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The inclination of the femoral medial posterior condyle was almost vertical and that of the lateral was tilted medially

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Abstract

Purpose The purpose of this study was to three-dimensionally analyse the size and shape of the femoral posterior condyles of the normal knee.

Methods A total of 62 healthy Japanese volunteers (37 males and 25 females) providing a sample of 124 normal knee joints, who had no knee-related symptoms and no history of major trauma, underwent computed tomography scans of the bilateral femur and tibia. Three-dimensional digital models of the femur were constructed from computed tomography data using visualisation and modelling software. The following parameters were evaluated: (1) the radii of the posterior condyles approximated to spheres and (2) the inclination angle of the posterior condyles in the coronal plane of the femoral coordinate system.

Results The radii of the medial and lateral condyles approximated to spheres were 17.0 ± 1.6 and 17.1 ± 1.8 mm, respectively and were not different. The inclination angles of the medial and lateral condyles in the coronal plane were − 0.6° ± 4.6° and 9.7° ± 5.7°, respectively. The medial condyle was almost vertical, whereas the lateral one was medially tilted.

Conclusions This study found an asymmetrical inclination between medial and lateral condyles. This may be related to the asymmetrical motion of the knee, which is known as medial pivot motion. This finding provides valuable morphological information and may be useful for implant designs for total knee arthroplasty.

Level of evidence IV.

Keywords Knee · Femur · Computed tomography · Three–dimensional · Total knee arthroplasty

Abbreviations

3D	Three dimension
CT	Computed tomography
ICC	Intraclass correlation coefficient
MRI	Magnetic resonance imaging
TKA	Total knee arthroplasty

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Introduction

It is important to clarify the articular shape of the distal femoral condyles to understand knee kinematics and the aetiology of knee joint diseases. The surface of the femoral posterior condyles is the joint surface at the flexion phase of the knee joint motion. It is well known that, throughout flexion, the normal knee exhibits a medial pivot motion with external rotation of the femur relative to the tibia [1, 6, 7, 17, 21]. It is thought that this asymmetrical knee motion is somewhat related to the shape of the posterior condyles. In recent years, some studies have reported satisfactory clinical results following medial pivot type total knee arthroplasty (TKA) [11, 14]. However, almost all medial pivot type TKA models still have a symmetrical shape of the medial and lateral condyles. Some studies have reported the morphology of normal knee joints [1, 4, 15, 17, 23]; however, most of those studies have investigated the size of the posterior condyles that were approximated to a circle or sphere. The three-dimensional (3D) shape of the posterior femoral condyles, including the inclination angle of the articular surface, is not yet entirely understood. There are also studies that report sex differences in the size of the distal femoral condyle [5, 13], but few previous studies have described the relationship between posterior condyle size and physique.

The purpose of this study was to three-dimensionally analyse the size and shape of the distal posterior femoral condyles in normal knee joints. The hypotheses of the study were that the posterior condyles had some inclination and had morphological differences between the medial and lateral condyles. The inclinations of the femoral posterior condyles in healthy cases are considered to be reference data for elucidating the pathological condition of a disease such as osteochondritis dissecans or osteoarthritis of the knee. Furthermore, these data may be reflected in TKA implant design, especially medial pivot type implant.

Materials and methods

First, a total of 69 Japanese subjects who had no knee symptoms and no history of trauma or surgery of the lower extremities were enrolled. They were included staff in our hospital, patients who visited in our hospital for other reasons that were unrelated to the lower extremity. They were assessed their lower extremity conditions through physical and radiographic examinations and excluded seven subjects who were assessed as radiographic knee osteoarthritis (OA). Finally, a total of 62 healthy Japanese volunteers (37 males and 25 females) participated in this study, providing a sample of 124 normal knee joints. Their mean age was 49.9 ± 16.7 years (range 24–69 years); mean height was 164.8 ± 8.9 cm (range 143.0–186.0 cm; male mean 170.5 ± 5.6 cm and female mean 155.8 ± 5.6 cm); and body mass indices were 21.6 ± 2.2 kg/m^2. This study was performed according to a protocol approved by the Investigational Review Boards of our institution (Niigata University, 2017-0006). All subjects were provided informed consent to participate in this study.

