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Morphometric analysis of the distal femur in total knee arthroplasty and native knees

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Aims
Analysis of the morphology of the distal femur, and by extension of the femoral components in total knee arthroplasty (TKA), has largely been related to the aspect ratio, which represents the width of the femur. Little is known about variations in trapezoidicity (i.e. whether the femur is more rectangular or more trapezoidal). This study aimed to quantify additional morphological characteristics of the distal femur and identify anatomical features associated with higher risks of over- or under-sizing of components in TKA.

Methods
We analysed the shape of 114 arthritic knees at the time of primary TKA using the pre-operative CT scans. The aspect ratio and trapezoidicity ratio were quantified, and the post-operative prosthetic overhang was calculated. We compared the morphological characteristics with those of 12 TKA models.

Results
There was significant variation in both the aspect ratio and trapezoidicity ratio between individuals. Femoral trapezoidicity was mostly due to an inward curve of the medial cortex. Overhang was correlated with the aspect ratio (with a greater chance of overhang in narrow femurs), trapezoidicity ratio (with a greater chance in trapezoidal femurs), and the tibio-femoral angle (with a greater chance in valgus knees).

Discussion
This study shows that rectangular/trapezoidal variability of the distal femur cannot be ignored. Most of the femoral components which were tested appeared to be excessively rectangular when compared with the bony contours of the distal femur. These findings suggest that the design of TKA should be more concerned with matching the trapezoidal/rectangular shape of the native femur.

Take home message: The distal femur is considerably more trapezoidal than most femoral components, and therefore, care must be taken to avoid anterior prosthetic overhang in TKA.

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In total knee arthroplasty (TKA), the selection of components of an appropriate size is a compromise between achieving adequate cover of the bone to prevent subsidence, while avoiding prosthetic overhang, which compromises the outcome.1-3 The morphology of the distal femur and proximal tibia varies greatly, and components are available in a limited range of sizes and morphologies, primarily for economic reasons. Surgeons are often obliged to compromise when selecting the size of a component and this may interfere with rotation and with the balancing of the soft-tissues. It has been reported that components are over-sized in between 66%1 and 76% of TKAs.3

During the past decade, special attention has been paid to the ‘aspect ratio’ of the distal femur2,4,6 and several manufacturers have introduced narrower versions of their femoral components (often known as ‘gender-specific’ implants given the narrower femoral geometry in women), in order to improve bone-implant fit.5-10 Recently, Mahfouz et al11 described the complex variations in femoral morphology and suggested that it is an over-simplification to categorise femurs as being simply ‘wide’ or ‘narrow’. Instead, they proposed categorising the distal femur in the transverse plane as being ‘rectangular’ or ‘triangular’, and ‘symmetrical’
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Patients and Methods

A consecutive series of 114 knees in 112 patients (64
females and 50 males) were analysed retrospectively for the
purposes of this study. All patients had undergone primary
TKA between January 2008 and June 2009 by a single sur-
geon (MB), and all had a routine pre-operative CT scan.1,5

Patients were excluded if they had had previous surgery or
trauma or if the CT scan was unclear because of artefacts
from the surrounding metal or contrast agent. The mean
age of the patients was 72 years (56 to 88), their mean
weight was 81 kg (45 to 125) and their mean height was 168

or ‘asymmetrical’. They quantified these variations with
three normalised ratios, from which they distinguished six
morphotypes of the distal femur, which may be related to
gender and ethnicity. Their findings raise the question of
whether specific implants are required to accommodate
each of these anatomical variations.

The evidence in this area is limited. There are no studies
which seek to establish whether oversizing of the compo-
nent is more likely in femurs with a specific morphology,
and neither is it clear whether the introduction of gender-
specific implants has led to improvements in outcome.9,10

The shape of femoral components in different designs of
TKA has been largely analysed and quantified using the
aspect ratio. However, it is not known whether components
are basically trapezoidal or rectangular, symmetrical or
asymmetrical.

The aims of this study were to analyse the morphological
characteristics of arthritic femurs using Mahfouz’s11 new
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Our hypotheses were that both narrow and trapezoidal
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age of the patients was 72 years (56 to 88), their mean
weight was 81 kg (45 to 125) and their mean height was 168

cm (144 to 194). The indication for TKA was osteoarthritis
(OA) in 110 knees and spontaneous necrosis of the medial
femoral condyle in four. OA was restricted to the medial
compartment in 81 knees, to the lateral compartment in 15
knees, the patellofemoral joint in six and was bi-compartment-
mental in eight. Pre-operative long-leg radiographs were
available in 107 knees. In these knees, the mean tibiofemo-
ral angle (TFA) was 176° (160° to 194°). A total of 80
knees had varus alignment with a TFA angle < 180° and 27
knees had valgus alignment with a TFA angle > 180°. All
patients received HLS Noetos (Tornier SA, Montbonnot,
France) components.

