scaled G, a product of muscle size and G, correlated more strongly with the absolute joint torque (Yagi et al., 2020). Thus, muscle size-scaled G could eliminate most of the inter-individual variability that is observable for G. Moreover, the muscle size-scaled G could be compared among subjects as muscle force index during the same absolute torque exertion. Thus, this study used the muscle size-scaled G as the muscle force index, and the VM-scaled G, RF-scaled G, and VL-scaled G were evaluated.

2.3.5. The knee society score and pain during gait

To assess knee symptoms and function, all participants were evaluated using the KSS (Scuderi et al., 2012). Symptom scores were assigned to pain during gait and stair climbing using a scale of 0 to 25 points (score of 25 indicated no symptom). Function scores were graded using a scale of 0 to 100 points (score of 100 indicated the highest function). We used the NRS to assess pain during gait (score of 0 indicated no pain).

2.3.6. Passive range of motion

As described previously (Peters et al., 2011), passive knee flexion and extension RoM were measured in the supine position using a two-arm goniometer (Sakai Medical Co., Ltd., Tokyo, Japan). The endpoint of motion was defined as the point at which each participant felt stiff, and the examiner could not perform further motion.

2.4. Data analysis

All statistical analyses were conducted using IBM SPSS Statistics 22 (IBM SPSS, Armonk, NY). To reveal the differences between groups, we compared the body height, body weight, body mass index, KSS symptom and function subscores, NRS scores for pain during gait, the ratio of 20 Nm (test torque), MVC torque, muscle force index, and CSA of each muscle. For each indicator, the normal distribution and homogeneity of variance were assessed in each group using the Kolmogorov–Smirnov test and Levene's test, respectively. When both normal distribution and homogeneity of variance were found, Student's *t*-test was performed. When only normal distribution was found, the Welch's t-test was performed. The Mann-Whitney *U* test was performed when neither a normal distribution nor homogeneity of variance was found. We also estimated effect sizes for these analyses.

To clarify whether cartilage thickness was correlated with muscle function, the Pearson correlation coefficient (r) was calculated for cartilage thickness and muscle CSA, muscle size-scaled G of each muscle, or MVC torque in each group. To clarify whether pain during gait was correlated with muscle function in the KOA group, Spearman's correlation coefficient (ρ) was calculated for pain and the aforementioned muscle functions.

$P < 0.05$ was considered statistically significant. The results are presented as mean ± standard deviation (SD).

3. Results

Compared with the control group, the KOA group had higher body weight and BMI, more severe pain during gait, and lower flexion and extension RoM (Table 2). The KSS symptom and function subscores of the KOA group were lower than those of the control group. The cartilage thickness of the KOA group was lower than that of the control group. There were no significant differences in other parameters between the groups.

As shown in Table 2, MVC torque in the KOA group was 33.3% lower than that in the control group. Compared with VL-scaled G in the control group, VL-scaled G was 23.7% lower in the KOA group; however, VM-scaled G and RF-scaled G were not different between groups. No differences in CSA were found between groups. The KOA group exerted higher test torque (20 Nm/MVC torque) than the control group during the low-load tasks.

The correlation coefficients of cartilage thickness or pain and muscle

Table 2
Comparison of characteristics between KOA patients and control group participants.