Computed tomography (CT) (SOMATOM® Sensation 16; Siemens, Munich, Germany) scans of bilateral femurs and tibias were obtained for all subjects, with a 1-mm interval. For radiation exposure in CT, the mean of CT dose index (CTDI) volume and dose length product (DLP) were 8.33 ± 1.19 mGy and 896.7 ± 129.9 mGy × cm, respectively. Effective dose (ED) was calculated from the DLP using the appropriate body region-specific conversion factor for extremity CT (hip = 7.31, knee = 0.44, ankle = 0.23, µSv/mGy × cm) [2, 8]. The mean ED was about 2.4 mSv for this study.

3D digital models of the femur were constructed from CT data using 3D visualisation and modelling software (ZedView®; LEXI, Tokyo, Japan). The anatomical coordinate systems were established by referencing several bony landmarks according to the definitions reported by Sato et al. [19]. For the femoral coordinate system, the femoral *x*-axis (positive right) was determined by the geometric center axis that is the line that connected the centers of the spheres representing the medial and lateral posterior femoral condyles. The midpoint between the centers of these posterior condylar spheres was defined as the origin of the coordinate system. The femoral *y*-axis (positive anteriorly) was a perpendicular line from the origin of the femoral coordinate system to the plane consisting of the geometric center axis and the center of the femoral head. The cross product of the *y*- and *x*-axes was the femoral *z*-axis (positive superiorly) (Fig. 1). When constructing the coordinate system, the medial and lateral condyles of the femur were approximated to a sphere [1, 19] (Fig. 2).

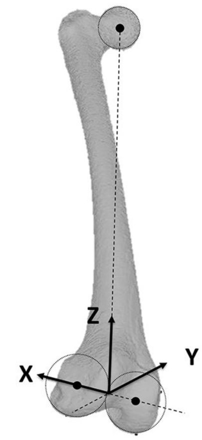

Fig. 1 The femoral coordinate system was established referencing several bony landmarks

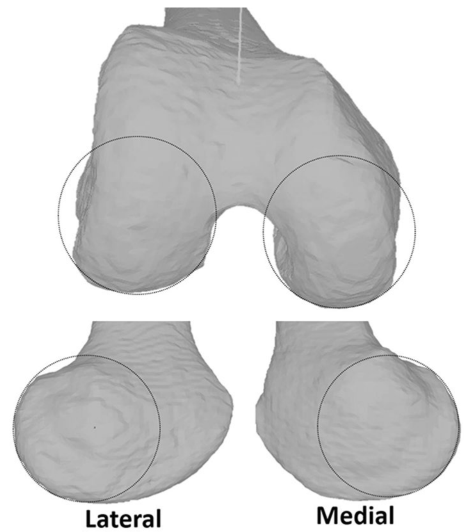

Fig. 2 When the femoral coordinate system was established, the both posterior condyle were approximated to spheres

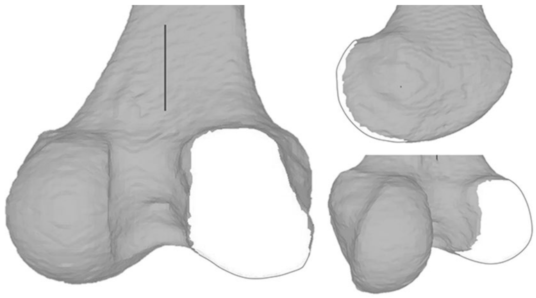

Fig. 3 The articular surface of posterior condyles was selected and extracted: from upper border of posterior condyle to the most distal level of femur in the coordinate system

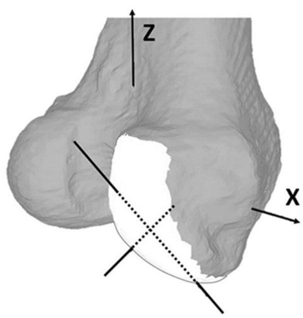

Fig. 4 The axis of the ellipsoid approximate to the posterior condyle was calculated

The 3D models of the femur, including the coordinate systems were input to the original software, and only the articular surface of the posterior condyles was selected and extracted. This area of the articular surface of the posterior condyles was, in the coordinate system, defined as from the upper border of the posterior condyles to the most distal level of the femur (Fig. 3). This extracted articular surface was approximated to an ellipsoid (Fig. 4). The long axis of this approximated ellipsoid was projected onto the coronal plane of the femoral coordinate system and defined as the inclination of the articular surface (Fig. 5). An inclination tilting towards the proximal intercondylar fossa was defined as a positive value in both the medial and lateral condyles (Fig. 6).

