Clinical relevance

Gender analysis of the anterior femoral condyle geometry of the knee

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A B S T R A C T

Background: No study has used 3-D anatomic knee models to investigate the gender differences in anterior femoral condyles. Therefore, this study aims to determine the morphologic differences between genders in anterior femoral condyles of the knees using 3-D anatomic knee models.

Methods: Ninety-six male and sixty-five female 3D anatomic knee models were used to measure lateral and medial anterior condyle heights, anterior trochlear groove heights, and anterior condyle width, which were normalized by the anterior–posterior and medial–lateral dimensions of the knee, respectively. The shape of anterior condyle groove was also analyzed.

Results: The mean lateral anterior condyle height, medial anterior condyle height and anterior condyle width of females were 6.6 ± 1.8 mm, 2.0 ± 2.3 mm, and 44.7 ± 4.2 mm, respectively. These data were significantly smaller (p < 0.05) than those of males (7.7 ± 1.8 mm, 2.9 ± 2.0 mm and 50.0 ± 3.4 mm). However, after normalization by the femur size, the aspect ratios had no gender differences. Both the ranges of lateral and medial condyle of females were significantly smaller than those of males, and the geometry curve of anterior condyle was different between genders.

Conclusion: Although the gender differences in anterior femoral condyle sizes no longer existed after normalization with the femur size, the shape and the peak position of anterior condyle groove still have gender differences. The data may have important implications on the current debate of gender-specific TKAs.

Clinical relevance: This study provides a better understanding of gender differences in anterior femoral condyle geometry.

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1. Introduction

Anatomic variations between the knees of men and women have been reported in many studies [1–3]. Some studies reported that the female knee has a less pronounced anterior femoral condyle height than the male knee [4,5], leading to the development of gender-specific knee implant designs that have a thinner and narrower anterior flange to avoid the patellofemoral joint being overstuffed in female knees [6].

However, others argued whether there is a gender difference in anterior femoral condyles of the knee. Fehring et al. [7] analyzed magnetic resonance images of the knee and found that there is no significant difference between men and women when the anterior condyle heights were normalized by the femoral mediolateral dimensions. Brattstroem [8] performed a radiographic-anatomic study and found that women had lower lateral and medial anterior condyles than men, but that was attributed to the smaller size of the women. A gender-specific anterior flange design for femur component was therefore questioned in recent literature [7,9,10]. Merchant et al. reviewed the evidence presented to support that females have less prominence of the anterior medial and lateral condyles and concluded that these differences do not exist [9]. Greene et al. also concluded that there was little evidence to support that gender-specific changes in TKA components lead to better outcomes and suggested further research to assess the gender-specific designs [10].

A literature review indicated that most recent studies used plane radiographic or MRI images to study the gender differences of anterior femoral condyle morphology [4,7,8]. No study has used 3-D anatomic knee models to investigate the gender differences in anterior femoral condyles. Therefore, the aim of this study is to determine the gender morphologic difference in anterior femoral condyles of the knees using 3-D anatomic knee models. The heights of the lateral anterior femoral condyle, medial anterior femoral condyle, anterior trochlear groove, and the width of anterior condyle were measured in both male and female knee models. These parameters were then normalized by the anterior–posterior and medial–lateral dimensions of the knee to calculate the aspect ratios of the anterior condyle and trochlear groove heights as well as the anterior condyle width. We hypothesize that there is a gender difference in anterior femoral condyle morphology between the male and female knees.
2. Materials and methods

2.1. Subjects

We analyzed 161 Caucasian knees (96 males and 65 females) that were collected from our previous studies with approval of institutional review board. The knees were examined with no anatomical abnormality. The males were 38.3 ± 10.2 years old and the females were 35.5 ± 10.1 years old. The average height and weight were 179.8 ± 6.3 cm and 80.9 ± 16.3 kg for males, and 166.3 ± 4.8 cm and 68.3 ± 9.5 kg for females, respectively.

