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# Sagittal shapes of current fixed-bearing unicompartmental knee replacements differ from those of normal knees

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ABSTRACT

*Background:* The principle when performing unicompartmental knee replacements (UKR), is to restore the natural alignment as well as the ligament tension. The tension in the ligaments is determined by the position of the joint line and the geometry of the articulating surfaces of the joint. If the surface geometry of the femoral component in a UKR is different from that of the natural knee it might cause abnormal ligament tension. This study was undertaken to determine the surface geometry of the native knee and to compare that with the geometry of different commercially available UKR femoral components.
*Methods:* Thirty-six native femurs and seven different UKR femoral component designs were included in this study. The sagittal shapes of the native femoral condyles and the prostheses were quantitatively described with the radius ratio (RR) and transition position index (TPI), which were calculated from the radii and transition point of the extension and flexion facets.
*Results:* The different prostheses showed a wider shape variability than the native medial condyles, having at least two times greater coefficient of variation for the RR and TPI. The sagittal shape of three prostheses corresponded to the native medial femoral condyles whereas five prostheses corresponded to the lateral condyles. One prosthesis had curves that fell far outside the native knee shape.
*Conclusion:* There was a wider sagittal shape difference between the femoral components compared to the native knees. Clinically, the sagittal position of the prostheses can compensate for these differences, but it might be technically challenging.


## 1. Introduction

In unicompartmental knee replacement (UKR), the aim is to restore the patient's constitutional alignment and at the same time balance the ligaments to their natural tension. This allows the replaced compartment to bear its original contralateral compartment loads without overloading it. Overstuffing or understuffing of the replaced compartment changes the load in the opposite compartment. Clinically, overstuffing is of greater concern than understuffing. A load increase in the adjacent joint compartment was observed with as little as one millimeter of overstuffing [1]. Overstuffing increases the strain in medial collateral ligaments and is associated with early failure [2]. Numerous mid- to long-term follow-up studies confirmed that overstuffing is more detrimental for the joint survival than undercorrection [3].

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With standard instrumentation for UKR, overstuffing can be avoided by resecting the correct amount of bone and choosing an appropriate thickness of tibial insert. The ligament tension should be correct in both flexion and extension and this can be relatively easily attained by performing the correct tibial resection and then cutting the distal and posterior femur parallel to the tibial cutting plane under the correct ligament tension. Mid-flexion ligament tension is, however, influenced by the sagittal curve design of the prosthesis and is difficult to control once the distal and posterior femoral cuts are performed. If the sagittal curve design of the prosthesis differs from that of the native knee, mid-flexion overstuffing or understuffing can occur. This can lead to mid-flexion instability in an understuffed knee or to a cam-effect, ligament tightness followed by sudden looseness, in mid-flexion in an overstuffed joint.

In order to examine how well the sagittal curve geometry of UKR femoral components corresponds to that of the native knees, a study was undertaken comparing the difference between the native knees and seven commercially available UKR femoral components. A comparison was also carried out between the different UKR femoral designs. Two quantitative parameters, namely the radius ratio (RR) and the transition position index (TPI) between the extension and flexion facets, were measured. To our knowledge, the sagittal curves of the normal native femoral condyles and the prosthetic UKR femoral condyles have not been quantitatively compared previously.

## 2. Methods

### *2.1. Sagittal curve acquisition of native knees*

Eighteen volunteers (seven male and 11 female), between the ages of 19 and 65 years, who had no history of knee pain, injury, or surgery, participated in this study with informed consent. Ethical approval was granted by the Committee for Human Research, Faculty of Health Sciences, Stellenbosch University (NO8/02/029/2008). The 36 knees were analyzed for the sagittal curve characteristics. Computed tomography (CT) scans of the femurs were segmented (Mimics, Materialise, Leuven, Belgium) into three-dimensional (3D) virtual models and aligned (3Matics, Materialise, Leuven, Belgium) using the same reference frame (Figure 1). First the posterior condylar plane was defined; this is parallel to the anatomical axis and coincident with the posterior condylar line. The distal condylar plane was defined as a plane perpendicular to the posterior condylar plane and coincident with the distal condylar line. The X–Y plane, which serves as the sagittal plane, was defined as a plane that is perpendicular to both the distal condylar and posterior condylar planes. The medial and lateral sagittal planes were defined to be coincident on, respectively, the most posterior points of the medial and lateral condyles. This enabled the generation of medial and lateral intersection curves which allowed the femoral curvatures to be compared. The intersection curves are presented as dotted lines in Figure 1(c). The X-axis was defined as parallel to the anatomical axis while the Y-axis was perpendicular to the anatomical axis in the sagittal view.