The following parameters were evaluated: (1) the radii of the posterior condyles approximated to spheres, and (2) the inclination angle of the posterior condyles in the coronal plane of the femoral coordinate system.

To evaluate inter and intra-obsever reliability, two observer measured all subjects twice with an interval of 6 weeks. The intra- and inter-observer reliability of the inclination angle measurements of the medial and lateral condyles were examined by intra-class correlation coefficients (ICC). ICC (1, 2) of observer 1 were 0.982 and 0.987, ICC (1, 2) of observer 2 were 0.981 and 0.991, and

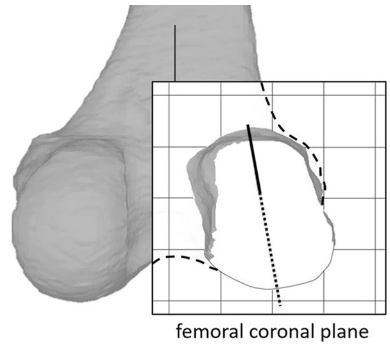

Fig. 5 The long axis of approximated ellipsoid was projected onto the coronal plane of the femoral coordinate system

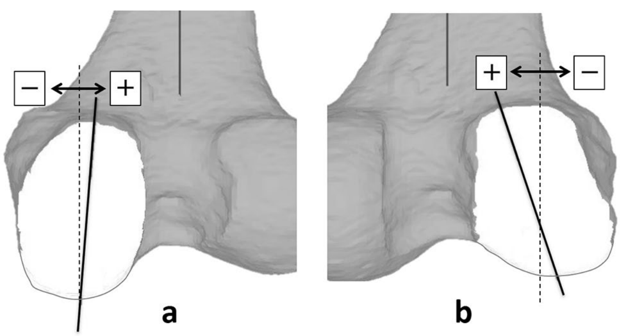

Fig. 6 The inclination tilting towards the proximal intercondylar fossa was defined as the positive value in both medial (**a**) and lateral condyle (**b**)

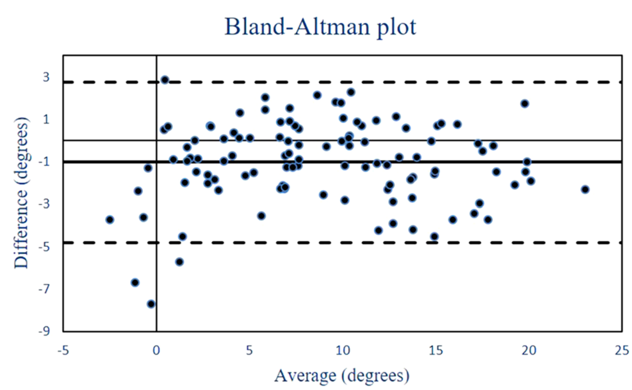

Fig. 7 Bland–Altman plot of the intra-test reliability of the inclination angle measurements of the lateral condyle. Solid line denotes bias (mean of difference) and dashed lines denote 95% limits of agreement (2 SD of difference). *SD* standard deviation

ICC (3, 1) between observer 1 and 2 were 0.975 and 0.967, respectively. Bland–Altman plot in the intra-test reliability showed no fixed bias in the 95% limits of agreement and no proportional bias (Fig. 7).

The precise measurement was calculated using the difference of inclination angle measurements in the femoral coordinate system:

$$\frac{(1^{st} - 2^{nd})_{case1} + (\ )_{case2} + (\ )_{case3} + (\ )_{case4} + \cdots (\ )_{case144}}{144}$$

Mean differences and 95% confidence intervals (CI) at different inclination angles in the femoral coordinate systems were calculated. In the precision, the mean and maximum differences were 1.03° and 7.71°, respectively. The 95% CI on the differences was 0.67–1.39°.