2.2. Three-dimensional knee models

Among these knees, 34 were scanned using a computer tomographic (CT) scanner (GE Medical System, Milwaukee, WI). The images were acquired along the axial direction between the mid shafts of the femur and tibia and with a slice thickness of 0.625 mm and an in-plane resolution of 0.3 mm × 0.3 mm. The rest 127 knees were MRI scanned using a 3.0 Tesla magnet (Siemens, Erlangen, Germany) with a fat suppressed 3D spoiled gradient-recalled sequence. Parallel sagittal plane images of 1 mm in thickness with no space between were obtained with a field of view of 180 mm × 180 mm and an in-plane resolution of 512 × 512 pixels.

The CT images of the knees were segmented using a region-growing method, and the MRI images of the knees were segmented using a manual segmentation method [11] to construct 3D bony models of the knee. Each segmented bony contours were reviewed by an experienced surgeon and corrected on slice-by-slice basis. A 3D surface model of the distal femur was reconstructed using the contours of the knee. Although two imaging techniques were used to compare the geometric characteristics, a 3D deviation analysis between MRI and CT femoral models of one subject revealed that the average ± standard deviation of the distance in between was −0.39 ± 0.64 mm for the femur. A compatible accuracy of MRI models with respect to CT models was also reported [12].

2.3. Measurement of anterior condyle geometry

To measure the anterior femoral condyle geometry and to simulate TKA anterior condyle cuts, a trans-epicondylar axis (TEA) was defined on each knee model [13]. An orthogonal coordinate system was then established at the lateral end point of the TEA on the surface model (Fig. 1). The X axis was defined as the TEA; the Y axis was defined as a line parallel with the femur mechanical axis which is 6° valgus with the anatomical axis (the line along the femoral shaft) in the coronal plane [14]; and the Z axis was vertical to the X and Y axes, passing through the lateral end point of the TEA (Fig. 1). A customized script using MATLAB (The Mathworks Inc., Natick, MA) was developed to create cutting planes through the distal femur [15]. The cutting planes rotated around the femoral TEA in 1° increments from −45° to 30° (Fig. 2A). On each cutting plane, the middle lowest point was used to define the height of the anterior trochlear groove; the medial and lateral highest points were selected to define the heights of the medial and lateral anterior condyles (Fig. 2B).

The position of each selected point could be determined using its coordinate values (x, y, z). The z-value of each point is vertical to the femoral shaft and defined as the height of the point: the anterior lateral condyle height (H1), anterior medial condyle (H2) and anterior trochlear groove height (H3) (Fig. 2B). An anterior condyle flush cut [16] which was along the anterior femur cortex surface, parallel to the femoral shaft and without anterior femoral notching was performed on each femur (Fig. 1A). The distance between the TEA and the anterior cutting plane was measured as H0 (Fig. 2A). Therefore, the lateral anterior condyle height (LACH) with respect to the anterior cortex was obtained as H1–H0, medial anterior condyle height (MACH) as H2–H0 and anterior trochlear groove height (ATGH) as H3–H0 (Fig. 2B). A positive value indicates that the point is higher than the anterior femur cortex, and a negative value means that the point is lower than the anterior femur cortex.

2.4. Anterior and distal condyle resection

A distal femur cut of 7 mm (considering a 2 mm thickness of cartilage [17]) above the lowest point of the medial femoral condyle was made on each femur (Fig. 1A). The femoral medial–lateral dimension (fML) was measured on the distal femoral cut surface in medial–lateral direction that is parallel to the TEA in the transverse plane. The femoral anterior–posterior dimension (fAP) was defined as the distance between the lowest lateral condyle with the lateral anterior cortex of the distal femur (Fig. 1B). The width of anterior condyle (ACW) was defined as the largest width of the resected anterior condyle which was parallel to the distal cut (Fig. 1A).

