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ORIGINAL ARTICLE

Difference in coronal curvature of the medial and lateral femoral condyle morphology by gender in implant design for total knee arthroplasty

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Abstract

Purpose The purpose of this study was to investigate the morphometric data obtained from the three-dimensional magnetic resonance images of ethnic Korean knee osteoarthritis, and to evaluate the morphological differences between the coronal curvature of the female and male femoral condyles.

Methods The differences in coronal curvature of the femoral condyle morphology of 1990 patients (1689 females and 301 males) were evaluated in three dimensions. A close-fit diameter was, respectively, generated on the medial and lateral femoral condyle articular surfaces, and these diameters reflect the coronal diameter of the femoral condyle curvature. These measurements were compared with those of the femoral design of five different commonly used total knee arthroplasty (TKA) implant designs.

Results The average diameter of the curvature of the medial condyles was significantly larger than that of the lateral condyles ($P<0.05$). This trend was found in the male and female groups. In addition, the average diameter of the curvature of the femoral condyles was found to significantly differ between males and females ($P<0.05$). For four TKA implant designs, the average diameter of the coronal curvature of femoral condyle was smaller than that obtained via our measurements, whereas one TKA implant design yielded a smaller average diameter. Furthermore, the medial and lateral coronal curvatures of the femoral condyle were symmetric in all TKA implant designs.

Conclusion The study provided a reliable and consistent evaluation of the coronal curvature of femoral condyles in the Korean population. These results showed that a gender-specific or asymmetric femoral component design is required to regenerate the coronal curvature of the femoral condyles for ethnically Korean males and females.

Keywords Korean patients · Morphometry · Femur condyles · Coronal radius

Introduction

It is well understood that total knee arthroplasty (TKA) should optimally restore the original knee geometry so as to provide better post-operative outcomes [5, 10, 14]. A better understanding of knee morphology can lead to the development of prostheses that adequately reflect the diversity of global anatomy. During the past few decades, many studies have found that the geometry of knee joints can differ between genders, and among ethnic groups. The shape and size of the femur and tibial plateaus may contribute to the differing knee biomechanics between genders, ethnic groups, and age groups. However, different results have been reported about gender or ethnicities [7–9]. There are significant variations in the physiological requirements of knee joints between species, and the kinematics are significantly

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influenced by the complex three-dimensional (3D) femoral geometry [19]. The specific roll-back-mechanism of knee joints is a combined interaction of the asymmetric medial and lateral femoral condyles [19]. The anatomy of the curvature of femoral condyles has been studied to develop 3D geometric models for computational simulations on the function of the knee and for the implant design [16, 18]. In addition, analysis of joint curvature is particularly useful in epidemiological studies for osteoarthritis [11].

Previous authors have used a range of imaging modalities, including radiography and computer tomography which does not show the cartilage, and measurements of cadavers in which shrinkage may have occurred [16]. The most accurate knee alignment data, including that for the cartilage, is best obtained using magnetic resonance imaging (MRI), which allows many simultaneous views to be correlated without interference from other anatomical parts [16]. A few studies evaluated the sagittal and coronal curvatures of the femoral condyles by projecting images on to the parasagittal planes, or the parasagittal sections of the knee joint [16, 19, 22, 25]. Moreover, most studies focused on sagittal curvature of femoral condyles. It is a fact that sagittal curvature of femoral condyles plays an important role in knee joint kinematics, and coronal curvature of femoral condyles in knee joint stability. As mentioned previously, there are many studies investigating the difference between gender or ethnic groups for femoral condyle anatomy. However, no data have been reported on the coronal curvature of the femoral condyles among Asia–Pacific population. In addition, the femoral condyles are a complex 3D structure, and measurements based on the above-mentioned methods are dependent on the measuring coordinate system and direction of the slicing plane; this dependence can lead to significant variability in the results [22]. Therefore, it seems impossible to develop a reliable method to measure the coronal radius of the femoral condyles by utilizing single circular arcs; this is because slicing a cylinder at different oblique angles yields different elliptic arcs [20, 22, 26].

Therefore, the purpose of this study was to investigate the morphometric data from 3D magnetic resonance images of Korean knee osteoarthritis. To evaluate the morphological differences in the coronal curvature of the femoral condyles by gender using close-fit sphere. We hypothesized that the coronal curvature of the femoral condyles differs between females and males.

