Notching is less, if femoral component sagittal positioning is planned perpendicular to distal femur anterior cortex axis, in navigated TKA

Raj Kanna1*, Chandramohan Ravichandran1 and Gautam M. Shetty2,3

Abstract
Purpose: In navigated TKA, the risk of notching is high if femoral component sagittal positioning is planned perpendicular to the sagittal mechanical axis of femur (SMX). We intended to determine if, by opting to place the femoral component perpendicular to distal femur anterior cortex axis (DCX), notching can be reduced in navigated TKA.

Methods: We studied 171 patients who underwent simultaneous bilateral computer-assisted TKA. Femoral component sagittal positioning was planned perpendicular to SMX in one knee (Femur Anterior Bowing Registration Disabled, i.e. FBRD group) and perpendicular to DCX in the opposite knee (Femur Anterior Bowing Registration Enabled, i.e. FBRE group). Incidence and depth of notching were recorded in both groups. For FBRE knees, distal anterior cortex angle (DCA), which is the angle between SMX and DCX, was calculated by the computer.

Results: Incidence and mean depth of notching was less (p = 0.0007 and 0.009) in FBRE versus FBRD group, i.e. 7% versus 19.9% and 0.98 mm versus 1.53 mm, respectively. Notching was very high (61.8%) in FBRD limbs when the anterior bowing was severe (DCA > 3°) in the contralateral (FBRE) limbs.

Conclusion: Notching was less when femoral component sagittal positioning was planned perpendicular to DCX, in navigated TKA.

Level of evidence: Therapeutic level II.

Keywords: Anterior femoral bowing, Computer-assisted knee replacement, Femoral component positioning, Sagittal alignment in TKA, Anterior femoral notching

Introduction
Human femur has different degrees of anterior bowing [1] (Fig. 1a), which implies that the distal femur anterior cortex axis (DCX) is more flexed than the sagittal mechanical axis of femur (SMX) (Fig. 1b). Studies show that the angle between the DCX and SMX varies widely [2–4], and this can influence the sagittal placement of the femoral component in total knee arthroplasty (TKA) [5]. Further, in navigated TKA, the optimal sagittal alignment of the femoral component is still unknown [6], and most surgeons to date plan to align it either perpendicular [7–9] or in slight (3–5°) flexion [10, 11] to SMX. However, studies show that the risk of anterior femoral notching is high if the femoral component positioning is planned perpendicular to the SMX in navigated TKA [6, 12].
In conventional TKA, the intramedullary rod deviates anteriorly to the SMX in the presence of anterior femoral bowing and the femoral component ends up in a more flexed position [5, 12], which reduces the risk of notching [5]. Hence, we hypothesised that, by opting to place the femoral component perpendicular to the DCX, the risk of notching can be reduced in navigated TKA. The present study is done to compare the incidence and depth of notching between knees in patients undergoing simultaneous bilateral navigated TKA, where femoral component sagittal positioning was planned perpendicular to DCX in one knee and perpendicular to SMX in the opposite knee.

**Materials and methods**

**Study design and participants**

We prospectively studied 200 patients who underwent same-day bilateral computer-assisted TKA between March 2015 and February 2019. We excluded three patients with previous femur fracture, four who had previous knee surgery, six with inflammatory disease, four with severe liver or kidney problem, two who used steroids, four with femoral stem extenders and six more who failed to follow up. The inclusion criteria were patients who underwent primary, cruciate-substituting, computer-assisted TKAs for primary osteoarthritis of both knees. Our institutional review board approved the study, and informed consent was obtained from all patients.

**Surgical technique and sagittal positioning**

All TKAs were performed by a single surgeon (R.K.) using the Kick computer navigation system with its software (Knee 2.6.0, Brainlab, Germany). All patients underwent simultaneous bilateral navigated TKA. A standard medial parapatellar approach was used in all cases. Femoral component sagittal positioning was planned perpendicular to DCX using the femur anterior bowing registration enabled (FBRE) setting in one knee and, perpendicular to SMX, using the femur anterior bowing registration disabled (FBRD) setting in the opposite knee. Randomisation was done using a sealed study number envelope, which was opened before the skin incision was made, and it was blinded to the patients.