![Fig. 1](image-url) The femoral model and bony cuts to simulate a standard TKA procedure. A 2 mm cartilage thickness was considered in the resection. Definitions of lateral anterior condyle height (LACH), medial anterior condyle height (MACH), anterior trochlear groove height (ATGH), anterior condyle width (ACW), femoral anterior–posterior dimension (fAP) and femoral medial–lateral dimension (fML) were shown. (A) The anterior femoral condyle cut viewed in coronal plane; and (B) the anterior femoral condyle cut and distal femur cut viewed in transverse plane.
2.5. Data analysis

In order to determine whether the femur size has an effect on the sizes of the anterior femoral condyles, the anterior condyle geometry was normalized using the dimensions of the knee [7]. We calculated the aspect ratio (R) by dividing the anterior condylar heights using the fAP and noted as LACH-R, MACH-R, ATGH-R, respectively, and dividing the anterior condylar width (ACW) using the fML and noted as ACW-R. Using the LACH-R, MACH-R and ATGH-R values on cutting planes around the TEA (Fig. 2A), we obtained LACH-R, MACH-R and ATGH-R curves which represent the geometric shapes of the anterior femoral condyle (Fig. 3). We then determined the ranges of the anterior lateral and medial condyles and the positions of the highest points of the lateral, medial condyles and anterior trochlear groove from these curves. The geometric curves of the lateral and medial condyles only contain the points with values of LACH-R or MACH-R > 0, because we defined the medial or lateral condyle as the points that are higher than the anterior femur cortex (Fig. 1). Since most of the trochlear groove points were lower than anterior femur cortex, we defined the range of the anterior groove the same as the anterior lateral condyle (Fig. 3). We defined the peak values of LACH, MACH and ATGh of each distal femur as LACH, MACH and ATGh.

2.6. Statistical analysis

An independent student-t test [7] was used to determine if the morphological measurements of the anterior femoral condyle, including MACH (MACH-R), LACH (LACH-R), ATGH (ATGH-R) and ACW (ACW-R), were statistically different between the genders. Based on the mean and standard deviation of the knee width and depth of recruited subjects, a priori power analysis (α = 0.05) indicated that 28 subjects in total will have more than 95% power to detect the differences in the knee. In this study, 96 male and 65 female knee models were recruited for measurement of the anterior femoral condylar geometry. The sample size is sufficient to detect a difference in anatomy.

3. Results

3.1. Anterior condyle geometry curve

The fAP of the males is 59.2 ± 3.4 mm that was significantly larger than that of the females (54.6 ± 3.0 mm). The fML of the males was 75.1 ± 4.5 mm that was also significantly larger than that of the females (65.7 ± 2.8 mm) (Table 1).

The range of the cutting angles through the anterior condyle curve revealed that in general, there was a gender difference in the lateral and medial condyles (Table 1). The ranges of the cutting angles of the lateral condyle were 67.7° ± 4.3° and 64.1° ± 6.3° for the males and females, respectively (p > 0.05). The ranges of the medial condyle were 38.2° ± 14.9° and 32.3° ± 20.1°, respectively for males and females (p > 0.05). The ranges of the anterior trochlear groove were the same with the lateral condyle for both males and females (Table 1). In general, the anterior groove curves were under the anterior femur cortex in all females and most males. The range where the ATGH values of males were positive was only from −15° to −4° (Fig. 3).

The position of the LACH (LACH-R) was −1.3° ± 4.1° and 0.38° ± 4.7° for males and females respectively and has no gender difference (p > 0.05). The positions of the MACH (MACH-R) were 2.7° ± 5.8°, 4.6° ± 6.8° and of ATGH (ATGH-R) were −3.3° ± 5.1°, −4.4° ± 5.1° for males and females, respectively (p > 0.05) (Table 1).

3.2. Anterior condyle parameters

The LACH, MACH and ACW values of females were 6.6 ± 1.8 mm, 2.0 ± 2.3 mm, 44.7 ± 4.2 mm, respectively, and were significantly smaller (p < 0.05) than those of males (7.7 ± 1.8 mm, 2.9 ± 2.0 mm, 50.0 ± 3.4 mm). The ATGH dimension of the females (−0.2 ± 2.2 mm) has no significant difference with that of males (0.4 ± 1.7 mm) (Table 2).

3.3. Aspect ratio

After normalized by the femur size, the aspect ratios of the lateral and medial condyle heights (LACH-R, MACH-R) of females (0.121 ± 0.035, 0.037 ± 0.043) have no significant difference with those of males (0.131 ± 0.033, 0.049 ± 0.034). The aspect ratios of the trochlear groove height (ATGH-R) were −0.002 ± 0.041 and 0.006 ± 0.029 for the females and males, respectively (p > 0.05). The aspect ratios of the condyle width, ACW-R, were 0.665 ± 0.033 and 0.673 ± 0.047 for the females and males, respectively (p > 0.05) (Table 2).