	KOA ($n = 22$)	Control group ($n = 15$)	*p*-value	Effect size
Age (years)	69.5 ± 5.4	70.1 ± 6.3	0.75[a]	0.06
Height (m)	155.2 ± 6.0	153.8 ± 4.9	0.47[a]	0.12
Weight (kg)	57.2 ± 11.0	47.8 ± 5.0	**0.001**[b]	0.53
BMI (kg/m^2)	23.7 ± 3.8	20.2 ± 1.8	**0.003**[a]	0.48
RoM flexion (°)	140.3 ± 14.4	154.3 ± 9.7	**0.003**[c]	0.49
RoM extension (°)	−3.8 ± 4.0	−1.1 ± 1.9	**0.024**[c]	0.37
KSS symptom (/25 points)	15.1 ± 5.1	22.3 ± 4.3	**<0.001**[c]	0.67
KSS function (/100 points)	69.0 ± 15.8	92.7 ± 9.4	**<0.001**[c]	0.71
Knee pain during gait	2.5 ± 2.0	0	**<0.001**[c]	0.77
Cartilage thickness (mm)	1.0 ± 0.5	1.5 ± 0.4	**0.001**[a]	0.53
Radiographic OA severity Kellgren/Lawrence (grade: n)	Grade II:9, III:8, IV:5	–	–	–
VM-scaled G (kPa•cm^2)	306.9 ± 127.5	318.5 ± 132.9	0.79[a]	0.05
RF-scaled G (kPa•cm^2)	153.1 ± 102.4	149.2 ± 114.9	0.91[a]	0.02
VL-scaled G (kPa•cm^2)	328.0 ± 92.4	429.7 ± 111.3	**0.005**[a]	0.49
VM CSA (cm^2)	11.4 ± 2.0	11.0 ± 1.8	0.584[a]	0.09
RF CSA (cm^2)	6.7 ± 1.3	6.8 ± 1.8	0.900[a]	0.02
VL CSA (cm^2)	12.2 ± 2.3	12.2 ± 2.1	0.996[a]	0.01
MVC torque (Nm/kg)	1.4 ± 0.4	2.1 ± 0.3	**<0.001**[a]	0.71
test torque (% MVC torque)	26.4 ± 0.7	20.4 ± 0.3	**<0.001**[b]	0.57

a: unpaired t-test, b: Welch's t-test, c: Mann-Whitney U test, Bold font: $p < 0.05$. BMI: Body Mass Index, RoM: Range of Motion, KSS: the Knee Society Score, NRS: numeric rating scale, VM: Vastus medialis, RF: Rectus femoris, VL: Vastus Lateralis, Scaled G: muscle-size scaled shear elastic modulus, CSA: cross-sectional area, MVC: maximal voluntary contraction.

Table 3
Correlations between muscle function and cartilage thickness or Pain.

	KOA group ($n = 22$)				Control group ($n = 15$)	
	Cartilage thickness (mm)		Pain during gait		Cartilage thickness (mm)	
	r	p-value	ρ	p-value	r	p-value
VM-scaled G (kPa•cm^2)	0.57	**0.006**	−0.24	0.28	0.18	0.518
RF-scaled G (kPa•cm^2)	−0.45	**0.038**	0.24	0.29	0.05	0.849
VL-scaled G (kPa•cm^2)	0.45	**0.035**	−0.56	**0.007**	0.03	0.926
VM CSA (cm^2)	−0.05	0.843	0.16	0.49	0.2	0.474
RF CSA (cm^2)	−0.33	0.135	−0.02	0.93	0.01	0.967
VL CSA (cm^2)	0.07	0.751	0.08	0.77	−0.17	0.538
MVC torque (Nm/kg)	0.13	0.561	−0.29	0.19	0.47	0.078

Bold font: $p < 0.05$. r: Pearson's correlation coefficient, ρ: Spearman's correlation coefficient, VM: Vastus medialis, RF: Rectus femoris, VL: Vastus Lateralis, Scaled G: muscle-size scaled shear elastic modulus, CSA: cross-sectional area, MVC: maximal voluntary contraction.

function are shown in Table 3. VM-scaled G ($r = 0.57$; $p = 0.006$) and VL-scaled G ($r = 0.45$ and $p = 0.035$) were positively correlated with cartilage thickness, whereas RF-scaled G ($r = -0.45$ and $p = 0.038$) was negatively correlated with cartilage thickness. Additionally, VL-scaled G was negatively correlated with pain during gait ($\rho = -0.56$ and $p = 0.007$); however, other indicators in the KOA group were not correlated with cartilage thickness or pain during gait (Table 3).