Registration was done as per manufacturer’s recommendation. Tibial and femoral arrays were mounted on Schanz pins inserted into the proximal tibia and distal femur. On the femoral side, the following registration steps were common for the knees navigated with FBRE setting (FBRE group) and FBRD setting (FBRD group). First, the computer registered the SMX based on the acquisition of its proximal and distal points, which were centre of the femoral head (acquired by pivoting the femur) and a point 1 cm anterior to the superior border of the intercondylar notch, respectively. Then, the medial and lateral epicondylar points were acquired, and the femoral anterior sizing point, which represents the level of anterior femoral resection, was registered by placing the tip of the pointer on the lateral side of the distal femur anterior cortex, just proximal to the proximal limit of trochlea. Subsequently, the acquisition of the Whiteside’s line was done by holding the pointer along this line, and the surface of the femoral condyles was painted using the pointer, to acquire their most distal and most posterior points, which allowed the software to accurately calculate the distal femoral resection level and the femoral component size. Points were also acquired on the anterior aspect of distal femur to further define the bone model.

In addition, for the knees in the FBRE group, the cutting block adapter was placed over the distal femur anterior cortex for a few seconds until the computer registered the DCX (Fig. 2a, b). Common pitfalls during DCX registration and the strategies to avoid them are summarised in Table 1 and illustrated in Fig. 2b. For the knees in the FBRD group, this step was skipped, and therefore DCX was not registered.

On the tibial side, all registration steps were identical for knees in both the FBRE and the FBRD group. The proximal and distal points of the tibial mechanical axis were defined by acquiring the posterior aspect of the ACL insertion point and the software calculation based on the medial and lateral malleoli reference points, respectively. Then, the most medial, lateral, and anterior points of the proximal tibia were acquired, and the anteroposterior axis of the proximal tibia was registered by holding the pointer horizontally along the line that connected the tibial attachment of the PCL and the medial third of the tibial tubercle. Modelling of the tibial
plateaus were done by placing the tip of the pointer in the deepest point of the plateaus and moving it spirally outwards. Lastly, points were acquired on the anterior aspect of proximal tibia to further define the bone model.

Distal anterior cortex angle (DCA) is the angle between SMX and DCX, and it essentially quantifies the degree of flexion of the DCX, with respect to the SMX (Fig. 3a). For the knees in the FBRE group, the software calculated the DCA, and using navigation, femoral component sagittal positioning was planned perpendicular to DCX (Fig. 3b) by flexing the femoral component (with respect to the SMX) to the same angle as the calculated DCA. For the knees in FBRD group, DCX was not registered, and therefore DCA values were not calculated and the femoral component sagittal positioning was planned perpendicular to SMX (Fig. 3c).

The rest of the surgical steps were the same in both the FBRE and the FBRD group. Gap balancing technique was used to decide the femoral component rotation, and anterior referencing was used for anteroposterior positioning of the femoral component in both the FBRE and the FBRD group. The P.F.C. Sigma prosthesis (DePuy Orthopaedics, Warsaw, Indiana) was used in both knees of 93 patients, and Attune prosthesis (DePuy Orthopaedics, Warsaw, Indiana) was used in both knees of 78 patients. Surgical technique (including soft tissue release and gap balancing) was identical for both P.F.C. Sigma and Attune knees, except for the fact that, to perform the anterior femoral cut, we used unslotted and slotted cutting blocks in PFC-Sigma and Attune knees, respectively. Cemented implants were used in all patients, and all had resurfacing of the patella in both knees.
Standing full-length (hip to ankle) weight-bearing radiographs were obtained in all patients, and the degree of coronal knee deformity or HKA angle was determined before and after surgery.

**Incidence and depth of notching**
Post-surgery lateral knee radiograph was obtained in all patients, and notching, if present, was documented and its depth measured as the perpendicular distance from anterior cortex line to the point where the anterior resection surface abutted the implant (Figs. 4, 5, 6). Notch depth was assessed by a second observer and by the first observer at an interval of minimum 2 weeks from the date of initial assessment, to evaluate inter-observer and intra-observer variability. The following comparisons were done.

a) Incidence and depth of notching were compared between FBRE and FBRE groups, in overall patients and in subset of patients with PFC-Sigma and Attune implants.

b) Incidence and depth of notching were compared between patients with PFC-Sigma and Attune implants, within the FBRD and FBRE groups.

c) Influence of severity of anterior bowing (mild versus severe) on notching was studied in FBRD limbs, where the femoral component sagittal positioning was planned perpendicular to SMX, regardless of the severity of anterior bowing. As the DCA values of FBRD limbs were not available, comparison of incidence and depth of notching within the FBRD limbs was done, based on the DCA values of the contralateral (FBRE) limbs. Our assumption that the DCA values do not differ significantly between the right and left lower limbs was based on the study by Chung et al. [3]. Femur anterior bowing was classified as mild or severe, if the DCA value was ≤3° or >3°, respectively.