### *2.2. Sagittal curve acquisition of the femoral components*

Seven different fixed-bearing UKR femoral component designs were analyzed. The details of the femoral components are given in Table 1. The trial components were reverse engineered using a 3D laser scanner (3D Scanner Ultra HD, NextEngine, CA, USA) to acquire digital models. The models were aligned using the same reference frame for all models (Figure 2). The distal cuts of the models were aligned in parallel, similarly to the normal surgical protocol, where the distal femoral resection is the first femoral cut and it serves as a reference for all other femoral resections. The X–Y plane, which serves as the sagittal plane, is perpendicular

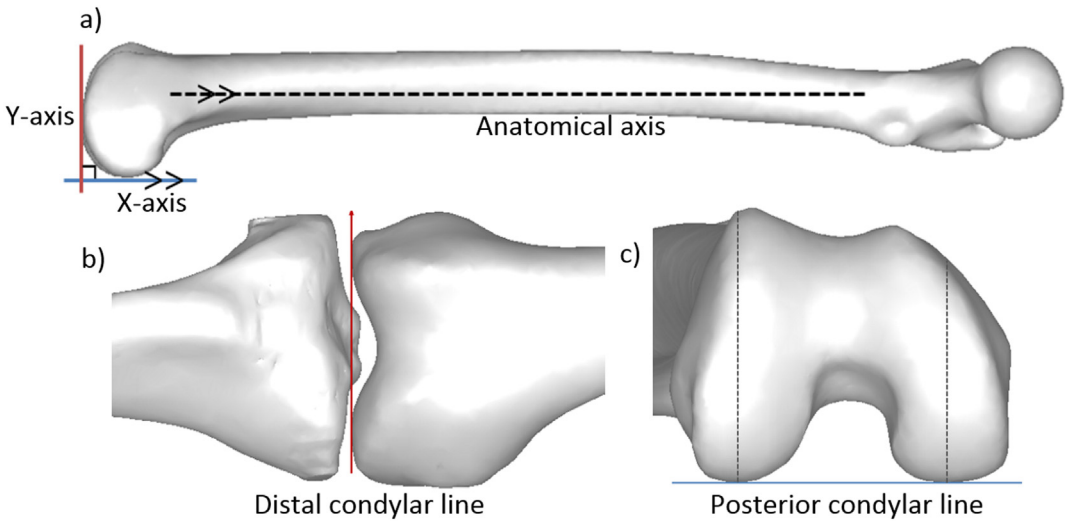


**Figure 1.** Reference frame for native knee measurements. (a) Sagittal view, (b) coronal view, and (c) axial view.

**Table 1**
Details of the off-the-shelf femoral components analyzed in this study.

| Prosthesis no. | Type | Size | Model name | Manufacturer |
|---|---|---|---|---|
| 1 | Anatomical | 5 | iBalance UKA | Arthrex |
| 2 | Symmetrical | 3 | GMK UNI | Medacta |
| 3 | Anatomical | 5 | GMK UNI | Medacta |
| 4 | Anatomical | 5 | SIGMA HP | DePuy Synthes |
| 5 | Symmetrical | 3 | U-KneeTec | Corin |
| 6 | Anatomical | 5 | JOURNEY UNI | Smith & Nephew |
| 7 | Anatomical | 1 | Physica ZUK | Lima Corporate |

to both the distal and posterior resection planes. The intersection curve, as shown in Figure 2(b) by a dotted line, was generated using the surface of the prosthesis and the sagittal plane that bisected the posterior part of the prosthesis. The X-axis was defined as perpendicular to the distal resection plane and the Y-axis was parallel to the distal resection plane.

### *2.3. Sagittal curve analysis*

Normal sagittal curve characteristics of the native knees have been previously described with circular arc regions: the extension facet (EF), the flexion facet (FF), and the posterior horn facet (PHF) [4–7]. A least-squares method was used to identify the EF and FF of the sagittal curves acquired from the native knees and prostheses (Matlab, MathWorks, Massachusetts, USA). The tolerance was set at 0.2 mm for the prosthetic sagittal curves. The set tolerance was 0.5 mm for the native knees because the curves acquired from the native knees were not as smooth as the curves from the prostheses due to segmentation.

Once the EF and FF were identified, the radius of the EF ($R_{EF}$) and that of the FF ($R_{FF}$) were measured (Figure 3). The RR of $R_{EF}$/$R_{FF}$ was recorded to quantify how much greater $R_{EF}$ is than $R_{FF}$. To be able to quantitatively compare the position of the transition point from the EF to the FF, the arc lengths were measured (Figure 3). The arc length of the EF ($AL_{EF}$) was measured between the most distal point and the transition point. The arc length of the FF ($AL_{FF}$) was measured between the transition point and the most posterior point. The TPI was calculated as $AL_{EF}/(AL_{EF} + AL_{FF})$.

### *2.4. Statistical analysis*

For all the measurements ($R_{EF}$, $R_{FF}$, RR, $AL_{EF}$, $AL_{FF}$ and TPI) of the native knees, a paired *t*-test was used to compare the difference between the left and right femur and the difference between the medial and lateral condyles at a 95% level of confidence. The variability was calculated with the coefficient of variation in terms of a percentage (%) for all the measurements.

## 3. Results

The radius ($R_{EF}$, $R_{FF}$ and RR) and curve length ($AL_{EF}$, $AL_{FF}$ and TPI) measurements for the native knees are summarized in Table 2. No statistically significant difference was observed between the radius and curve length measurements of the left and right knees, except for the EF radius ($R_{EF}$) with a *P*-value of 0.02. Consequently, the RR showed a statistically significant difference between the left and right knees ($P = 0.04$). All measurements were significantly different between the medial and lateral condyles with $P < 0.001$. The RR of the lateral condyles was significantly greater than the RR of the medial condyles, while the TPI of the