4. Discussion

This paper presented a comprehensive comparison of the 3D geometrical parameters of the anterior femoral condyles of normal male and female knees. The data indicated that the female knees have...
significantly smaller anterior femoral condyle heights and width (LACH, MACH and ACW) than the male knees, but, the normalized values showed no significant gender differences. The trochlear groove height was found close to or slightly below the anterior femoral cortex and no significant gender difference was found in both ATGH and ATGH-R values.

Several studies had reported the gender differences of the anterior femoral condyle using different methods (Table 3). Polievche et al. [4] reported a significant gender difference in anterior condyle heights (13.74 mm laterally and 10.63 mm medially for males, and 12.26 mm laterally and 8.96 mm medially for females). These values were larger than ours because they used the lowest point of the anterior trochlear groove to measure the lateral and medial condyle heights and our data also did not include the cartilage thickness (~2.75 mm)[17]. The data of Zimmer gender knee solutions [6] used the anterior condyle heights of 10.9 mm laterally and 6.4 mm medially for males, and 10.1 mm laterally and 5.1 mm medially for females. The trend of these data was similar to our data too (Table 3). These studies did not report the aspect ratios of the anterior femoral condyle heights. Fehring et al. [7] analyzed transverse plane MR Images of the knee and reported an average anterior condyle height of 7.3 mm laterally and 5.7 mm medially for males, and 6.8 mm laterally and 4.6 mm medially for females. They indicated that after normalizing the data by medial–lateral (MLL) size of the femur, both lateral and medial aspect ratios are not significantly different between the males and females, similar to our observations. The different values of their measurements and our results may be caused by the measurement methods as they measured the anterior condyle heights using MR images in a transverse plane of the knee that was 10 mm above the lowest trochlear groove point while our measurement used 3D models and simulated TKA cuttings. Kwak [13] reported an average ACW of 51.2 mm and 44.3 mm for males and females respectively of a Korean population, which were similar to our results. However, no data has been reported on the ACW of Caucasian population.

The data reported in literature as well as obtained from our study showed that the LACH and MACH are significantly lower in females than in males [4,6–8]. However, the aspect ratios, LACH-R and MACH-R, are similar between genders, indicating similar shape in anterior femoral condyle heights between the males and females [7]. Therefore, to better fit the anterior femoral condyles of female patients, lower anterior femoral condyle heights of TKA components may be necessary, as advocated by the gender knee concepts [5,6]. However, these lower anterior femoral condyle heights for female knees could be achieved using smaller sized components of contemporary TKA design.

Our data indicated that the females have significantly smaller range of lateral anterior and medial anterior condyle heights than males. Therefore, the females may have anterior flange overhang when using contemporary TKA components. Results also showed that the females have shorter ACW than males. However, the ACW-R was similar between the males and females, females may not need a narrower anterior flange as proposed by the gender–knee design [6]. Smaller sized components may well fit the female knees in the anterior condyles if different size components have similar aspect ratios.

Our study revealed an interesting phenomenon in the anterior trochlear groove heights. A higher groove can cause “overstuffing” of the knee anteriorly [12,18–20]. Most recent studies focused on the orientations of the trochlear groove [3,21]. Few data has been reported on the trochlear groove. Our results showed that males and females have similar ATGH and ATGH-R values. The cartilage thickness was assumed as 2 mm [17] during the bony resection. Although the baseline for measurements of LACH, MACH and ATGH would be changed with different cartilage thickness, it doesn’t affect the curves and peak points on the anterior condyle heights. The ATGH was almost on or slightly below the anterior femoral cortex. The ATGH of the females was under the anterior femur cortex in the whole range (Fig. 3), which means that the patients may be overstuffed using contemporary TKA implants since the anterior femoral condyles of the TKAs are all above the anterior femoral cortex of the knee. The ATGH positions of the males were significantly more proximal than the females (Table 1, Fig. 3). Therefore, as the results showed in this study, the shape of the trochlear groove may need to be designed gender-specific and more anatomical in TKA components if the anatomical trochlear groove is to be reproduced.