**Knee flexion and Knee Society Score (KSS)**
Active knee flexion was measured using a goniometer with the patient in supine position. Clinical and functional assessment was done using the KSS (Insall, 1989), which is divided into two sections: a clinical knee score (Knee Society Knee Score, KSKS) and a function score (Knee Society Function Score, KSFS). Knee flexion, KSKS and KSFS were documented before surgery and at two years post-surgery.

**Anterior knee pain (AKP) and femoral component size**
At two years post-surgery, patients who had AKP were asked to record pain scores on a visual analogue scale ranging from 0 to 100. The sagittal size of the femoral component initially suggested by navigation and the one chosen finally (after downsizing, because of mediolateral overhang) was noted in all patients.
Loosening and other complications
Weight-bearing anteroposterior and lateral knee radiographs were obtained in all patients two years post-surgery and were scrutinised for radiolucent lines and signs of loosening. Patients were also scrutinised for complication of notching and navigated TKA, such as periprosthetic fracture, pin site fracture, pin tract infection, surgical site infection, etc., until two years post-surgery. All radiographs were obtained by an experienced technician and uploaded using a computerised imaging system.
system linked to a picture archiving and communication system (PACS). Radiographic images were analysed and measured using ImageJ image processing and analysis software version 1.41 (National Institutes of Health, Bethesda, MD, USA).

Statistical analysis
Based on literature [12], the actual number of patients required for our study with the precision/absolute error at 10% and at 95% confidence interval, for a power of 80%, was estimated to be 54. Intra-class correlation estimates and their 95% confident intervals were calculated for intra-observer variability with mean-rating ($k = 2$), two-way mixed-effects model. Spearman's correlation was used as a measure of inter-rater reliability. Comparison of notch depth, HKA angle, knee flexion, KSFS and KSKS was done using independent t-test. Fisher’s exact test was used to compare the incidence of notching and AKP. A $p$-value of $< 0.05$ was taken to be statistically significant. Data were statistically evaluated with IBM SPSS Statistics for Windows, version 22.0. (IBM Corp., Chicago, IL).

Results
Patient demographics
Complete data of 171 patients were available for analysis. Mean age of patients at the time of surgery was 66.5±8.5 years (range 44–89 years). There were 60 (35.1%) male and 111 (64.9%) female patients. Mean body mass index was 29±4 kg/m² (range 21.2–45.4 kg/m²).

Intra-observer and inter-observer variability
There was good test–retest reliability and strong, positive agreement between two observers on notch depth for the knees in FBRD and FBRE groups and the intra-observer and inter-observer agreements were statistically significant (Table 2).

DCA of FBRE limbs
Out of 171 FBRE limbs, the DCA calculated by the computer was between 0.1–2.0°, 2.1–4.0°, 4.1–6.0° and 6.1–8.0° in 65 (38%), 47 (27.5%), 17 (9.9%) and 10 (6.0%) limbs respectively, and the mean DCA was 2±1.7° (range 0–7°).

Incidence and depth of notching
Comparison of incidence and depth of notching between the FBRD and FBRE groups, in overall patients and in subset of patients with PFC-Sigma and Attune implants, are summarised in Table 3. Notch depth of >3 mm occurred in 1.17% (2/171) knees in the FBRD group and in none of the 171 knees in the FBRE group. The incidence and mean depth of notching were significantly higher in FBRD limbs when the contralateral (FBRE) limbs had severe anterior bowing, i.e. DCA >3° (Table 4).