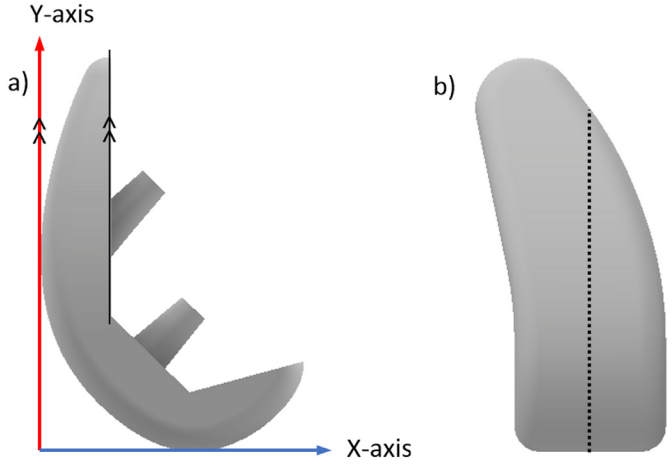


**Figure 2.** Graphical representation of the reference frame for the analysis of femoral components.

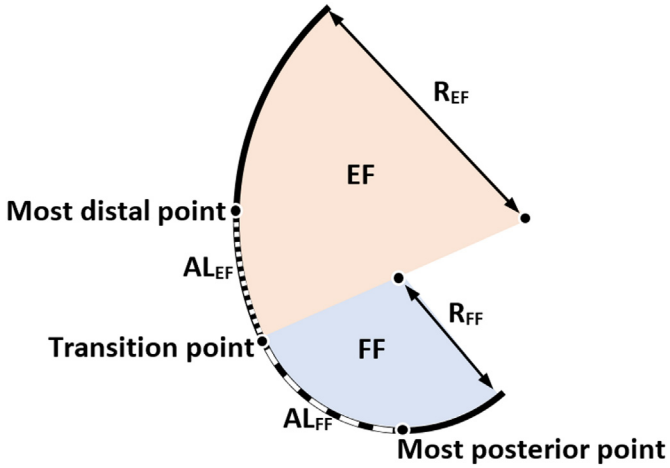


**Figure 3.** Sagittal curve analysis. $AL_{EF}$, EF arc length; $AL_{FF}$, FF arc length; EF, extension facet; FF, flexion facet; $R_{EF}$, radius of the EF; $R_{FF}$, radius of the FF.

medial condyles was significantly greater than that of the lateral condyles. The lateral condyles had a higher sagittal curve variability than the medial condyles with all measurements. The TPI showed a higher variability than the RR for both the medial and lateral condyles.

The graphical representations of sagittal curves of the off-the-shelf femoral components are presented in Figure 4, and all the measurements are listed in Table 3. The sagittal shape measurements of the prostheses showed a wide variability. The coefficient of variation of the measurements from the prostheses was at least 1.5 times greater and at most 2.8 times greater than that of the medial condyles. The coefficient of variation of the prosthesis measurements was between 0.9 and 1.7 times the coefficient of variation of the lateral condyle measurements (Tables 2 and 3).

Box and whisker plots were generated to compare the RR and TPI of the native knees and the prostheses (Figures 5 and 6). Only one prosthesis, Prosthesis 4, had the RR and TPI within the interquartile range of the native medial condyles exhibited. There was no prosthesis that had the RR and TPI values within the interquartile range of the lateral condyles. Prostheses 3, 4 and 7 had both the RR and TPI values within the range of the medial condyles. Prostheses 3, 4, 5, 6 and 7 had the RR and TPI that fell within the range of the lateral condyles. Prosthesis 2 fell outside the range of both the medial and lateral condyles for RR, but the TPI value still stayed within the range of the native medial and lateral condyles. The RR and TPI measurements of Prosthesis 1 were outside the range of both the medial and lateral condyles of the native knees. Prosthesis 1 had an EF that was outside the curve between the most distal and most posterior points, having a single radius for the EF and FF. Therefore, Prosthesis 1 had a RR value of 1 and a TPI of 0.

## 4. Discussion

The most important findings of the study are firstly that the sagittal shape of the different femoral prostheses varies widely, and secondly that the sagittal shape of the different femoral prostheses has a wider variation than the native medial condyles. This study described the sagittal curve characteristics of the native knees and prostheses quantitatively in terms of the RR and TPI, which are dimensionless measurements. Only one out of the seven prostheses had the RR and TPI within the native interquartile range and three prostheses within the range of the native medial condyle. The sagittal shape of the lateral condyle, in the natural knee, varied more widely than the medial condyle and was comparable to the variability given by the prostheses. Five out of the seven prostheses had RR and TPI values within the range of the native lateral condyles. To our knowledge, the shapes of different UKR femoral prostheses have not been described in literature nor been compared in the same study with that of the native knees.