Materials and methods

MRI scans were performed for 2053 consecutive patients undergoing TKA in our institution between January 2015 and September 2018. Patients with a history of primary osteoarthritis and TKA were included only. Patients with any history of previous surgery or trauma to the affected knee were excluded. Finally, 1689 female and 301 male patients were included in this study. The internal review board of our hospital (i.e., Yonsei Sarang Hospital Institutional Review Board No.: 18-DR-03, Protocol No.: 3D-MRI ver.1.0) approved the study. Patient age, gender, mechanical axis and body mass index (BMI) were recorded (Table 1). There were no significant differences within the following demographics: age, mechanical axis, and BMI.

The MRI images were obtained using a 1.5-T MRI scanner (Achieva 1.5 T; Philips Healthcare, Best, Netherlands). For the non-fat saturation condition, the MRI consisted of an axial proton-density sequence. A high-resolution setting was used for the spectral pre-saturation inversion recovery sequence [echo time, 25.0 ms; repetition time, 3590.8 ms; acquisition matrix, 512 × 512 pixels; number of excitations (NEX), 2.0; field of view, 140 × 140 mm]. This method entailed the use of patient-specific instruments that allowed for effectively developed reconstructed 3D models. The MRI scans were imported into modeling software (Mimics version 17.0; Materialise, Leuven, Belgium), and segmented to construct 3D femoral and cartilage models [12]. The 3D reconstruction reproducibility analysis was similar to that described in our previous study [13]. To define the coronal plane, the mechanical and transepicondylar axes of the femur were defined. The mechanical axis of the femur was first obtained by connecting the centers of the femoral head and intercondylar notch (Fig. 1a). The transepicondylar axis was defined using the lateral and medial epicondyles (Fig. 1b). The mechanical axis was implemented as the z-axis. The transepicondylar axis was projected onto the plane perpendicular to the z-axis and the projected line was implemented as the x-axis. The coronal plane was set as the xz-plane. On

Table 1 Comparison of the age, BMI and varus–valgus deformity between Korean males and females

Parameter	Whole patients ($n=1990$) Mean ± SD (range)	Female ($n=1689$) Mean ± SD (range)	Male ($n=301$) Mean ± SD (range)	P value
Age	68 ± 6.8 (46.0, 94.0)	68.9 ± 6.6 (50.0, 88.0)	69.1 ± 7.8 (46.0, 94.0)	$0.66^{n.s}$
BMI (kg/m^2)	30.3 ± 7.5 (27.1, 36.8)	30.3 ± 2.7 (29.1, 36.8)	30.0 ± 2.9 (27.1, 35.2)	$0.09^{n.s}$
Varus–valgus angle (°)	7.9 ± 4.8 (− 17.5, 21.9)	8.0 ± 4.9 (− 17.5, 21.9)	7.4 ± 5.2 (− 9.8, 20.8)	$0.07^{n.s}$

$^{n.s}$ non significant

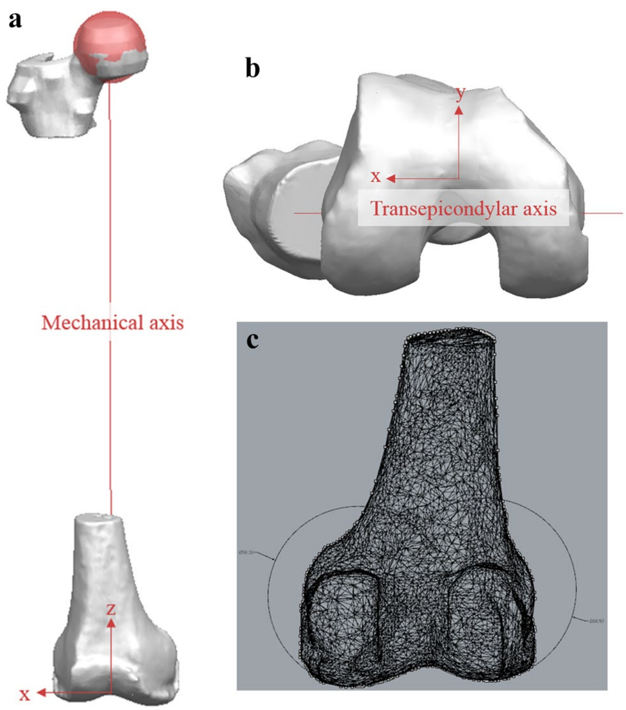

Fig. 1 Schematic representation for **a** femur mechanical axis, **b** transepicondylar axis and **c** curve fitting on coronal plane

the coronal plane, the two best-fit circles were drawn for the medial and lateral condyles. The points on the boundary of the coronal femur were extracted, and an automatic circle-fitting function was applied (Fig. 1c) [19].