HKA angle, knee flexion, KSFS and AKP
Comparison of mean HKA angle, knee flexion, KSFS, and KSFS between the FBRE and FBRD groups, both before and after surgery, is summarised in Table 5. Mean knee flexion improved from 128.8±12.9° before surgery to 133.5°±10.6° two years after surgery in the FBRD group ($p = 0.0089$) and from 129.3±13.4° before surgery to 133.5°±12.2° two years after surgery in the FBRE group ($p = 0.0037$). Mean KSFS improved from 57.7±5.6 before surgery to 90.7±4.7 two years after surgery in

### Table 3: Comparison of incidence and depth of notching between FBRD and FBRE groups, in overall patients and in subset of patients with PFC-Sigma and Attune implants

| Parameters                  | FBRD group | FBRE group | p-Value |
|-----------------------------|------------|------------|---------|
| Overall patients            | n = 171    | n = 171    |         |
| Incidence of notching       | 34/171 (19.9%) | 12/171 (7%) | 0.0007  |
| Mean notch depth (mm)       | 1.53±0.71  | 0.98±0.53  | 0.009   |
| (R = 0.2–3.3)               | (R = 0.3–2.2) |         |         |
| Patients with PFC-Sigma implant | n = 93  | n = 93    |         |
| Incidence of notching       | 24/93 (25.8%) | 10/93 (10.8%) | 0.0128  |
| Mean notch depth (mm)       | 1.58±0.76  | 1.07±0.53  | 0.035   |
| (R = 0.2–3.3)               | (R = 0.6–2.2) |         |         |
| Patients with Attune implant | n = 78    | n = 78    |         |
| Incidence of notching       | 10/78 (12.8%) | 2/78 (2.6%) | 0.0315  |
| Mean notch depth (mm)       | 1.41±0.58  | 0.55±0.35  | 0.0934  |
| (R = 0.5–2.2)               | (R = 0.3–0.8) |         |         |

**FBRD**: femur anterior bowing registration disabled; **FBRE**: femur anterior bowing registration enabled; **mm**: millimetre; **n**: number of knees; **R**: range

*p < 0.05* is considered statistically significant (bold)
the FBRD group ($p < 0.001$) and from $57.3 \pm 5.2$ before surgery to $91.7 \pm 4$ two years after surgery in the FBRE group ($p < 0.001$). Similarly, mean KSFS improved from $50.8 \pm 5.8$ before surgery to $91.7 \pm 4.8$ two years after surgery ($p < 0.001$) in both the FBRE and the FBRD group.

The incidence of AKP was less in the FBRE than in the FBRD group, i.e. $11.1\%$ (19/171) versus $16.4\%$ (28/171), but the difference was not significant ($p = 0.2086$).

**PFC-Sigma versus Attune knees**

Basic demographics of patients with PFC-Sigma and Attune implants and comparison of means of various parameters between PFC-Sigma and Attune knees within FBRD and FBRE groups, both before and after surgery, are summarised in Table 6.

**Femoral component sagittal size**

In 32/171 (18.7%) patients, the computer suggested one sagittal-size-bigger femoral component for the knees in the FBRD group, compared with that in the FBRE group. Out of these 32 knees in the FBRD group, one sagittal-size-smaller component was used in 15 knees (to avoid mediolateral overhang). A femoral component with same sagittal size, as recommended by the computer, was used in the rest of the 156 knees of the FBRD group and in all 171 knees of the FBRE group. Within the FBRD group, the incidence of notching was not significantly high ($p = 0.5021$) in the 15 knees, where one sagittal-size-smaller femoral component was used, in comparison with that in the rest of the 156 knees, where the same sagittal size component as recommended by the computer was used, i.e. $4/15$ (26.7%) versus $30/156$ (19.2%).

**Loosening and other complications**

None of the knees showed progressive radiolucent lines or loosening in the postoperative radiographs at two years post-surgery. Supra-condylar fracture occurred one year post-surgery in one of the knees of the FBRD group which had notching (Fig. 7). The fracture was treated by open reduction and internal fixation, and the patient recovered uneventfully. One patient who developed deep
infection 3 weeks after surgery in the FBRE group was treated by debridement and exchange of polyethylene insert and recovered completely. None of the knees had navigation-related complications such as pin tract infection or pin site fracture.

Discussion

Optimal positioning of the femoral component in the sagittal plane has not yet been defined [13, 14]. Surgeons using navigation, for sagittal positioning of femoral component, continue to make the distal femoral cut perpendicular to SMX [8, 9], although studies have shown that this can increase the risk of notching in navigated TKA [6, 12]. The present study intends to determine, by opting to place the femoral component perpendicular to DCX rather than perpendicular to SMX, if one can reduce the incidence and depth of notching in navigated TKA.