Our findings in the native knees are similar to those of other studies in the literature. The RR measurements acquired from this study agree with the mean RR values, calculated from the mean $R_{EF}$ and mean $R_{FF}$ values, as reported in the literature [4,7–10]

**Table 2**
Summary of radius and arc length of extension and flexion facets of the native knees (values in brackets indicate the ranges).

| | EF radius, $R_{EF}$ (mm) | FF radius, $R_{FF}$ (mm) | Radius ratio, RR | EF arc length, $AL_{EF}$ (mm) | FF arc length, $AL_{FF}$ (mm) | Transition position index, TPI |
|---|---|---|---|---|---|---|
| Medial condyle | 36 (27–53) | 19 (15–23) | 1.90 (1.43–2.80) | 21 (8–35) | 23 (12–30) | 0.48 (0.20–0.68) |
| Coefficient of variation for medial condyles (%) | 15 | 9 | 14 | 27 | 18 | 21 |
| Lateral condyle | 49 (29–80) | 21 (17–26) | 2.34 (1.51–3.55) | 11 (0–27) | 30 (15–41) | 0.26 (0.01–0.61) |
| Coefficient of variation for lateral condyles (%) | 25 | 10 | 20 | 66 | 21 | 60 |

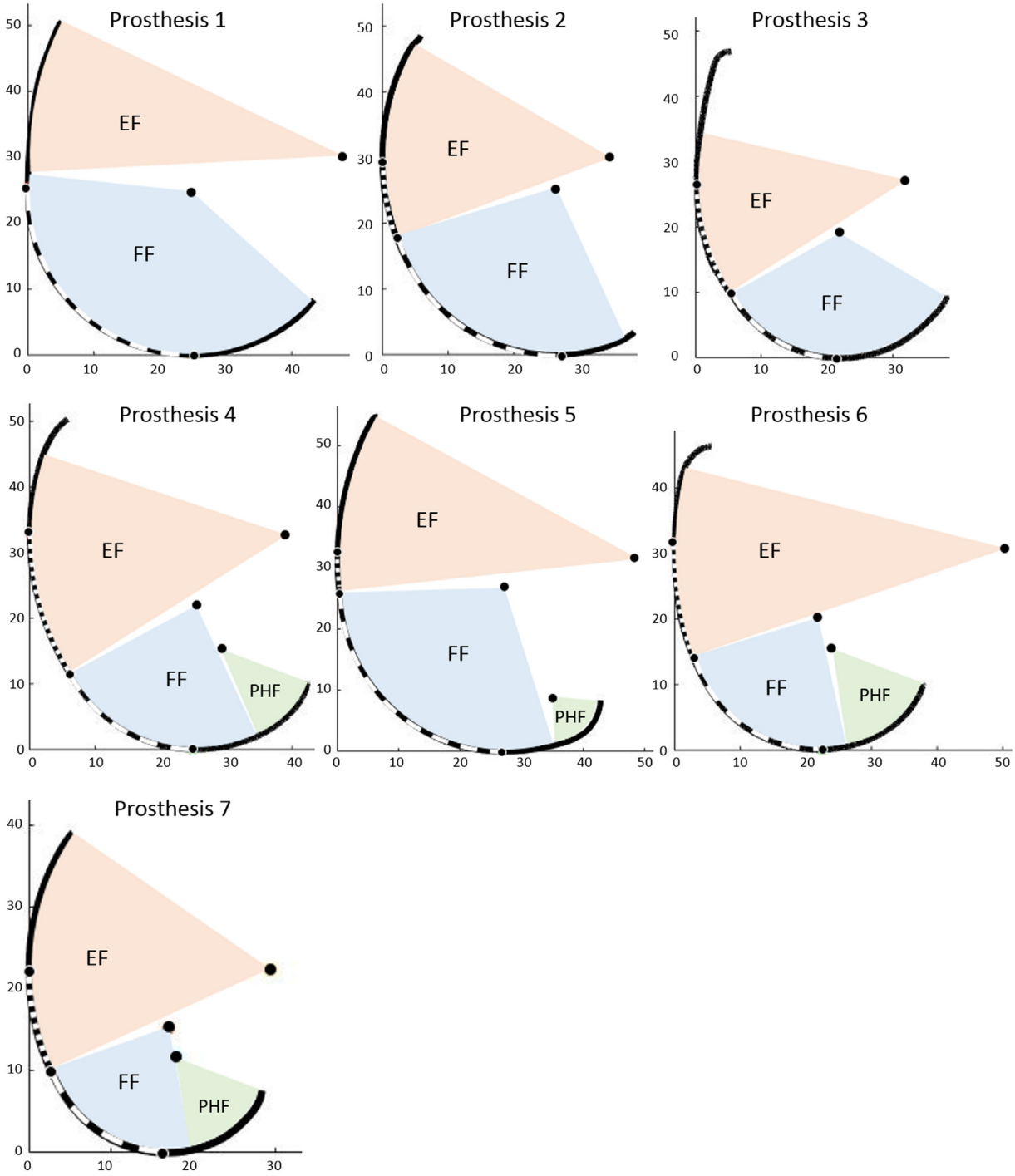


**Figure 4.** Graphical representations of sagittal curve analysis of femoral components. EF, extension facet; FF, flexion facet; PHF, Posterior horn facet.

(Figure 5, Table 4). The mean RR based on literature ranges from 1.33 to 1.92 for the medial condyles (mean RR of this study: 1.90) and from 1.51 to 2.17 (mean RR of this study: 2.34) for the lateral condyles. The sagittal curves of the lateral condyles are less described than the curves of the medial condyles in literature. As a result, the studied sample size is smaller, and the range of mean RR can be less comprehensive.

