Differences in Patellofemoral Alignment Between Static and Dynamic Extension Positions in Patients With Patellofemoral Pain

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Background: Considering that patellofemoral pain (PFP) is related to dynamic factors, dynamic extension on 4-dimensional computed tomography (4-DCT) may better reflect the influence of muscles and surrounding soft tissue than static extension.

Purpose: To compare the characteristics of patellofemoral alignment between the static and dynamic knee extension position in patients with PFP and controls via 4-DCT.

Study Design: Cross-sectional study; Level of evidence, 3.

Methods: Included were 39 knees (25 patients) with PFP and 37 control knees (24 participants). For each knee, an image of the dynamic extension position (a single frame of the knee in full extension [flexion angle of -5° to 0°] selected from 21 frames of continuous images acquired by 4-DCT during active flexion and extension) and an image of the static extension position (acquired using the same equipment with the knee fully extended and the muscles relaxed) were selected. Patellofemoral alignment was evaluated between the dynamic and static extension positions and between the PFP and control groups with the following parameters: patella-patellar tendon angle (P-PTA), Blackburne-Peel ratio, bisect-offset (BO) index, lateral patellar tilt (LPT), and tibial tuberosity-trochlear groove (TT-TG) distance.

Results: In both PFP patients and controls, the P-PTA, Blackburne-Peel ratio, and BO index in the static extension position were significantly lower ($P < .001$ for all), while the LPT and TT-TG distance in the static extension position were significantly higher ($P \leq .034$ and $P < .001$, respectively) compared with values in the dynamic extension position. In the comparison between groups, only P-PTA in the static extension position was significantly different (134.97° ± 4.51° [PFP] vs 137.82° ± 5.63° [control]; $P = .027$). No difference was found in the rate of change from the static to the dynamic extension position of any parameter between the study groups.

Conclusion: The study results revealed significant differences in patellofemoral alignment characteristics between the static and dynamic extension positions of PFP patients and controls. Multiplanar measurements may have a role in subsequent patellofemoral alignment evaluation.

Keywords: alignment; 4-DCT; dynamic; kinematics; patellofemoral pain

Patellofemoral pain (PFP), among the most common disorders of the lower extremities, has been reported to affect 22.7% and 28.9% of the general population and adolescents, respectively.[30] It is defined as retropatellar or peripatellar pain,[21] which is aggravated by daily activities such as squatting and jumping.[12] The impact of PFP can be profound, reducing the physical functioning and quality of life of patients.[11,14] In addition, PFP may evolve into subsequent patellofemoral osteoarthritis.[34]

Although the exact cause of PFP remains unclear, it has been commonly assumed that an imbalance of the extensor mechanism can lead to patellar malalignment and maltracking, increasing the stress on the joint.[26] This imbalance in the extensor mechanism involves dynamic factors

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that cannot be evaluated by static imaging.[25] Although several studies have presented measurements (for motion-related parameters) based on static magnetic resonance imaging (MRI) scans obtained at different knee flexion angles,[19,28] it is difficult to incorporate muscle factors that may affect the patellofemoral function.[29,27]

A meta-analysis demonstrated that the assessment of patellofemoral alignment together with quadriceps activation improves the ability to diagnose maltracking.[17] However, the type (dynamic or static) and intensity of muscle contraction varied among studies. Although several studies have compared the patellofemoral joint alignment in knee extension with and without quadriceps contraction,[5,18] most studies included analysis of the patellofemoral joint alignment without knee motion and with quadriceps isometric contraction. Isotonic contraction of the quadriceps can truly reflect the physiological exercise of the patellofemoral joint.

Four-dimensional computed tomography (4-DCT) is a new technology that aims to provide kinematic evaluation of joints. It allows the acquisition of several phases during joint movement with active muscle loading.[7] Therefore, a frame with quadriceps isotonic contraction during the knee flexion-extension movement can be obtained. Several studies have reported the dynamic and kinematic benefits of 4-DCT in assessments of patellofemoral anatomy.[10,32] Although 1 study observed that the most significant lateralization of the patella was at 20° of flexion,[29] most analyses of the patellofemoral alignment were performed using full extension of the knee; in clinical practice, computed tomography (CT)-based assessment of the patellofemoral alignment is also performed with the knee fully extended. It remains unclear whether the assessments of patellofemoral alignment in the quadriceps isotonic contraction position (the dynamic extension position) differ from those in the quadriceps relaxation position (the static extension position).