Statistical analyses

The distribution and variance were examined using a Shapiro–Wilk and Levene test, respectively. Differences in the data were statistically analysed using the Student's *t* test when the data had a normal distribution and equal variances and using the Welch's *t* test when the data had a normal distribution and unequal variances. The correlations were evaluated using the Pearson product–moment correlation when the data had a normal distribution and using the Spearman's rank–order correlation when the data did not have a normal distribution, respectively. The statistical significance level was set at $p < 0.05$. Statistical analyses were performed using statistical software (IBM SPSS statistics version 21; IBM Corp., Armonk, NY, USA). The post-hoc power analysis comparing male and female were as follows: the radii of the medial condyle: power = 1.00, $p < 0.001$; the radii of the lateral condyle: power = 1.00, $p < 0.001$; the inclination angle of the medial condyle: power = 0.57, $p = 0.03$; the inclination angle of the lateral condyle: power = 0.23, $p = 0.22$. Data are presented as mean and standard deviations unless indicated otherwise.

Results

Radii of the posterior condyles approximated to spheres

The radii of the medial and lateral condyles approximated to spheres were 17.0 ± 1.6 mm and 17.1 ± 1.8 mm, respectively (Table 1). The ratio of the radii of the medial to lateral condyles was 1.0 ± 0.06 (range 0.86–1.19). There were significant differences between male and female subjects with regards to the sizes of the medial and lateral condyles. The correlation coefficients (CC) between the radii of medial and lateral condyles and body height were 0.66 ($p < 0.0001$) and 0.78 ($p < 0.0001$), respectively (Fig. 8).

Inclination angle of the posterior condyles approximated to ellipsoids

The inclination angles of the medial and lateral condyles in the coronal plane were – 0.6° ± 4.6° and 9.7° ± 5.7°, respectively (Table 1). The inclination of the medial condyle was almost vertical and that of lateral condyle was medially tilted. There was a significant difference between male and female subjects in the inclination angle of the medial condyle only (medial condyle, $p = 0.033$; lateral condyle, $p = 0.22$). CC between body height and the inclination angles for the medial and lateral condyles were – 0.37 ($p < 0.0001$) and 0.10 ($p = 0.27$), respectively. CC between the ratio of the radii of medial to lateral condyles and inclination angles for the medial and lateral condyles were 0.10 ($p = 0.25$) and 0.10 ($p = 0.25$), respectively. There were no significant correlations, suggesting that size variations of the posterior condyles did not affect the inclination angles.

Discussion

The most important finding of the present study was that the inclination of the medial condyle was almost vertical and that of the lateral condyle was medially tilted. This asymmetrical inclination between medial and lateral condyles

Table 1 Radii and inclination angles of medial and lateral condyle

	All subjects	Male	Female	Male vs female *p* value
Radii of medial posterior condyle	17.0 ± 1.6 mm (range 13.7–21.8 mm)	17.8 ± 1.4 mm	16.1 ± 1.2 mm	< 0.0001*
Radii of lateral posterior condyle	17.1 ± 1.8 mm (range 14.2–20.7 mm)	18.1 ± 1.4 mm	15.6 ± 0.9 mm	< 0.0001*
Inclination angles of medial posterior condyle	– 0.6° ± 4.6° (range – 10.7°–9.7°)	– 1.4° ± 4.6°	0.5° ± 4.6°	0.033*
Inclination angles of lateral posterior condyle	9.7° ± 5.7° (range – 0.6°–24.2°)	10.2° ± 5.4°	8.9° ± 6.2°	0.22