In our study, the RR values of the lateral condyles were significantly higher than those of the medial condyles. Similar trends can be observed in the reported values in literature which described both the medial and lateral condyles [4,7,8], as shown in Table 4. The RR represented how much greater the EF radius was than that of the FF. The higher the RR value, the flatter the

**Table 3**
Summary of radius and arc length of extension and flexion facets of the prostheses (values in brackets indicate the ranges).

| Prosthesis no. | EF radius, $R_{EF}$ (mm) | FF radius, $R_{FF}$ (mm) | Radius ratio, RR | EF arc length, $AL_{EF}$ (mm) | FF arc length, $AL_{FF}$ (mm) | Transition position index, TPI |
|---|---|---|---|---|---|---|
| 1 | 48 | 25 | 1 or 1.92[a] | 0 | 40 | 0 |
| 2 | 35 | 25 | 1.39 | 11 | 33 | 0.25 |
| 3 | 32 | 19 | 1.68 | 18 | 21 | 0.46 |
| 4 | 39 | 22 | 1.75 | 20 | 25 | 0.44 |
| 5 | 49 | 27 | 1.83 | 4 | 42 | 0.09 |
| 6 | 66 | 20 | 3.24 | 15 | 29 | 0.34 |
| 7 | 29 | 15 | 1.94 | 11 | 20 | 0.37 |
| Coefficient of variation (%) | 28 | 17 | 28 | 59 | 27 | 58 |

[a] Extension facet was outside the curve between the most distal and the most posterior points.

EF would be. These results confirmed the findings from previous studies, which showed that the lateral condyles of the natural knees had a flatter EF than that of the medial condyles in the sagittal plane.

The TPI was significantly greater for the medial condyles than the value for the lateral condyles. The TPI value represented the proportion of the extension curve length over the total curve length between the distal and posterior apexes of the sagittal curves. Having a greater TPI meant that the curve had a longer EF, and that the EF–FF transition point was located more posteriorly. The lateral condyles had a transition point located more anteriorly than that of the medial condyles. This result can explain the findings of Bicer et al. [11], which showed that the sagittal flexion of the femoral component was significantly greater for the medial than the lateral UKRs. The sagittal flexion position of the prosthesis that Bicer et al. used was determined by the anatomy of the femur rather than by the tibial slope. It was postulated that the sagittal difference they found was influenced by the geometrical difference between the lateral and medial condyles. As demonstrated in Figure 7, the lateral condyles have a flatter EF with the FF that extends more anteriorly (lower TPI value) than the medial condyles. This affects the sagittal position of the prostheses.

Heyse et al. [12] observed an unexpected mid-flexion tightness in balanced knees during their cadaveric study. We observed a similar phenomenon intraoperatively; unwanted tightness or looseness in the mid-flexion range. In our clinical experience Prosthesis 1 exhibited mid-flexion tightness more commonly than the others. In the subsequent measurement studies, it was found that the sagittal shape parameters of Prosthesis 1 least represented the shape of the native medial condyles, while Prosthesis 4 best represented them. A native knee was selected randomly and the sagittal curves of Prostheses 1 and 4 of the same size were superimposed on its medial condyle to visually demonstrate how different sagittal curve characteristics affect the fit, as shown in Figure 8. The native medial condyle had a RR of 1.55 ($R_{EF}$: 31 mm $R_{FF}$: 20 mm) and a TPI of 0.39. Both the RR and TPI of Prosthesis 4 were closer to that of the native knee than Prosthesis 1. Furthermore, the sagittal curve of Prosthesis 4 presented the native curve more closely than did Prosthesis 1, as shown in Figure 8(a). During the measurements acquisition, the effect of flexion–extension positioning was eliminated using a reference frame that ensured all the prostheses were aligned to the same distal cutting plane, which served as the reference for the other femoral resections.

It is important to realize that the flexion–extension position of the femoral component also influences location of the transition point between the EF and FF, thereby changes the curve characteristics. For example, Prosthesis 4 could be placed in slight extension to match more closely to the native curve by reducing understuffing in the mid-flexion area, as visualized in Figure 8(b). Placing Prosthesis 4 in more extension decreased the TPI by moving the transition point more anteriorly. Conversely, Figure 8(c) demonstrates that if Prosthesis 1 is positioned in flexion, the overstuffing is reduced in the mid-flexion area. Placing Prosthesis 1 in flexion moved the transition point posteriorly and increased the TPI. However, even in the flexed position, there is a mismatch of the FF radius between Prosthesis 1 and the native knee. Figure 8(c) visually demonstrates that if the prosthesis is downsized and the amount of flexion is increased, a better fit can be achieved. These examples confirm that, with an appropriate sizing and flexion–extension positioning, understuffing or overstuffing can be reduced. However, with a conventional technique, it is limited because the distal femoral cut is the first femoral cut that is being made and technically it is not possible to re-cut the correct amount and re-size the prosthesis for a better fit. Furthermore, changing the flexion or extension position of the prosthesis