In our study, the incidence of notching was 19.9% in the FBRD group. Similarly, Lee et al. [12] showed that, when the distal femoral cut was made perpendicular to the SMX, the incidence of notching was 16.7% in navigated TKA. In our study, 7% of knees had notching in the FBRE group, and we believe cutting error could be a reason for the notching seen in these knees [15, 16]. Notching was significantly less ($p = 0.0364$) in Attune knees compared with PFC-Sigma knees in the FBRD group, and the difference was nearing significance ($p = 0.0674$) in the FBRE group. We used anterior referencing for both Attune

Table 6 Basic demographics of patients with PFC-Sigma and Attune implants and comparison of means of various parameters between PFC-Sigma and Attune knees within FBRD and FBRE groups, both before and after surgery

| Parameters | PFC-Sigma implant | Attune implant | p-Value |
|------------|-------------------|----------------|--------|
| Total number of patients | 93 | 78 | |
| Males | 35 (37.6%) | 25 (32.1%) | 0.5206 |
| Females | 58 (62.4%) | 53 (67.9%) | |
| Age (years) | 65.8 ± 8.6 (44–83) | 67.5 ± 8.5 (50–89) | 0.1867 |
| BMI (kg/m²) | 28.9 ± 3.5 (21.2–40.2) | 29.2 ± 4.5 (21.9–45.4) | 0.6503 |
| FBRD group (before surgery) | n = 93 | n = 78 | |
| HKA angle (degrees) | 167 ± 8.5 (150.8–189.1) | 166 ± 7.6 (150.3–182) | 0.4473 |
| Knee flexion (degrees) | 128.4 ± 13.6 (100–155) | 129.2 ± 12 (100–154) | 0.6888 |
| KSFS | 57.5 ± 5.8 (45–69) | 57.9 ± 5.5 (45–68) | 0.5822 |
| FBRE group (before surgery) | n = 93 | n = 78 | |
| HKA angle (degrees) | 167.3 ± 8.2 (153.2–190.5) | 165.9 ± 7.8 (151.4–183.8) | 0.2669 |
| Knee flexion (degrees) | 128.6 ± 13.3 (100–158) | 130.2 ± 13.5 (94–155) | 0.4288 |
| KSFS | 57 ± 5.1 (44–66) | 57.6 ± 5.2 (46–68) | 0.4378 |
| Incidence of notching | 19 (20.4%) | 9 (11.5%) | 0.1475 |
| FBRE group (after surgery) | n = 93 | n = 78 | |
| HKA angle (degrees) | 179.4 ± 1.9 (175.1–185.6) | 179.4 ± 1.5 (176.5–183) | 0.8581 |
| Knee flexion (degrees) | 128.9 ± 10.9 (100–154) | 132.2 ± 10.1 (102–155) | **0.0406** |
| KSFS | 90.3 ± 4.7 (80–99) | 91.1 ± 4.7 (82–99) | 0.2498 |
| Incidence of notching | 24 (25.8%) | 10 (12.8%) | **0.0364** |
| Incidence of AKP | 19 (20.4%) | 9 (11.5%) | 0.1475 |
| FBRD group (after surgery) | n = 93 | n = 78 | |
| HKA angle (degrees) | 179 ± 1.8 (175.2–183) | 179.3 ± 1.7 (176.3–183.6) | 0.2038 |
| Knee flexion (degrees) | 131.7 ± 11.9 (94–157) | 135.7 ± 12.2 (102–158) | **0.0326** |
| KSFS | 91.2 ± 4.4 (79–99) | 92.3 ± 3.5 (85–99) | 0.0674 |
| Incidence of notching | 10 (10.8%) | 2 (2.7%) | 0.0674 |
| Incidence of AKP | 13 (14%) | 6 (7.7%) | **0.0674** |

Range of parameters is shown within brackets

HKA hip–knee–ankle; KSKS Knee Society Knee Score; KSFS Knee Society Function Score; AKP anterior knee pain; FBRD femur anterior bowing registration disabled; FBRE femur anterior bowing registration enabled; n number of knees