The present study was designed to compare the characteristics of patellofemoral alignment between the static and dynamic knee extension position in patients with PFP versus a control group of patients with no PFP. We hypothesized that there would be greater lateral patellar displacement and increased patellar height in the dynamic extension position will lead to greater lateral patellar displacement and increased patellar height compared with the static extension position. We also hypothesized that, in the dynamic extension position, patients with PFP and without previous patellar dislocation or severe patellofemoral deformity will show no significant differences on most patellofemoral alignment parameters compared with controls.

METHODS

Study Groups

The study protocol received ethics committee approval. This prospective study included patients with PFP who were recruited consecutively from January 1 to October 31, 2021. Two independent orthopaedic knee surgeons took a history and conducted the physical examination of patients to check the stability of the patellofemoral joint and to rule out anterior knee pain at sites other than the patellofemoral joint and other pain triggers. Patients were included in the PFP group based on the following criteria: (1) consecutive PFP symptoms for at least 6 months, and (2) no ligament or meniscal injury seen on MRI examination. The exclusion criteria were as follows: (1) participants with traumatic PFP onset or a history of knee surgery, (2) previous patellar dislocation and severe patellofemoral joint deformity, (3) presence of severe osteoarthritis (Kellgren-Lawrence grade ≥3) or inflammatory arthritis, and (4) patients who could not undergo CT examination (eg, pregnant women, those preparing for pregnancy, and those who could not perform the required knee movements). The control group included patients with anterior cruciate ligament rupture who required CT examination for the preoperative planning of anterior cruciate ligament repair surgery; those with no PFP history in the knees were included in the control group, whereas exclusions were made following the same exclusion criteria as those used to exclude patients.

4-DCT Protocol

The 4-DCT scans were performed on a wide-detector scanner with 320 0.5-mm detectors (Aquilion ONE, Canon Medical Systems). This CT system delivers 160 mm of coverage in a single rotation of the gantry. We used the dynamic CT continuous scan mode (no table feed) to get 3-dimensional kinematic images.

Patients were placed in a supine position with the calves suspended in the gantry (Figure 1A) and practiced continuous active knee flexion and extension, completing approximately 1.5 cycles of knee motion (flexion-extension-flexion) during a 10-second scan. The active knee motion was slow and uniform, with the thighs remaining stable and the knees and feet kept together during the process (Figure 1B,C). A total of 21 frames of continuous images were acquired using 4-DCT. The frame with the knee fully extended (flexion angle, -5° to 0°) was selected as the image of the dynamic extension position; participants with no

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Figure 1. Examination process of dynamic extension position and static extension position. (A-C) Acquisition of dynamic extension position during knee flexion and extension. (D) Acquisition of static extension position.

frame meeting the criteria of the dynamic extension position were excluded. The imaging protocol was as follows: time interval 0.5 s, display field of view (DFOV), 500 × 500 × 160 mm, slice thickness 0.5 mm, slice spacing 0.5 mm, tube rotation 0.35 s, and tube output 100 kV and 70 mA. Static knee extension position images were also acquired using the same equipment with patients placed in the supine position with the lower extremities fully extended and relaxed and the knees and feet kept together (Figure 1D). The imaging protocol was as follows: DFOV 250 × 250 × 160 mm, slice thickness 0.5 mm, slice spacing 0.5 mm, tube rotation 0.5 s, and tube output 100 kV and 70 mA. During imaging, each participant (from the neck to the proximal thigh) was covered with a lead protector. Tanaka et al[33] reported that the effective dose for a 64-slice scanner was more than 3 times that of the 320 detectors CT scanner when obtaining the same amount of information.

Image Analyses

Five quantitative parameters, including the Blackburne-Peel ratio, patella-patellar tendon angle (P-PTA), bisect-offset (BO) index, tibial tuberosity-trochlear groove (TT-TG) distance, and lateral patellar tilt (LPT), were used to evaluate the position of patella in both the static and dynamic knee extension positions. Two fellowship-trained musculoskeletal radiologists (Y.C. and J.L., with 2 and 9 years of clinical experience, respectively) performed the measurements independently after all the data from the 2 groups had been mixed blindly and distributed randomly. All measurements were then repeated by 1 of the radiologists (J.L.) after an interval of at least 4 weeks. The intraclass correlation coefficient (ICC) was used to assess the inter- and intrarater reliability of the quantitative measurements.