There are some limitations in this study. We analyzed the bony surface models of the knee, so we did not include the cartilage thickness in the analysis. Both CT and MRI based models were analyzed since these models were obtained from our previous investigations. Although two different imaging techniques were used, the small differences resulted from these techniques have been confirmed [12]. Due to the concern of radiation of CT scan and the limitation of feasible region of MRI, only distal femur models were obtained. The distal femoral cut of 7 mm above the lowest point of the medial femoral condyle was made along the estimated mechanical axis which was 6° valgus with respect to the anatomical axis based on the clinical observations of previous studies [22,23]. The distal femoral cut may be slightly changed if

### Table 1
Average ± standard deviation (minimum–maximum) of knee sizes, the range and peak of the cutting angles through the lateral anterior condyle heights (LACH-), medial anterior condyle height (MACH-) and anterior trochlear groove height ratio (ATGH-R).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>LACH-R position</th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td>LACH-R</td>
<td>67.7° ± 4.3°</td>
<td>−1.3° ± 4.1°</td>
<td>38.2° ± 14.9°</td>
<td>2.7° ± 5.8°</td>
</tr>
<tr>
<td>MACH-R</td>
<td>67.7° ± 4.3°</td>
<td>−9.3° ± 5.1°</td>
<td>59.2 ± 3.4</td>
<td>75.1 ± 4.5</td>
</tr>
<tr>
<td>Femur parameter</td>
<td>Range</td>
<td>ATGH-R position</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FLAP (mm)</td>
<td></td>
<td>55.7° ± 6.5°</td>
<td>64.1 ± 8.3°</td>
<td>65.7 ± 2.8°</td>
</tr>
<tr>
<td>FLL (mm)</td>
<td></td>
<td>64.1 ± 8.3°</td>
<td>54.6 ± 3.0°</td>
<td>65.7 ± 2.8°</td>
</tr>
</tbody>
</table>

* Statistic difference with male.

### Table 2
Morphological data of the anterior femoral condyle (mean ± SD).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>LACH-R</th>
<th>MACH-R</th>
<th>ATGH-R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LACH (mm)</td>
<td>7.7 ± 1.8</td>
<td>0.131 ± 0.033</td>
<td>2.9 ± 2.0</td>
<td>0.049 ± 0.034</td>
</tr>
<tr>
<td>(Range)</td>
<td>(2.9–12.1)</td>
<td>(0.045–0.210)</td>
<td>(−1.4–8.2)</td>
<td>(−0.026–0.147)</td>
</tr>
<tr>
<td>Female</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LACH (mm)</td>
<td>6.5 ± 1.8</td>
<td>0.121 ± 0.035</td>
<td>2.0 ± 2.3°</td>
<td>0.037 ± 0.043</td>
</tr>
<tr>
<td>(Range)</td>
<td>(3.2–12.3)</td>
<td>(0.062–0.239)</td>
<td>(−2.5–7.9)</td>
<td>(−0.043–0.152)</td>
</tr>
</tbody>
</table>

* Means statistic difference with male.
there is an individual difference between the femoral mechanical axis and anatomical axis. However, this may only affect the measures of the fML and the corresponding ratio normalized using fML. The measures based on anterior condyle cuts (i.e. fAP, LACH, MACH and ATGH) would not be changed. In future investigation, we will keep adding more knee models into the analysis and to compare our data with contemporary total knee replacement components. In addition, we are also interested in investigation of race effect on the anterior femoral condyle geometries.

5. Conclusion

Our study found that the gender differences in anterior femoral condyle sizes (including LACH, MACH, ATGH and ACW) disappeared when normalized by the anterior−posterior and medial−lateral dimensions of the knee. However, the ATGH and MACH positions of the males were significantly more proximal than the females. Although the anterior groove height and aspect ratio have no significant gender differences, the shape and the peak positions of anterior condyle groove have gender differences. The data may have important implications on the current debates on gender-specific TKAs.

6. Conflict of interest

The authors of this manuscript have nothing to disclose that would bias our work.

References