*p < 0.05 is considered statistically significant (bold)
and PFC-Sigma knees, and the anterior flange angle was same (5°) in both implant systems. However, to perform the anterior femoral cut, we used slotted cutting block in Attune and unslotted cutting block in PFC-Sigma knees. Inadvertent lifting of the saw can happen while making the bone cuts in TKA [17] and the propensity to use the saw blade as a lever is high, when an unslotted cutting block is used [18]. This could have increased the cutting error and, therefore, the incidence of notching in PFC-Sigma knees. Ajuied et al. [18] showed that, in the hands of an experienced orthopaedic surgeon, the mean tibial sagittal plane cutting error was significantly high when unslotted versus slotted cutting block was used, i.e. 0.74° ± 0.40° versus 0.67° ± 0.23°, and similarly, on the femoral side, although the difference was not significant, the mean sagittal plane cutting error was high when unslotted versus slotted cutting block was used, i.e. 1.5° ± 0.29° versus 1.2° ± 0.36°. Also, Love et al. [16] showed that deliberate lifting of the saw blade or using unslotted cutting block can cause significant sagittal plane cutting error in TKA.

In our study, mean notch depth was 1.53 ± 0.71 mm for the knees in the FBRD group, whereas in the study by Lee et al. [12] > 3 mm notching was seen in at least 9% (7/78) of their navigated TKAs. While we used anterior referencing, in the latter study [12] the authors used posterior referencing, and this could be the reason for the differences in the results between the two studies.

To the best of our knowledge, the current study is the first to evaluate the influence of severity of anterior bowing on notching in TKA. The incidence and mean depth of notching were significantly higher in FBRD limbs when the contralateral limbs had severe anterior bowing, i.e. DCA > 3° (Table 4). Chung et al. [3] measured the DCA of right and left femurs from their true lateral radiograph in 100 adults, and showed that that there was no significant difference in the mean angles (p = 0.675) between the sides, i.e. 2.9° ± 1.9° versus 3.0° ± 1.8°, respectively. Also, in their study, more than 2° difference in DCA between the sides was seen in only 6% of subjects.

Past studies show that surgeons have aimed to position the femoral component within 3° [10] or 5° flexion [11] with respect to the SMX, while using navigation. However, in 19.9% (34/171) of knees the DCA was > 3°, and in 3.5% (6/171) of knees it was > 5°, in the FBRE group in our study. Therefore, in theory, flexing the femoral component up to 3° or 5° with respect to the SMX may still not be adequate to avoid notching in knees with DCA > 3° or > 5°, respectively. The maximum DCA recorded in our study was 7°. Similarly, a maximum DCA of 7.2° and 8.5°
was recorded in the studies by Bao et al. [2] and Chung et al. [3], respectively.

In the present study, the mean knee flexion was significantly higher for the knees in the FBRE group compared with that in the FBRD group at two years post-surgery. Further, within FBRD and FBRE groups, the mean knee flexion was significantly high in Attune knees compared with PFC-Sigma knees at two years post-surgery. Antony et al. [20] showed that there was a positive correlation between the femoral component sagittal angle and the knee flexion, and Song et al. [21] in their study of 600 TKAs showed that Attune knees had better range of motion in comparison with PFC-Sigma knees.

In our study, mean KSKS was significantly higher for the knees in the FBRE group compared with that in the FBRD group at two years post-surgery. Further, mean KSKS was higher for Attune knees compared with PFC-Sigma knees in the FBRE group, and this difference was nearing significance \((p = 0.0674)\) at two years post-surgery. Similarly, studies have shown that, with flexed femoral component, the quadriceps moment arm increases, resulting in improved KSFS in TKA [22, 23], and different authors [21, 24] have shown favourable clinical results with Attune knees in comparison with those with PFC-Sigma knees.

Although insignificant \((p = 0.2086)\), the incidence of AKP was high in the FBRD versus FBRE group, i.e. 16.4% versus 11.1% at two years post-surgery, in the present study. Scott et al. [25] showed that femoral component extension of \(\geq 0.5^\circ\) predicted AKP with 87% sensitivity, and Kang et al. [26] concluded that, in comparison with the extended condition, a neutral-to-mild flexed femoral component decreased the patella-femur contact stress, which may contribute to decreasing the AKP in TKA. Similarly, although insignificant \((p = 0.1475\) and 0.228), the incidence of AKP was less in Attune versus PFC-Sigma knees in both the FBRD and the FBRE group in our study. Similarly, past studies [27, 28] have shown that the incidence of AKP was less in patients with Attune implant in comparison with that in patients with PFC-Sigma implant.