The Blackburne-Peel ratio was calculated as the perpendicular distance from the inferior edge of the patellar articular surface to the line from the tibial plateau surface divided by the maximum length of the patellar articular surface (Figure 2A).[6] The P-PTA was defined as the angle between the upper pole and lower pole and the upper margin of the tibial tuberosity (Figure 2B).[13] The BO index quantifies the amount of patellar lateralization relative to the trochlear groove and was measured as the percentage of the patella that was lateral to the projected line through the deepest portion of the trochlear groove (Figure 2C).[33,36] The LPT represented the angle between the line joining the maximum width of the patella and the tangent line of the posterior femoral condyles (Figure 2C).[24] The TT-TG distance was measured as the distance between parallel lines through the deepest point of the trochlear groove and the middle of the tibial tuberosity. Here, both parallel lines were drawn perpendicular to the tangent line of the posterior femoral condyles (Figure 2D).[31,35]

Statistical Analysis

SPSS Version 26.0 (IBM) was used for data analysis. Demographic data were analyzed using descriptive

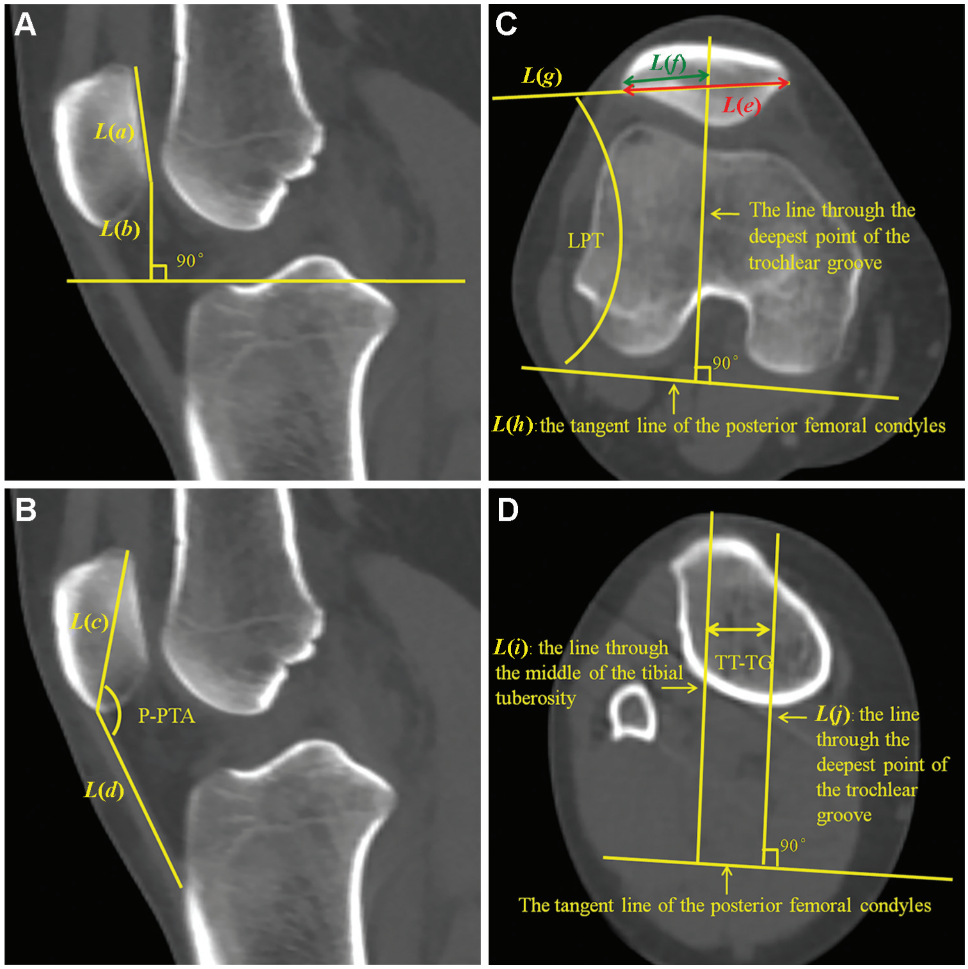

Figure 2. Measurements of the patellofemoral parameters. (A) The Blackburne-Peel ratio is calculated as $L(b)/L(a)$. (B) The P-PTA is the angle formed by $L(c)$ and $L(d)$. (C) The BO index is calculated as $L(f)/L(e) \times 100\%$, and the LPT is the angle formed by $L(g)$ and $L(h)$. (D) The TT-TG distance is the distance between $L(i)$ and $L(j)$. BO, bisect-offset; LPT, lateral patellar tilt; P-PTA, patella-patellar tendon angle; TT-TG, tibial tuberosity-trochlear groove.