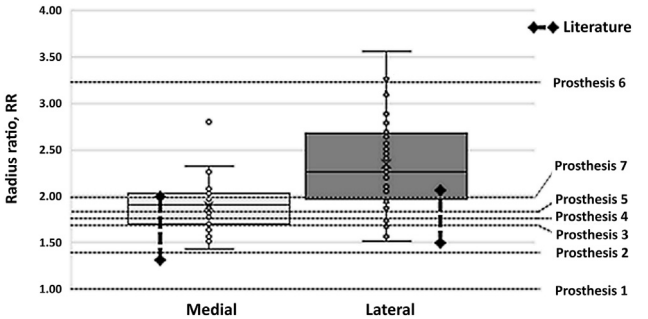


**Figure 5.** The radius ratio of the native knees versus that of the prostheses.

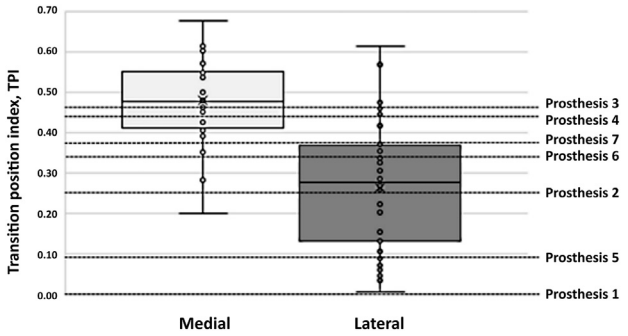


**Figure 6.** The transition position index of the native knees versus that of the prostheses.

drastically should be avoided because there is a danger of creating an overhang at the anterior or posterior tip. Therefore, selecting the prosthesis that represents the shape of the patient's knee more closely would reduce the probability of needing a re-cut or experiencing an unplanned overstuffing or understuffing.

Because the sagittal shapes of the prostheses and native knees vary widely, there is no prosthesis design that would fit perfectly to all native knees. Preoperatively, with a true lateral X-ray, it is possible to measure the RR and TPI to select the most appropriate prosthesis design. However, reproducing the planned cut during the surgery can be a challenge. With a robotic surgery, regardless of its native geometry registration technique being intraoperative or preoperative from CT, it is possible to explore various prosthesis design and positioning options for the optimum fit between the native and prosthetic condyles. The planned cuts can accurately be reproduced during the surgery with a robotic system.

The slope of the tibia also plays a role. When there is an increased posterior slope, with flexion and rollback, the tension on the medial collateral ligament will be reduced and the wear kinematics will improve [13]. Most surgeons prefer to make the flexion gap slightly bigger than the extension gap if an over-tightness is caused by abnormal sagittal shape of the prosthesis. Making these compromises, to account for abnormal sagittal shape of the femoral component, is not desirable because an increased slope beyond eight degrees increases the risk of anterior cruciate ligament (ACL) rupture [14]. For UKR, the patient's original tibial posterior slope has to be respected and the slope between three degrees and seven degrees is suggested to be an ideal compromise [14,15].

Representing the 3D geometry of femoral condyles into simple two-dimensional (2D) sagittal curves can be a limitation. The sagittal curve characteristics of the native condyles differ depending on the medial–lateral position of the sagittal plane [16,17]. However, the advantage of this study is that it offers a simple method that quantitatively compares the native and prosthetic condyles. The limitation was minimized by following a standardized reference regime. The posterior condylar point was selected as the reference for selecting the medial and lateral sagittal planes on the native knees. The mid-sagittal plane of the prosthesis was defined as the plane that bisected the posterior condyle of the femoral component. This plane passes through the posterior condylar point of the prosthesis. Furthermore, the sagittal curves extracted from this study approximate the most prominent paths, which drive the knee kinematics.

Another limitation of this study is that the native knee curve analysis is based on the CT scans, which represent the bony geometry, not the articulating surface. The findings of this study however were similar to that of other studies where the articular surfaces were investigated [4,7,8]. Different sizes of prostheses were used for the analysis because of limited accessibility to all the sizes of the different manufactures. Four prostheses were a size 5, two of the prostheses were a size 3 and one was a size 1. This difference in size was addressed using a consistent reference frame across all knees and prostheses and using dimensionless measurements. The RR and TPI enabled objective and quantitative comparisons between the sagittal shape of the prostheses and the native knees for the mid-flexion range and were independent of the size of the prostheses and the femurs.

This study did not consider the effect of the valgus or varus rotation of the femoral component relative to the tibial component. Kang et al. [18] demonstrated the importance of the coronal alignment of the femoral component by demonstrating that a valgus or varus malalignment of the femoral component affects the collateral ligament loading patterns as well as the opposite compartment. In practice, although rare, the femoral component varus rotation can be inevitable to avoid an overhang at the

**Table 4**
Radius ratio (RR) of the native knees reported in other studies.

| Reference | Number of subjects | RR | |
|---|---|---|---|
| | | Medial | Lateral |
| Iwaki et al. [4] | 6 | 1.45 | 1.51 |
| Martelli and Pinskerova [7] | 6 | 1.56 | 2.17 |
| Monk et al. [10] | 25 | 1.33 | – |
| Nuño and Ahmed [8] | 12 | 1.72 | 1.85 |
| Siu et al. [9] | 5 | 1.92 | – |
| Current study | 36 | 1.90 | 2.34 |