To evaluate variations among the conventional TKA femoral component designs, we compared the medial and lateral the diameter of the femoral condyles with similar measurements that were obtained from five conventionally used TKA designs: Triathlon (Stryker Howmedica Osteonics, Allendale, NJ, USA), Vanguard (Biomet, Warsaw, IN, USA), Legion (Smith & Nephew Inc., Memphis, TN, USA), and Nexgen and Persona (Zimmer, Warsaw, IN, USA). The specimens were individually scanned using a 3D optical scanning machine (ATOS II, GOMmbH, Braunschweig, Germany). The system had a measurement resolution of 0.05 mm, and an overall accuracy of ± 0.01 mm. These conditions enabled full manipulation and comprehensive measurements through the use of UnigraphicsNX software (version 7.0; Siemens PLM Software, Torrance, California, USA). All measurements were obtained by an experienced observer. To test the intra-observer variability and inter-observer variability, 100 of the 3D MRI scans from 50 female and 50 male patients were re-measured by the same observer at least 1 week after the initial measurements, in addition to a second observer.

Statistical analysis

The statistics were analyzed using SPSS (version 18.0; SPSS, Chicago, IL, USA), and independent samples *T* test was used to examine the significance of differences between genders in 1689 female and 301 male patients. In addition, paired *t* tests were used to evaluate the intra-gender differences between the medial and lateral diameters. Correlation between coronal diameter of the femoral condyles and femoral anterior–posterior (AP) length was analyzed with a linear-by-linear association test. The differences were regarded as significant when $P < 0.05$. G*Power 3.1 was used to perform a post hoc power analysis for inter-group medial diameter comparison. The alpha value was 0.05, and the statistical power was calculated to be 100%.

Results

The coronal curvature diameters of the medial and lateral femoral condyles were 63.1 ± 15.9 mm and 50.5 ± 10.5 mm, respectively (Table 2). For females, the average coronal curvature diameters of the medial and lateral femoral condyles were 62.5 ± 15.6 mm and 49.4 ± 10.0 mm, respectively (Table 2). For males, the average coronal curvature diameters of the medial and lateral femoral condyles were 67 ± 16.8 mm and 56.8 ± 10.8 mm, respectively (Table 2). The diameter of the coronal curvature of the medial condyle was significantly greater than that of the lateral condyle in both females and males ($P < 0.05$). In addition, the average diameters of the coronal curvatures of femoral condyles significantly differed between females and males ($P < 0.05$). The coronal curvatures of the femoral condyles were evaluated with respect to the femoral AP difference (Table 3). As femoral AP size increased, there was a significant effect on the diameter of the coronal curvature of the femoral condyles ($r = 0.250$; $P < 0.05$). There was a significant effect on the diameter of the coronal curvature as AP Size of femoral

Table 2 Comparison of anthropometric measurements between Korean males and females

Parameter	Whole patients ($n = 1990$) Mean ± SD (range)	Female ($n = 1689$) Mean ± SD (range)	Male ($n = 301$) Mean ± SD (range)	*P* value
Medial diameter	63.1 ± 15.9 (21.0, 146.2)	62.5 ± 15.6 (21.0, 146.2)	67 ± 16.8 (27.4, 133.7)	< 0.05
Lateral diameter	50.5 ± 10.5 (20.1, 108.2)	49.4 ± 10.0 (20.1, 108.2)	56.8 ± 10.8 (27.4, 100.3)	< 0.05
	< 0.05	< 0.05	< 0.05	

Table 3 Comparison of coronal curvature with respect to anterior–posterior difference

	Anterior–posterior difference					
	50.9	55.2	59.2	62.7	65.7	69.8
Medial diameter	62.6	59.1	61.9	63.4	67.3	70.4
Lateral diameter	57.0	46.3	49.0	51.2	54.4	59.0
Average diameter	59.8	52.7	55.5	57.3	60.8	64.7
Number of patients	3	155	1016	488	198	130

component increased in both female ($r = 0.148$; $P < 0.05$) and male ($r = 0.240$; $P < 0.05$). Comparison of the diameters of the femoral condyles coronal curvature measurements of the five different implants revealed that three of these implant designs yielded smaller diameters, whereas two of these implant designs yielded larger diameters than our measurements (Fig. 2a–c). The diameter of the coronal curvature of femoral condyles in one implant was greater and smaller than our measurement in small and large AP sizes, respectively (Fig. 2).

Discussion

The most important finding of this study was that gender difference was found in the coronal curvature of femoral condyles. The medial coronal curvature was greater than the lateral coronal curvature. In addition, there was a significant asymmetry in the medial and lateral coronal femoral condyles.