statistics. Continuous variables with a normal distribution were expressed as means and standard deviation. The Student t test was used to compare variables between the PFP and control groups, and the paired Student t test was used to compare variables between the static and dynamic extension positions. We also analyzed the rate of change of each parameter from the static extension position to the dynamic extension position, calculated as $[(\text{Value}_{\text{dynamic}} - \text{Value}_{\text{static}})/\text{Value}_{\text{static}}] \times 100\%$, and used the Student t test to compare the rate of change between the PFP and control groups. For all comparisons, a P value $<.05$ was considered significant.

TABLE 1
Participant Characteristics[a]

Characteristic	PFP (n = 25 patients, 39 knees)	Control (n = 24 patients, 37 knees)
Sex, No. of patients		
Male	4	15
Female	21	9
Age, ys[b]	35 ± 9 (17-55)	35 ± 9 (17-39)
Side, No. of knees		
Left	17	18
Right	22	19

[a]PFP, patellofemoral pain.
[b]Mean ± SD (range).

RESULTS

Demographic Characteristics of the Study Groups

During the study period, a total of 39 knees in 25 patients were included in the PFP group and 37 knees in 24 participants were included in the control group (Table 1). In addition, regarding the images of the dynamic knee extension position, 3 knees in the PFP group and 8 knees in the control group did not completely show the upper pole of the patella, which prevented accurate measurements of Blackburne-Peel ratio and P-PTA; thus, the sample sizes for these 2 parameters were 36 and 29, respectively.

Inter- and Intrarater Reliability of Quantitative 4-DCT Measurements

The ICCs for interrater reliability ranged from 0.845 to 0.983, and the ICC for intrarater reliability ranged from 0.920 to 0.970, indicating excellent reliability of the quantitative 4-DCT measurements (Table 2).

TABLE 2
Inter- and Intrarater Reliability[a]

Parameter	Interrater Reliability	Intrarater Reliability
P-PTA	0.942 (0.718-0.982)	0.920 (0.390-0.978)
Blackburne-Peel ratio	0.845 (0.659-0.934)	0.964 (0.915-0.985)
BO index	0.983 (0.955-0.993)	0.970 (0.929-0.988)
LPT	0.975 (0.939-0.990)	0.967 (0.922-0.986)
TT-TG distance	0.925 (0.827-9.969)	0.943 (0.865-0.976)

[a]Data are reported as intraclass correlation coefficient (95% CI). BO, bisect-offset; CI, confidence interval; LPT, lateral patellar tilt; P-PTA, patella-patellar tendon angle; TT-TG, tibial tuberosity-trochlear groove.

Radiological Evaluation

All parameters were significantly different between the static and dynamic extension positions in both PFP patients and controls (Table 3). The P-PTA, Blackburne-Peel ratio, and BO index in the static extension position were significantly lower than those in the dynamic extension position ($P < .001$ for all), while the LPT and TT-TG distance in the static extension position were significantly higher ($P \leq .034$ and $P < .001$, respectively). In the comparison between groups, only P-PTA in the static extension position was significantly different (134.97° ± 4.51° [PFP] vs 137.82° ± 5.63° [control]; $P = .027$) (Table 4). In the dynamic extension position, no significant differences in any parameters were found between the PFP and control groups. No difference was found between the 2 groups in

TABLE 3
Comparison Between Static and Dynamic Extension Positions in PFP and Control Groups[a]

Parameter	PFP (n = 39 knees)				Control (n = 37 knees)			
	Static	Dynamic	*t*	*P*	Static	Dynamic	*t*	*P*
P-PTA, deg	134.97 ± 4.51[b]	150.71 ± 4.57[b]	-19.669	**<.001**	137.82 ± 5.63[c]	152.35 ± 4.59[c]	-16.850	**<.001**
Blackburne-Peel ratio	0.98 ± 0.17[b]	1.15 ± 0.16[b]	-8.987	**<.001**	0.88 ± 0.26[c]	1.05 ± 0.25[c]	-6.757	**<.001**
BO index, %	67.15 ± 10.58	75.13 ± 11.82	-8.591	**<.001**	67.29 ± 7.24	73.76 ± 8.48	-6.403	**<.001**
LPT, deg	15.35 ± 5.33	13.96 ± 7.65	2.195	**.034**	15.54 ± 4.94	13.48 ± 6.76	2.977	**.005**
TT-TG distance, mm	14.60 ± 2.73	11.63 ± 3.90	6.538	**<.001**	14.91 ± 3.77	10.89 ± 4.00	8.881	**<.001**