Tibial and femoral cuts were made orthogonal to the
mechanical axis, with the tibia being cut first. Following the
distal femoral resection, the femur was sized using posterior
referencing to avoid notching of the anterior cortex. The
rotation of the femoral component was aligned along the
surgical transepicondylar axis, which was localised on the
pre-operative CT scan. In valgus knees, rotation of the fem-
oral component was adjusted to allow for hypoplasia of the
posterolateral condyle.12 The mediolateral alignment of the
femoral component was placed centrally on the distal femur.
The rotation of the tibial component was aligned to the cen-
tre of the anterior tibial tuberosity (ATT), and the tibia was
sized to match the cortical contours of the tibial cut.

CT scans were performed with an identical protocol in
all patients using a 64-slice multidetector scanner (Siemens
Sensation, Munich, Germany) in the supine position with
the knees fully extended and the legs fixed in neutral rota-
tion. The hip was scanned from the anterior inferior iliac
spine to the lesser trochanter, and the knee from 50 mm
above the superior margin of the patella to the inferior
aspect of the tibial tuberosity. DICOM images were pro-
cessed using OsiriX (Pixme o SARL, Bernex, Switzer-
land).13,14 This imaging software allows simultaneous
visualisation of CT cross-sections in the frontal, sagittal
and transverse plane, which in turn allows accurate identi-
fication of two transverse sections from which the femoral
dimensions may be identified. The first reference section
was the slice showing the most proximal attachment of the
posterior cruciate ligament,15 from which the maximum
anteroposterior (AP) size of the femur was measured (per-
pendicular to the posterior condylar margin) on the medial
(APM) and lateral (APl) sides. The second was the theore-
tical distal level of resection (10 mm proximal to the most
distal condyle) at which the medial and lateral cortical con-
tours were digitised using the ‘open polygon’ function,
recording point coordinates at intervals of 1 mm to 2 mm,
from the most anterior tips of the trochlea to the most pos-
terior points of the condyles (Fig. 1). Finally, the coordi-
nates of digitised contours were exported as a comma
delimited file to a spreadsheet, and the principal dimensions
of the distal femur were calculated using mathematical
functions as has been described previously. All points were digitised on the same native CT slice, which was assumed to be orthogonal to the mechanical axis of the femur, within ± 10° of error, hence there was taken to be negligible errors owing to malalignment of the femur within the scanner (maximum error = 1 – cos 10° = 1.5%).

**Morphological characteristics.** The values of the AP_M and AP_L were used to calculate an ‘average AP’ dimension. The mediolateral (ML) dimension was measured on the theoretical distal resection slice at three levels: the posterior region (ML_P), 10 mm anterior to the posterior condylar margin, the central region (ML_C) at 50% of the ‘average AP’ dimension, and the anterior region (ML_A), at 75% of the ‘average AP’ dimension.

The three femoral ratios defined by Mahfouz et al were deduced (Fig. 2). The aspect ratio (ML/AP) ratio quantifies how wide or narrow the distal femur is, and the asymmetry ratio (AP_L/AP_M) quantifies how symmetrical or asymmetrical the condyles are. For each ratio, we categorised the shape relative to the median value, thus femurs whose aspect ratio was below the median were considered “narrow” and femurs with trapezoidicity ratio above the median were considered “trapezoidal”. We also quantified the medial and lateral ‘narrowing angles’ in the anterior and central zones (α and β) (Fig. 3).

We compared ML_A and ML_C as measured on the preoperative CT scan with the corresponding dimensions of the implanted component, provided by the manufacturer, as previously described. The ‘size discrepancy’ was calculated in mm and was positive when the component was wider than the resected bone, and negative when it was narrower.

We formed a sample of 12 explanted femoral components and identified each specimen by its laser marking to determine its manufacturer, model, serial number, size and side. The specimens were scanned using a three-dimensional (3D) optical scanning machine (ATOS II, GOM mbH, Braunschweig, Germany) and its photogrammetric analysis software (TRITOP, GOM mbH, Braunschweig, Germany). The system has a resolution of measurement of 0.05 mm and overall accuracy of ± 0.01 mm. The 3D reconstructions of the specimens were manipulated using ProEngineer software (ProEngineer, Needham, Massachusetts) to calculate the equivalent AP and ML dimensions as those recorded from the CT scans of the patients. The study had ethical approval and all patients gave informed consent.