TKA has been widely employed in the clinical orthopedic field. Compatibility of the shape of the knee implant and the geometry of the resected surface is essential to operational success and long-term effectiveness [23]. However, previous reports on studies that evaluated anatomic variations provided minimal information on bone size or the ratio of the AP width to the mediolateral width of the femur [12, 21, 24]. In addition, previous studies that evaluated morphometric differences used cadavers, focused on ethnicity or gender, yielding diverse results [9, 15]. Direct intraoperative measurements and bone wafer measurements do not reveal the true shape, provide rotational references, or maintain the coordinate axes [5, 9]. The critical problem with intraoperative measurement is that the rotational orientation is lost. MRI allowed us to not only examine bone size, but also the 3D geometry. Our study compares the coronal curvature of femoral condyles in osteoarthritic male and female knees. Most related previous studies did not provide a comprehensive description of the femoral condyles in the sagittal plane [19, 22, 25]. The coronal curvature of femoral condyles is an important factor in TKA, as it is necessary to maintain contact stress and stability. Asseln et al. found that there were gender differences in knee morphology [1]. The radii of the medial and lateral femoral condyles were 23.69 ± 5.55 mm and 18.57 ± 3.90 mm, respectively [1]. This trend was similar to that observed in our results. Medial femoral condyle was greater than the lateral femoral condyle in our results as well. However, their reported average diameter is smaller than that measured in this study. These differences might be related to genetic, environmental, and sociocultural conditions and to lifestyle, health, and functional status. The large variation makes it difficult to provide a standard interpretation of their respective values. There have been many arguments on the inter-gender anatomical differences of the femur. Previous studies have analyzed the inter-gender anatomical differences in knee morphology using a comprehensive bone morphology atlas; they found the following three notable anatomical features that are specific to the knees of females: (1) a less prominent anterior condyles, (2) an increased *Q* angle, and (3) a reduced mediolateral:antero-posterior aspect ratio for the condyles [6]. However, some authors doubted the existence of gender-based variations in femoral dimensions. Blaha et al. did not identify inter-gender differences in the size and shape of the knee [2]. With the relatively larger sample size of 1990 normal knees of ethnic Koreans that were used in our study, we presented additional evidence for the support of gender-based differences. Our study showed that Korean males have a larger coronal curvature than Korean females. There is little detailed information in the literature for gender-specific differences in the diameter femoral condyles of the knee. We found that there was significant effect on the coronal diameter of femoral condyles as femoral AP size increased. There was also situation with greater coronal diameter of femoral condyles with large femoral AP size. However, this finding can be disregarded because the sample size was too small. In addition, the same coronal diameter is currently implemented in TKA designs, including the Vanguard, Legion, and Triathlon, regardless of the AP dimensions of the femoral component (Fig. 2a–c). We found that the coronal diameters of the medial femoral condyles and lateral femoral condyles were asymmetrical. However, the coronal diameters of the medial and lateral femoral condyles of all currently implemented TKA implants are symmetrical. Previous studies have confirmed that the loss of normal tibial screw-home motion and changes to internal–external rotation after