*$p < 0.05$

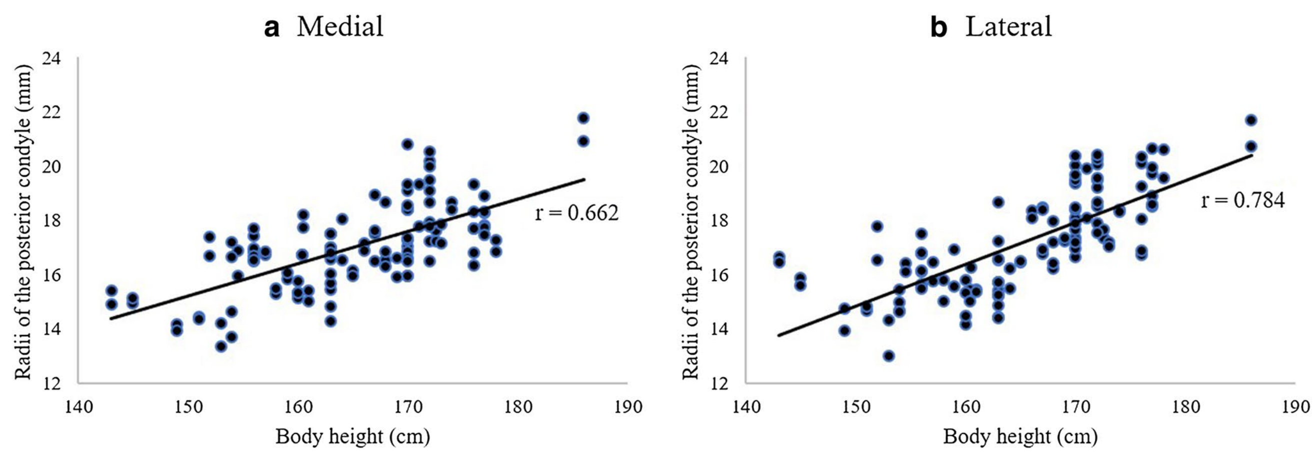

Fig. 8 The correlation coefficients between the radii of medial (**a**) and lateral (**b**) condyles and body height

Table 2 Previous reported sizes of the posterior condyles

Authors	Methods	Medial	Lateral
Elias et al. [4]	X-ray	21 mm	21 mm
Asano et al. [1]	CT	21.4 mm	20.8 mm
Yue et al. [23]	CT	17.3 mm	18.1 mm
Pinskerova et al. [17]	MRI	22 mm	21 mm
Monk et al. [15]	MRI	21 mm	21 mm

supported our hypothesis. The asymmetrical shape of the posterior condyles was thought to be related to the asymmetrical motion of the knee, which is known as medial pivot motion.

The sizes of the posterior condyles of the normal knee have been evaluated in many studies [1, 4, 15, 17, 23] (Table 2). However, these studies primarily reported two-dimensional measurements in the sagittal plane. We evaluated the sizes of the posterior condyles in 3D using CT and demonstrated that they were small compared with most previous studies, although the radii obtained were similar to those reported by Yue et al. [23]. Regarding the symmetry of the medial and lateral condyles, our results demonstrated that both had similar radii and were consistent with those of previous studies.

Some studies reported sex differences in the size of the distal femoral condyles. Li et al. [13] reported that the posterior condyles in male subjects were, on average, 12% to 13% larger than those of female subjects. Fan et al. [5] reported larger medial–lateral and anterior–posterior dimensions in the distal femur in male subjects than those dimensions in the distal femur of female subjects. We also found significant differences in the sizes of posterior condyles between male and female subjects; however, we believe this was explained by differences in physique rather than sex. Few previous studies have described the relationships between the size of the posterior condyles and body height; in our study, we found positive correlations between these parameters, which may have contributed to the differences between sex. It may be that the sizes of the posterior condyles in our results were smaller than previous studies because of the smaller physique of our subjects. In our study, the subjects were all Asian (Japanese) and small in height; by comparison, the subjects in the study of Yue et al. [23] were also all Asian, and this might account for the similar findings reported above.