**Statistical analysis.** The Mann–Whitney U test was used to verify significance in differences (dimensions, ratios and angles) between males and females and between knees with or without prosthetic overhang. Ascendant linear regression was used to evaluate the impact of different factors on oversizing. These factors were femoral morphology (aspect ratio, trapezoidicity ratio, asymmetry ratio), alignment (varus or valgus) and gender (male or female). Since there was a degree of correlation between some of the factors, the presence of multicollinearity was estimated using the variance inflation factor (VIF); in all cases, the VIF was < five.
indicating that the effect of the multicollinearity was negligible. No control for multiple testing was applied. The statistical package ‘R’ was used for all analyses. The level of statistical significance was set at 0.05.

**Results**

All AP and ML dimensions were significantly greater in males than in females (p < 0.001) (Table I). The mean aspect ratio was significantly greater in males (1.19 standard deviation (SD) 0.08; 0.98 to 1.31) than in females (1.14 SD 0.06; 1.02 to 1.28) (p < 0.001), indicating that females had narrower femurs. Gender had no significant influence on the trapezoidicity ratio or the asymmetry ratio (Table II).

Linear regression revealed no correlation between geometrical ratios and age, body mass index or TFA. The aspect ratio and trapezoidicity ratio had considerable variation between patients. Taking median values as limits to characterise knees as wide/narrow or rectangular/trapezoidal: 37 knees (32.5%) were narrow-trapezoidal, 20 (17.5%) were narrow-rectangular, 20 (17.5%) were wide-trapezoidal, and 37 (32.5%) were wide-rectangular (Fig. 4). Overall, narrow femurs were more frequently trapezoidal, whereas wide femurs were more frequently rectangular (Spearman coefficient correlation between aspect ratio and trapezoidicity ratio = -0.39, p < 0.001).

The scatter plots of digitised cortical contours (Fig. 5) illustrate the trapezoidicity and how the cortex narrows anteriorly, by curving inwards on the medial side, and by linear inclination on the lateral side. The medial narrowing angles (aM, 17.4º SD 2.9 and bM, 9.8º SD 5.1) were almost double the lateral narrowing angles (aL, 9.6º SD 4.8 and bL, 5.6º SD 7.0). The lateral narrowing angles were also significantly greater for males (aL, 12.4º SD 3.7 and bL, 9.8º SD 5.0) than for females (aL, 7.5º SD 4.4 and bL, 2.5º SD 6.7) (p < 0.001), whereas the medial narrowing angles were nearly identical for both genders. The narrowing angles and trapezoidicity ratios were smaller for patients with patellofemoral OA than for other diagnoses, but this difference was not statistically significant (Fig. 6).

Anterior prosthetic overhang was seen in 76 patients (67%), where the mean difference in width (MLA) between bone and component was 2.2 mm SD 4.7 (-10 to 13). Central overhang was observed in 34 patients (30%), where the mean difference in width (MLC) between bone and implant was -2.2 mm SD 4.8 (-15 to 7.7). Patients with prosthetic overhang in the anterior area had a narrower and a more trapezoidal femur (p = 0.006 and p = 0.014, respectively) (Table III).

Multivariate analysis indicated that there was a correlation between overhang and the aspect ratio (more overhang in narrow femurs, p = 0.002), and the trapezoidicity ratio (more overhang in trapezoidal femurs, p = 0.002), and the TFA (more overhang in valgus knees, p = 0.035). There was a correlation between TFA and overhang (multivariate analysis) but not between TFA and the geometric ratios (linear regression). This is probably because of the tendency

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<th>Table I. Distal femoral dimensions</th>
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*Between females and males (Mann–Whitney U test)
SD, standard deviation; M, medial; L, lateral; A, anterior; C, central; P, posterior

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<th>Table II. Distal femoral ratio and angles</th>
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*Between females and males (Mann–Whitney U test)
SD, standard deviation; ML, mediolateral; AP, anteroposterior; P, posterior; A, anterior; C, central; M, medial
to implant larger sized femoral components in valgus knees to compensate for hypoplasia of the lateral condyle. The mean femoral overhang was greater in females than in males, but after adjustment for other variables, the influence of gender appeared to be non-significant (p = 0.117) (Table IV).

The geometries of the 12 specimen components can be compared directly with the morphological findings of this study (Fig. 7). Some components had excessively low trapezoidicity ratios (i.e. were too rectangular) such as DePuy LCS, Stryker Scorpio and the Tornier Noetos. Other designs had trapezoidicity ratios closer to anatomical values such as Zimmer Nexgen, Zimmer Persona, DePuy Attune and Smith and Nephew Journey. Several components had excessively low anterior lateral narrowing angles ($\alpha_L$) such as DePuy LCS, Stryker Scorpio and the Tornier Noetos. All had insufficiently low medial narrowing angles.