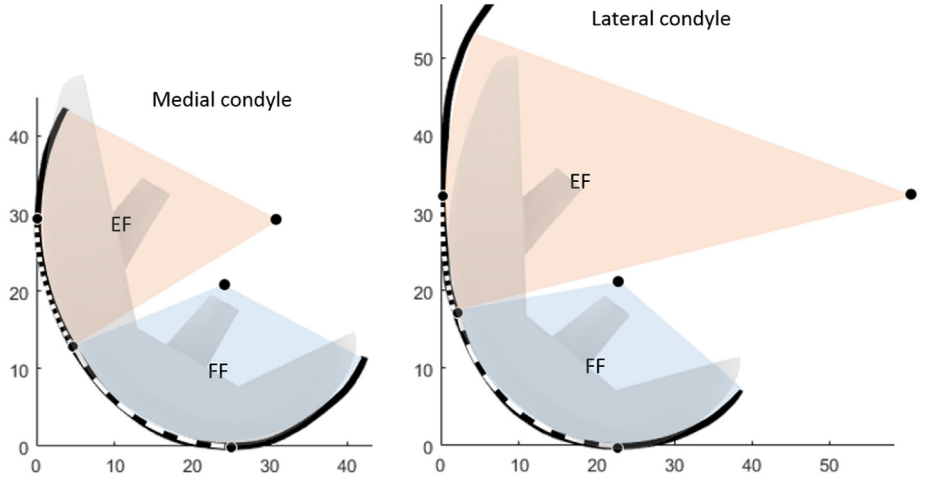


**Figure 7.** Sagittal curve analysis on the medial and lateral condyles of a native knee. Ideal sagittal positioning of a femoral component is demonstrated for medial and lateral condyles. EF, extension facet; FF, flexion facet.

anterior corner if the femur has an extreme axial J-curve. Such a case was not considered because this study focused on the case with an ideal coronal femoral alignment where the valgus–varus alignment of the femoral cuts is parallel to the tibial cut. This study was motivated by a clinical observation that an unexpected cam-effect or looseness was experienced at a mid-flexion range notwithstanding being well balanced in 90° flexion and full extension. The scope of this study was to compare the sagittal shape of the prosthesis to the native knees with quantitative measures.

## 5. Conclusion

There is a wide range in the sagittal shapes of the femoral components of different UKR designs. The sagittal shape of femoral prostheses varies widely especially in comparison with that of the native medial condyles. Some prostheses more closely match

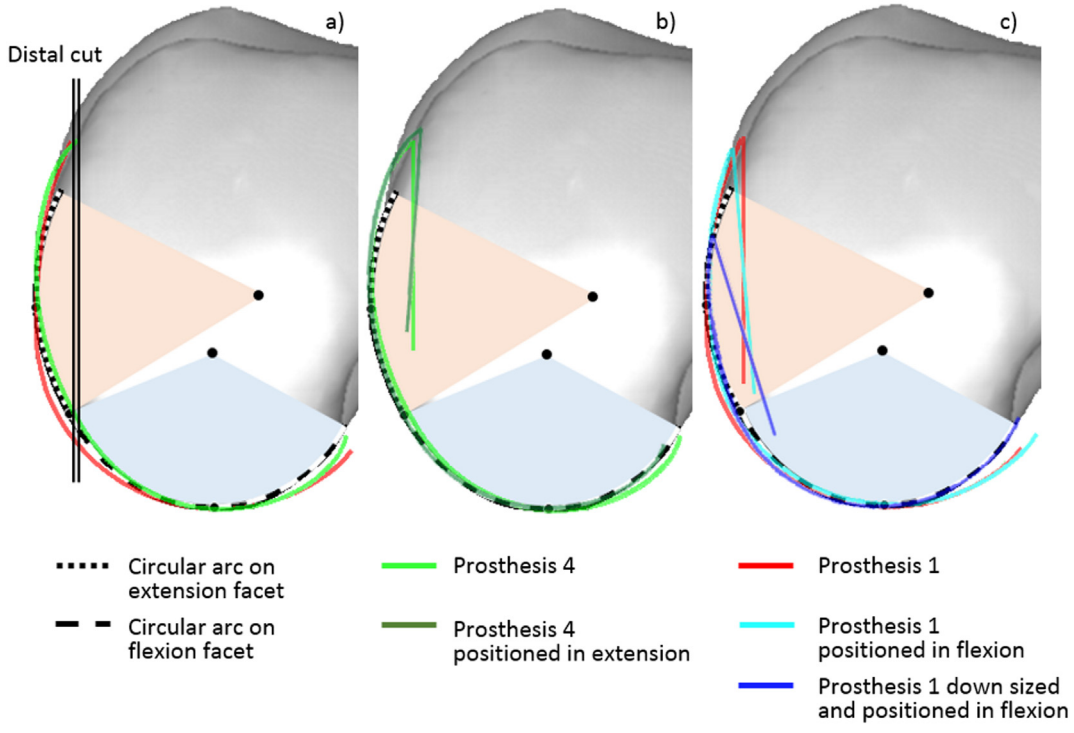


**Figure 8.** (a) Prosthesis 1 and Prosthesis 4 are superimposed on a native medial condyle. (b) Prosthesis 4 is positioned in extension for an optimum fit. (c) Prosthesis 1 is positioned in flexion and downsized for an optimum fit.

the shape of the native femoral condyles while others were less anatomical. Because of the variability within the native shape, there is no single femoral design that would fit to all native knees. The variation between the sagittal shape of the native femur and the prosthetic femur can cause a mid-flexion stiffness leading to a cam-effect. This potential problem can to some extent be addressed, on the tibial side, by increasing the posterior slope. On the femoral side, this potential problem is addressed by placing the prosthesis more anterior creating a bigger flexion gap or placing it in more flexion to shift the transition point. However, this might cause impingement of the patella on the anterior edge of the prosthesis. Therefore, surgeons should be aware of the wide sagittal shape variability in different prosthesis designs and should know that it affects their optimum sagittal positioning.