There have been many morphological studies of the knee joint, for example, those regarding the sulcus [10, 18] and tibial slope angles [9, 22]. To date, however, few studies have focused on the inclination angle of the femoral posterior condyles [20]. Our study found that the 3D inclination angles of the medial and lateral condyles projected onto the coronal plane were − 0.6° and 9.7°. Similar results using 3D anatomical analysis have been previously reported [20]. Siu et al. analysed the shape and geometry of asymptomatic cadaver knees, resected 10 cm above and below the joint line, using a 3D computerised reconstruction from CT scans and clipping and smoothing techniques in interactive computer graphics. They reported that the inclination angles of the medial and lateral condyles, converted to our definition, were 3° and 6°, respectively, when viewed in the coronal plane. These results are consistent with ours in terms of the more inclined versus medial tilt of the lateral condyle. In addition, the sum of the inclination angles of the medial and lateral condyles was 9°, which is similar to our results. However, Siu et al. [20] analysed resected cadaver knees rather than whole lower extremities; therefore, the accuracy of and reproducibility of their coordinate system were probably poorer. The inclination angles of the posterior condyles depend on the femoral coordinate system on which measurements are based. If they had used the same coordinate system with us, then their results might be very similar to ours.

The inclination of the medial condyle was almost vertical and that of the lateral condyle was medially tilted. This asymmetrical shape of the posterior condyles was thought to be related to the asymmetrical motion of the knee, which is known as medial pivot motion. In normal knee motion from full extension to 120° flexion, the medial condyle remains nearly stable, while the lateral posterior condyle backward rotates around the centre of the medial side [1, 6, 7, 17, 21]. The vertical and medial inclination angles of the medial and lateral condyles, respectively, are consistent with the external rotation of the femur during knee flexion. These findings may be useful for the design of TKA prostheses. Many modern TKA prostheses are designed with symmetric posterior condyles. However, the anatomical geometry of femoral posterior condyles is asymmetric, as shown in the present study. These design characteristics, which differ from the anatomical shape and geometry of the normal knee, might adversely influence knee kinematics, leading to altered knee function. Bull et al. [3] and Most et al. [16] have confirmed that the changes of internal–external rotation after TKA were related to the symmetrical design of posterior condyles.

In recent years, some studies have reported satisfactory mid- and long-term clinical results following medial pivot type TKA, which was designed to reproduce normal tibiofemoral joint kinematics [11, 14]. These systems have an asymmetrical tibial insert that reproduces the medial pivot motion, while retaining a symmetrical femoral component. By improving the shape of the femoral component so that it is asymmetrical and tilts the lateral femoral component medially, more physiological knee motion may be achieved. Accordingly, improved postoperative range of motion, and clinical outcomes may be expected.

There are limitations that should be noted in the current study. First, our study population was relatively small and thus susceptible to sampling bias. If a larger sample size had been studied, additional significant differences might have been found. Second, this study evaluated the articular surface of posterior condyles using CT data without data on cartilage thickness. Analyses using MRI, which include cartilage thickness, are needed to evaluated the articular surface. However, to construct an accurate coordinate system, CT including the whole length of the femur is advantageous compared with MRI and it is thought to be acceptable for evaluations of the inclination of joint surface. Third, there was the problem of radiation exposure. However, CT was needed to construct accurate coordinate system and the radiation dose was less than half of the limit that health care workers can expose in a year. Finally, only Japanese subjects were investigated in this study. Differences in morphological features of the distal femur between and within various ethnicities have been reported [12]. Therefore, subjects from different ethnicities might have different sizes or shapes of distal femoral condyles.

Conclusions

Our study reported inclination angles of the medial and lateral femoral posterior condyles of − 0.6° and 9.7°, respectively, in the coronal plane. The inclination angle of the medial condyle was almost vertical and that of lateral condyle tilted medially. This asymmetrical inclination between medial and lateral condyles may be related to the medial pivot motion. The result of this study provides valuable morphological information, which may be useful in the design of prosthetic implants for TKA.

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Author contributions Conception and design: Dr. OT. Collection of data and analysis and interpretation of the data: Drs. SH, OT, TM, TS, RK. Technical support for the system of extremity alignment assessment system: Dr. KK. Drafting of the article: Drs. SH, OT. Final approval of the article: Drs. NE, TS, TM, KK, RK, OT. All authors read and approved the final manuscript.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This study was performed according to a protocol approved by the Investigational Review Boards of our institution (Niigata University, 2017-0006). All subjects were provided informed consent to participate in this study.

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