**Discussion**

This study demonstrates that the shape of the distal femur has more complex variations than previously thought. Rather than simply being divisible into narrow or wide, the shape varies significantly between those that are trapezoidal and those that are more rectangular. Many of the
analysed implants were not trapezoidal enough compared with the native femur, making it challenging to match prosthetic coverage. To our knowledge, this is the first investigation to have considered the trapezoidal/rectangular shape of the distal femur in the design of TKA.

The findings confirm a high degree of variation of the aspect ratio of the distal femur, and that women have narrower femurs than men. We also found great variations in the trapezoidicity ratio between patients, some femurs having a rectangular shape and some having a trapezoidal shape, albeit that the variation is similar in women and men. This confirms the findings of Mahfouz et al, who reported ethnic variations but no gender difference for the trapezoidicity ratio. Overhang of the femoral component in the anterior-distal area was noted in 84% of the females and 54% of the males in our patients, which is close to the level of oversizing reported in the study of Mahoney et al. A higher rate of oversizing was observed in women in these two series but in our multivariate analysis gender was not an independent risk factor for oversizing. The three main morphological risk factors for femoral oversizing were a narrow or trapezoidal native femur, or valgus alignment. As may be expected, the risk of overhang is also increased when using rectangular implants in trapezoidal femurs as well as when using wide implants in narrow femurs.

This study has several limitations. First, only one design of TKA was used and it is not clear whether our conclusions
can be extended to other designs. However, it should be noted that the ML/AP aspect ratio of the design used is close to other more widely used designs.1 Secondly, the patients in this series were all Caucasian and morphological
characteristics cannot be extended to Asian or African patients. Thirdly, we analysed the dimensions in arthritic knees, which may have different dimensions compared with normal knees. Finally, we only analysed femoral morphology at the level of the distal cut, and did not investigate geometrical variations at the levels of the anterior or posterior cuts, where prosthetic overhang could also cause impingement against soft-tissues.

While early designs of TKA were available with only a single size of femoral component, knowledge of the anatomy of the knee and prosthetic design have improved significantly. Between the early 1970s and the late 1990s, implants increased in size proportionally, with different sizes sharing the same aspect ratio. In the early 2000s, several anatomical studies identified the variations of the aspect ratio of the distal femur, leading manufacturers to introduce narrower components. It is only recently that more complex variation in the shape of the distal femur and proximal tibia have been described.

Since the work of Hitt et al great attention has been paid by manufacturers to adapt the design of TKA to narrower femurs but our explant analysis shows that rectangular-trapezoidal variations have been underestimated. We observed that manufacturers adjusted the trapezoidicity ratios and narrowing angles in more recent designs to match the anatomy better (Fig. 4). It is interesting to note that the ‘trapezoidicity ratio’ of the Scorpio prosthesis - which shows a similar rate of anterior overhang - is similar to the Noetos prosthesis implanted in this series.

We compared the trapezoidicity ratio in the patients to that in several modern prosthetic designs. This comparison revealed that the mediolateral dimensions of the component fit both with the posterior and the anterior area only in the more rectangular femurs (Fig. 4). For most of our patients, a component which appears to be well-matched in the posterior area seems to be oversized anteriorly. Therefore surgeons often need to compromise and to accept some under-sizing at the MLP and MLC levels and did not investigate geometrical variations at the levels of the anterior or posterior cuts, where prosthetic overhang could also cause impingement against soft-tissues.

Surgeons may accept mediolateral femoral overhang in some patients to avoid anterior notching in a posterior-referencing technique, or to improve flexion stability in an anterior-referencing system. External rotation of the femoral component, when obtained by decreased postero-lateral resection, may also require oversizing of the component. Lastly, the surgeon may be obliged to oversize the femur simply to implant a size of component which is compatible with the tibial component.

**Supplementary material**

A table comparing the distal femoral ratio and angles in implant specimens compared with anatomy is available alongside the online version of this article at www.bjoline.org.uk

**Author contributions:**

M. P. Bonnin: Performed surgeries, main investigator, data analysis, manuscript redaction.
M. Saffarini: CT-scan analysis, explants analysis, manuscript redaction.
N. Bossard: Data analysis, statistical analysis.
E. Dantony: Data analysis, statistical analysis.
J. Victor: Data analysis, explant analysis, manuscript redaction.

No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

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**References**