[a]Data are reported as mean ± SD. Boldface *P* values indicate statistically significant difference between static and dynamic extension positions ($P < .05$). BO, bisect-offset; LPT, lateral patellar tilt; P-PTA, patella-patellar tendon angle; TT-TG, tibial tuberosity-trochlear groove.
[b]n = 36 knees.
[c]n = 29 knees.

TABLE 4
Comparison Between PFP and Control Groups in Static and Dynamic Extension Positions[a]

Parameter	Static Extension Position				Dynamic Extension Position			
	PFP (n = 39 knees)	Control (n = 37 knees)	*t*	*P*	PFP (n = 39 knees)	Control (n = 37 knees)	*t*	*P*
P-PTA, deg	134.97 ± 4.51[b]	137.82 ± 5.63[c]	-2.271	**.027**	150.71 ± 4.57[b]	152.35 ± 4.59[c]	-1.429	.158
Blackburne-Peel ratio	0.98 ± 0.17[b]	0.88 ± 0.26[c]	1.184	.074	1.15 ± 0.16[b]	1.05 ± 0.2[c]	1.834	.073
BO index, %	67.15 ± 10.58	67.29 ± 7.24	-0.068	.946	75.13 ± 11.82	73.76 ± 8.48	0.584	.561
LPT, deg	15.35 ± 5.33	15.54 ± 4.94	-0.156	.877	13.96 ± 7.65	13.48 ± 6.76	0.286	.766
TT-TG distance, mm	14.60 ± 2.73	14.91 ± 3.77	-0.396	.694	11.63 ± 3.90	10.89 ± 4.00	0.818	.416

[a]Data are reported as mean ± SD. Boldface *P* values indicate statistically significant difference between PFP and control groups ($P < .05$). BO, bisect-offset; LPT, lateral patellar tilt; P-PTA, patella-patellar tendon angle; TT-TG, tibial tuberosity-trochlear groove.
[b]n = 36 knees.
[c]n = 29 knees.

TABLE 5
Comparison Between PFP and Control Groups in Rate of Change From Static to Dynamic Extension Position[a]

	Rate of Change, %			
Parameter	PFP	Control	*t*	*P*
P-PTA	11.74 ± 3.80	10.63 ± 3.56	1.200	.235
Blackburne-Peel ratio	18.69 ± 13.17	21.79 ± 16.38	-0.848	.400
BO index	12.20 ± 9.09	9.86 ± 9.04	1.125	.264
LPT	-15.74 ± 38.66	-14.94 ± 34.76	-0.095	.925
TT-TG distance	-20.89 ± 20.50	-27.14 ± 18.26	1.402	.165

[a]Data are reported as mean ± SD. BO, bisect-offset; LPT, lateral patellar tilt; P-PTA, patella-patellar tendon angle; TT-TG, tibial tuberosity-trochlear groove.

the rate of change in any of the parameters from the static to the dynamic extension position (Table 5).

DISCUSSION

Consistent with our hypothesis, this study revealed a greater lateral patellar displacement, increased patellar height, deceased lateral patellar tilt, and greater anterior patellar tilt in the dynamic extension position compared with the static extension position. Furthermore, when comparing group differences, only P-PTA in the static extension position was significantly lower in the PFP group in the static extension position; the other static extension position parameters and all dynamic extension position parameters were similar between the PFP and control groups.

Currently, 4-DCT is the most representative noninvasive technique for the investigation of physiological kinematics of the knee joint and has a radiation exposure that is one-third of 64-row CT for the acquisition of the same amount of information.[33] Hence, 4-DCT is both safe and feasible for conducting dynamic knee examinations involving soft tissue and the quadriceps in patients with PFP.[9,16]

In the present study, when within-group comparisons were made, the dynamic extension position reflected the effect of the quadriceps isotonic contraction and soft tissue surrounding the patellofemoral joint on patellofemoral alignment at full extension. Both groups displayed increased Blackburne-Peel ratio and BO index in the dynamic extension position, reflecting significantly greater patellar height and lateral patellar displacement. These results are consistent with those of Guzzanti et al,[18] who demonstrated that the patella rose 0.3 to 1 cm with slight lateralization on quadriceps activation during the CT examination. Activation of the quadriceps elevated the patella and physiologically, the patella showed a lateralization of approximately 4 mm in terminal extension. In active full extension, the tight medial patellar retinaculum prevents lateral translation of the patella. In early flexion, this ligament slackens with the medial movement of the patella, with no full engagement of the patella in the trochlear groove, indicating significant patellar instability in this position.[4] This patellar lateral translation in terminal extension may be transient and therefore can be captured during dynamic extension.