## Conflict of interest

This research did not receive any specific grant(s) from funding agencies in the public, commercial, or not-for-profit sectors. There are no conflicts of interest.

## References

[1] Innocenti B, Bilgen ÖF, Labey L, van Lenthe GH, Vander Sloten J, Catani F, et al. Load sharing and ligament strains in balanced, overstuffed and understuffed UKA. A validated finite element analysis. J Arthroplasty 2014;29:1491–8. https://doi.org/10.1016/j.arth.2014.01.020.
[2] Perkins TR, Gunckle W. Unicompartmental knee arthroplasty: 3- to 10-year results in a community hospital setting. J Arthroplasty 2002;17:293–7. https://doi.org/10.1054/arth.2002.30413.
[3] Berger RA, Meneghini RM, Jacobs JJ, Sheinkop MB, Della Valle CJ, Rosenberg AG, et al. Results of unicompartmental knee arthroplasty at a minimum of ten years of follow-up. J Bone Joint Surg 2005;87:999–1006. https://doi.org/10.2106/JBJS.C.00568.
[4] Iwaki H, Pinskerova V, Freeman MAR. Tibiofemoral movement 1: the shapes and relative movements of the femur and tibia in the unloaded cadaver knee. J Bone Joint Surg Br 2000;82:1189–95. https://doi.org/10.1302/0301-620x.82b8.10717.
[5] Hill PF, Vedi V, Williams A, Iwaki H, Pinskerova V, Freeman MAR. Tibiofemoral movement 2: the loaded and unloaded living knee studied by MRI. J Bone Joint Surg Br 2000;82:1196–8. https://doi.org/10.1302/0301-620x.82b8.10716.
[6] Nakagawa S, Kadoya Y, Todo S, Kobayashi A, Sakamoto H, Freeman MAR, et al. Tibiofemoral movement 3: full flexion in the living knee studied by MRI. J Bone Joint Surg Br 2000;82:1199–200. https://doi.org/10.1302/0301-620X.82B8.10718.
[7] Martelli S, Pinskerova V. The shapes of the tibial and femoral articular surfaces in relation to tibiofemoral movement. J Bone Joint Surg 2002;84:607–13. https://doi.org/10.1302/0301-620X.84B4.12149.
[8] Nuño N, Ahmed AM. Three-dimensional morphometry of the femoral condyles. Clin Biomech (Bristol, Avon) 2003;18:924–32. https://doi.org/10.1016/S0268-0033(03)00172-4.
[9] Siu D, Rudan J, Wevers H, Griffiths P. Femoral articular shape and geometry: a three-dimensional computerized analysis of the knee. J Arthroplasty 1996;11:166–73. https://doi.org/10.1016/S0883-5403(05)80012-9.
[10] Monk AP, Choji K, O'Connor JJ, Goodfellow JW, Murray DW. The shape of the distal femur. Bone Joint J 2014;96–B:1623–30. https://doi.org/10.1302/0301-620X.96B12.33964.
[11] Kaya Bicer E, Servien E, Lustig S, Demey G, Ait Si Selmi T, Neyret P. Sagittal flexion angle of the femoral component in unicompartmental knee arthroplasty: is it same for both medial and lateral UKAs? Knee Surg Sports Traumatol Arthrosc 2010;18:928–33. https://doi.org/10.1007/s00167-010-1063-y.
[12] Heyse TJ, El-Zayat BF, De Corte R, Scheys L, Chevalier Y, Fuchs-Winkelmann S, et al. Balancing UKA: overstuffing leads to high medial collateral ligament strains. Knee Surg Sports Traumatol Arthrosc 2016;24:3218–28. https://doi.org/10.1007/s00167-015-3848-5.
[13] Weber P, Schröder C, Schwiesau J, Utzschneider S, Steinbrück A, Pietschmann MF, et al. Increase in the tibial slope reduces wear after medial unicompartmental fixed-bearing arthroplasty of the knee. Biomed Res Int 2015;2015. https://doi.org/10.1155/2015/736826.
[14] Hernigou P, Deschamps G. Posterior slope of the tibial implant and the outcome of unicompartmental knee arthroplasty. J Bone Joint Surg 2004;86:506–11. https://doi.org/10.2106/00004623-200403000-00007.
[15] Deschamps G, Chol C. Fixed-bearing unicompartmental knee arthroplasty. Patients' selection and operative technique. Orthop Traumatol Surg Res 2011;97:648–61. https://doi.org/10.1016/j.otsr.2011.08.003.
[16] Zoghi M, Hefzy MS, Fu KC, Jackson WT. A three-dimensional morphometrical study of the distal human femur. Proc Inst Mech Eng H J Eng Med 1992;206:147–57. https://doi.org/10.1243/PIME_PROC_1992_206_282_02.
[17] Kosel J, Giouroudi I, Scheffer C, Dillon E, Erasmus P. Anatomical study of the radius and center of curvature of the distal femoral condyle. J Biomech Eng 2010;132:91002. https://doi.org/10.1115/1.4002061.
[18] Kang KT, Son J, Baek C, Kwon OR, Koh YG. Femoral component alignment in unicompartmental knee arthroplasty leads to biomechanical change in contact stress and collateral ligament force in knee joint. Arch Orthop Trauma Surg 2018;138:563–72. https://doi.org/10.1007/s00402-018-2884-2.