4. Discussion

In this study, we observed that MVC torque and VL force were lower in the KOA group than in the control group. In addition, the correlation analysis of the intra-KOA group showed that female KOA patients who exerted higher VM and VL force during the 20-Nm knee extension torque exertion had thicker cartilage, and KOA patients who exerted higher RF force had thinner cartilage. Additionally, KOA patients who exerted a higher VL force during the low-load task had lower pain. To the best of our knowledge, this is the first study to indicate that female KOA patients have decreased VL force in synergistic muscles, and that the individual forces of each quadriceps head are related to cartilage degeneration and pain.

In this study, the test torque during low-load contraction was not determined as the percentage of MVC torque; instead, it was purposely set to 20 Nm for all participants for three reasons. First, muscle size-scaled G could be compared between subjects only when the same absolute torque was exerted, as mentioned in the method section. Second was that the muscle force required during ADL was determined by task intensity (Alexander et al., 2021), which is often represented as % bodyweight or absolute value, not %MVC (Adouni et al., 2012; Crossley et al., 2012). Third, it is difficult for patients experiencing pain, such as KOA patients, to exert genuine MVC (Pietrosimone et al., 2011). If KOA patients did not exert genuine MVC, the comparison of the muscle force would have been at different relative and absolute levels of intensity even when the load was set at the same percentage of MVC. In this situation, it would have been difficult to clarify whether the inter-group differences in muscle force were due to individual features or the load amount. The percentage of MVC torque of both groups was not exactly the same because the KOA group had higher test torque compared to the control group in this study. Therefore, muscle force must be elucidated for the same controlled torque, and the constant torque allowed us to reveal patient-specific force distributions. Before this study, the torque amount, 20 Nm, was determined to be approximately 20% of the reported maximal knee extension torque (Taniguchi et al., 2015). We determined the test torque at approximately 20% MVC because the torque during low-load contraction set to 20–25% MVC (Crouzier et al., 2019; Hug et al., 2015a), and RF activated with about 20% MVC activity during gait (Lee et al., 2017).

The VL force of KOA patients was lower than that of control participants, the RF forces of both groups were not different, and the VL force was negatively correlated with pain, which conflicted with our hypothesis. Additionally, we did not observe any differences in the CSA of each muscle in both groups. Because pain and swelling of the knee caused decreased vasti muscle activities during gait, neuromuscular factors controlling muscle force may be influenced by KOA (Hubley-Kozey et al., 2006). G, which is correlated with muscle activity, decreases muscular pain (Hug et al., 2014; Yoshitake et al., 2014). As such, arthrogenic muscle inhibition could have influenced muscle force index. Furthermore, it is possible that we could have determined the reason for the observed decreased VL force by testing muscle tenderness. Within the vasti muscles, VM had severe muscle degeneration, such as fatty infiltration (Taniguchi et al., 2015), and the CSA measured using ultrasonography could have been overestimated. Because increased intramuscular connective and adipose tissues could increase muscle stiffness (Lee et al., 2015), muscle degeneration might lead to statistically similar VM force between groups. Based on our results, KOA patients could have decreased vasti forces, particularly VL force.

Although no differences in CSA were observed between the KOA group and control group, MVC torque in the KOA group was lower than that of the control group, supported by previous studies (Taniguchi et al., 2015). Several studies that measured muscle volume using MRI reported no difference between KOA patients and asymptomatic older adults (Beattie et al., 2012; Yamauchi et al., 2019), which supports our results. However, a study that used ultrasonography to compare the thickness of each quadriceps muscle showed that the VM was thinner in KOA patients than in asymptomatic older adults (Taniguchi et al., 2015). Further studies are needed to determine the site-specific decrease in muscle size.