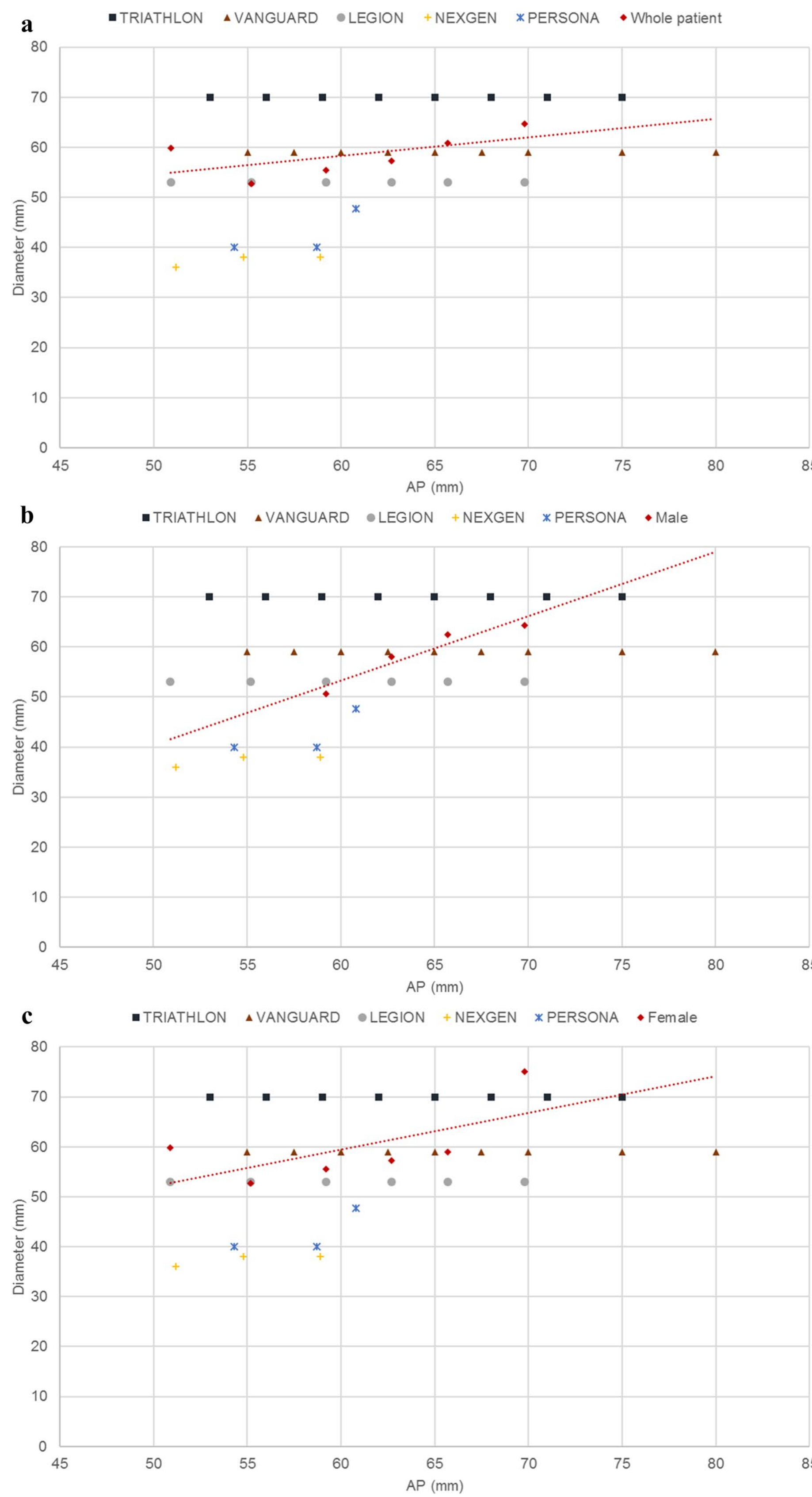

Fig. 2 Comparison of coronal diameters between five conventional TKAs and measurement data of **a** whole patient, **b** male, and **c** female

TKA were related to the symmetrical design of femoral condyles [3, 17]. A long-term follow-up study that compared patients with symmetric and asymmetric condylar designs of femoral components should be performed, particularly with younger patients with TKA implants. Our results can be used to design and fabricate customized knee implants. The gender-based morphological differences in the femoral condyles that have been described in this paper may have the potential to improve the design of TKA implants. However, further evaluation is required to determine whether these design changes will improve clinical outcomes.

There are many limitations to our study. First, MRI was employed to construct the 3D representation of the femur that was used in this study, and this could have led to errors in the computation model. Nevertheless, MRI allowed us to reconstruct soft tissues such as articular cartilage, and the inaccuracy of the 3D reconstruction could be reduced using the related protocol described in our previous study [12]. Second, our population lacked ethnic diversity, and the results may differ for other ethnic populations. Third, the underlying data were obtained from pathological knees. It has been shown that osteoarthritis also affects subchondral bone, and thus, affects the features that were measured. However, this predominantly affects the articulating areas of the tibiofemoral joint, meaning that only a few features might be affected. Fourth, 3D model for femoral component was developed throughout 3D scanner, but there could be minor errors in actual design. Fifth, the coronal diameter of femoral condyles was measured regardless BMI, height, and weight of patients. Finally, the post-operative clinical outcomes were not evaluated in this study because patients with TKA implants were not included. Nevertheless, the findings of this study provided valuable information on the 3D geometry of the femur and can be considered in the design of the femoral component of TKA implants to yield more anatomically suitable knee with natural kinematics [4, 19].

We concluded that the coronal curvature of the femoral condyles in females is significantly different from their male counterparts. The study provided a reliable and consistent evaluation of the coronal curvature of the femoral condyles in the Korean population. Furthermore, these results show that gender-specific or asymmetric femoral component designs are required to mimic the coronal curvature of the femoral condyles for ethnically Korean males and females.

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Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

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