Both the BO index and TT-TG distance are important parameters in the evaluation of patellar instability. Interestingly, we found higher BO index but lower TT-TG distance in the dynamic extension position compared with the static extension position. We assume that the decreased TT-TG distance in dynamic extension was due to the contraction of the quadriceps controlling the external rotation of the tibia.[15] However, further biomechanical studies are needed to confirm this assumption. We also found that the LPT was lower in the dynamic extension position compared with the static extension position. Biedert et al[5] reported an increased LPT in symptomatic knees on quadriceps contraction compared with those without quadriceps contraction; however, these authors did not observe a significant change in the control population. Another study by Jan et al[20] revealed a decreased LPT on quadriceps contraction in a subgroup with laterally tilted patella; this result is consistent with that of the present study. At present, available evidence on the effect of quadriceps contraction on LPT differs significantly, and hence more data are required in the future.

Study findings indicated that the P-PTA was higher in the dynamic extension position than that in the static extension position, revealing an anterior tilt of the patella in the sagittal plane under dynamic conditions. When intergroup comparisons were made, P-PTA was the only parameter that differed significantly between the 2 groups in the static extension position. Aksahin et al[1] evaluated the sagittal plane alignment in patients with chondromalacia patella and showed that the P-PTA was significantly lower compared with that in the control group. Another study demonstrated an increased P-PTA in patients with anterior knee pain following tibial nailing,[3] and this increased P-PTA was attributed to quadriceps atrophy. In the present study, the P-PTA was significantly lower in the PFP group than that in the control group, suggesting the existence of a sagittal patellar tilt in patients with PFP. Recent studies have focused on evaluating patellofemoral malalignment in the axial plane, while few studies have discussed patellofemoral malalignment in the sagittal plane. The patellar tilt in the sagittal plane is a novel concept and will help to reveal the underlying PFP pathophysiology.[2] The patella has a complete 6 degrees of freedom in its movement, and therefore, the evaluation of the patellofemoral alignment should be based on multiplanar movements.[22]

In the present study, no significant differences were observed between the PRP and control groups in terms of the Blackburne-Peel ratio, BO index, LPT, or TT-TG distance in either the dynamic or static extension positions. Carlson et al[8] observed that the patella of patients with PFP had significantly greater lateral displacement at 10°, 20°, and 30° of knee flexion compared with those in healthy controls. MacIntyre et al[23] also revealed that the patella in the PFP group was positioned more laterally than those in the control group at 19° of knee flexion. These results indicate that the biomechanical changes in the patellofemoral joint cannot be observed well in the extension position, and the patellar position varies with the angle of flexion due to the complex constraint of the surrounding soft tissues. The development of dynamic MRI and 4-DCT offers the possibility of dynamic assessment of the patellofemoral joint during the range of motion of the knee. Further studies of patellofemoral alignment should not be limited to only 1 position of the dynamic extension position but rather extend to the entire flexion and extension.

Limitations

This study has several limitations. First, the sample size was relatively small; this was related to the significantly larger radiation dose in 4-DCT scans compared with conventional CT and the stringent inclusion criteria of the study. Second, we compared the patellofemoral joint in only the extension position, which cannot reflect the effect of quadriceps contraction on the patellofemoral alignment characteristics during knee flexion and extension. Third, CT examinations involve the use of ionizing radiation; therefore, to comply with ethical requirements, the control group for our study could be selected from only among patients with anterior cruciate ligament rupture who required CT scans for preoperative planning.

CONCLUSION

The results of the present study revealed greater lateral patellar displacement, increased patellar height, deceased lateral patellar tilt, and greater anterior patellar tilt in the dynamic extension position compared with the static extension position. Based on the dynamic characteristics of the patellofemoral joint, multiplanar measurements may have a role in subsequent patellofemoral alignment evaluations.

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