The negative correlation observed between cartilage thickness and RF force supports our hypothesis; however, VM force and VL force were positively correlated with cartilage thickness. Although this study had a cross-sectional design and did not assess the causal relationship, we hypothesize two potential mechanisms to explain these correlations. First, the high load caused by the muscle force distribution, such as increased RF force, decreased cartilage thickness. Muscle force is determined by several biomechanical factors, such as muscle activity and CSA (Hug et al., 2015b). The distribution of muscle activity during low-load isometric tasks is similar to that during gait and pedaling (Crouzier et al., 2019). Increased RF force during gait may cause higher joint loading (van Veen et al., 2019). If the RF force increases during knee extension, the hip flexion torque may increase. This additional hip torque should be compensated by increased activation of the hip extensor muscles (e.g., hamstrings), and the compensatory activity would be a factor in increasing the knee stress because the hamstrings act on the knee joint. Thus, higher joint loading caused by muscle force distribution might result in more decreased cartilage thickness. Previous studies have shown that the central nervous system chooses the pattern of muscle activation to regulate internal joint variables (Alessandro et al., 2018; Barroso et al., 2019). KOA patients with thinner cartilage might not choose the force pattern to regulate the internal joint variables. The second could be that the swelling caused by cartilage degeneration may inhibit activities of the vasti muscles (Palmieri-Smith et al., 2007; Wang et al., 2016). Thus, less cartilage thickness might decrease the vasti force, which may lead to a compensatory increase in RF force.

Previous studies showed no consensus regarding the relationship between degeneration and thickness of cartilage and muscle size or maximal knee extension strength (Amin et al., 2009; Chin et al., 2019; Culvenor et al., 2019; Tuna et al., 2016). This study shows that these indicators are not correlated with cartilage thickness, which is in

agreement with the results of a previous study that reported no relationship between these indicators and cartilage degeneration (Amin et al., 2009; Culvenor et al., 2019). Although some previous studies reported relationships between cartilage thickness and MVC torque (Chin et al., 2019; Tuna et al., 2016), there were several methodological differences between these studies and the present study. For example, there were differences in the measured site and the assessed method for cartilage degeneration, study design (longitudinal or cross-sectional), and statistical analysis. Furthermore, subjects' characteristics (such as gender and with or without KOA) were different from those in the current study. This could have led to inconsistent results between previous studies and this study. As previously mentioned, muscle activity during gait was approximately 20% of the MVC value, and maximal knee extension strength could not be associated with mechanical stress of the knee during ADL (Lee et al., 2017; Lim et al., 2009). Considering the results of the previous study and the present study, maximal knee extension strength might not be a suitable indicator of cartilage thickness in KOA; however, the individual force of each quadriceps head during low-load contraction is a meaningful indicator of cartilage thickness and symptoms of female KOA patients.

We are aware that our research had some limitations. Cartilage degeneration was defined as cartilage thickness at a specific region of the medial femur measured using ultrasound with the knee fully flexed. We focused on the cartilage thickness in ROI because that region allowed exposure of the weight-bearing femoral cartilage surface (Okano et al., 2016) and the patients had medial KOA. Although cartilage degeneration was often assessed by grading cartilage thickness, echogenicity, and sharpness (Saarakkala et al., 2012), this study adopted cartilage thickness as an indicator of cartilage degeneration because we could assess it objectively and quantitatively. In addition, we used different ultrasound devices to measure the cartilage thickness in the control and KOA groups. Next, we could not confirm that the control group participants did not have KOA. Although the control group participants had no pain, at least on the targeted side, some participants had knee pain on the unmeasured side. Because cartilage thickness is related to the contralateral knee status, it is possible that early osteoarthritis with cartilage degeneration could have been included in the control group (Eckstein et al., 2019). Lastly, as this study included only female patients with medial KOA, we could not apply the results to other populations such as men and lateral KOA patients.

5. Conclusions

The female patients in KOA group had lower MVC torque normalized by body weight and VL force than the female participants in control group. Additionally, VM and VL forces were positively correlated, and RF force was negatively correlated with cartilage thickness in the KOA group. Moreover, a higher VL force during the low-load task was associated with lower knee pain. These results suggest that the individual forces of each quadriceps head in women with KOA could be related to decreased cartilage thickness and knee pain. Further studies should be conducted to observe whether individual forces of each quadriceps head could cause progressive symptoms and cartilage degeneration, and the results should be evaluated in greater detail.

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Declaration of Competing Interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clinbiomech.2021.105546.

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