In 32 out of 171 patients, the computer suggested one sagittal-size-bigger femoral component for the knees in the FBRD group, compared with that in the FBRE group in the current study. Nakahara et al. [29] showed that a 3° and a 5° extension of the distal femoral cut increased the sagittal femoral diameters by 2 and 3 mm, respectively, whereas a 3° and a 5° flexion of the distal cut decreased the sagittal diameter by 2 and 3 mm, respectively. Within the FBRD group, the incidence of notching was not significantly higher in the 15 out of total 171 knees, where one sagittal-size-smaller femoral component (as compared with the one recommended by the computer) was used, and this is understandable as we used anterior referencing for anteroposterior positioning of the femoral component in all knees in the present study.

In our opinion, registration of DCX is neither technically demanding nor time consuming (takes a few seconds), and although not within the scope of the current study, we believe that this additional step may have no noticeable impact on the learning curve involved in computer-assisted TKA. While flexed femoral component avoids notching [5] and helps in improving functional outcome [22, 23], excessive flexion of the component can cause tibial post-impingement [26], and this is design dependent [30]. However, when it comes to conventional TKA, Banks et al. [31] showed that neutral placement is biased by an average 10° of hyperextension between femoral and tibial components, secondary to the anterior femoral bowing and posterior tibial slope.

Our study has certain limitations. We used gap balancing technique in which the femoral component can be more externally rotated [32], and this can increase the risk of notchling [6]. Further, soft tissue release can influence femoral component rotation in gap balancing technique [33]. Femoral component rotational alignment was not assessed in the present study. However, the mean pre- and post-operative HKA angles were not significantly different between the FBRD and FBRE groups, and we used the same soft tissue release technique in all knees. Therefore, it is unlikely that our technique would have influenced the final outcome of the present study. Although notch depth can be accessed more accurately using 3D computer topography (CT) scan, we used radiographs for these measurements as they are easily available and are cost-effective, not to mention the risk of radiation involved in 3D CT scanning of both knees. Further there was good test–retest reliability and strong agreement between two observers for notch depth in our study.

Conclusion

The present study shows that, irrespective of the implant used (PFC-Sigma or Attune), by opting to position the femoral component perpendicular to DCX rather than perpendicular to SMX, notching can be reduced in navigated TKA. Surgeons using navigation should be cautious when they suspect significant anterior bowing, as the risk of notchling was very high (61.8%) in the FBRD group when the contralateral limbs had severe anterior bowing \((DCA > 3^\circ)\). Further, in such cases, surgeons should consider an implant which allows maximal hyperextension between components, to avoid cam-post impingement.
Prosthesis manufacturers should consider future designs which can accommodate more hyperextension, to deal with populations where severe bowing is not uncommon.

Abbreviations
DCX: Distal femur anterior cortex axis; SMX: Sagittal mechanical axis of femur; TKA: Total knee arthroplasty; FBRE: Femur bowing registration enabled; FBRO: Femur bowing registration disabled; DCA: Distal anterior cortex angle; HKA: Hip–knee–ankle; KSS: Knee Society Score; KSFS: Knee Society Knee Score; KSF: Knee Society Function Score; AKP: Anterior knee pain; PACS: Picture archiving and communication system.

Acknowledgements
Not applicable.

Authors' contributions
Clinical data analysis and interpretation: RK, CR, GMS. Drafting of the manuscript: RK, CR. Measuring of data: RK, GMS. Approval of final manuscript: all authors.

Funding
None.

Availability of data and materials
All data generated or analysed during this study are included in this published article.

Declarations

Ethics approval and consent to participate
The study was approved by the institutional review board and ethics committee of the hospital. Informed consent was obtained from all the patients.

Consent for publication
Not applicable.

Competing interests
The authors admit that there is no conflict of interest pertaining to this article.

Author details
1Department of Orthopaedic Surgery, Prashanth Super Specialty Hospital, Velachery Main Road, Chennai 600042, India. 2Knee & Orthopaedic Clinic, Mumbai, India. 3AIMD Research, Mumbai, India.

Received: 16 May 2021 Accepted: 8 December 2021
Published online: 24 December 2021

References
1. Schmutz B, Kmiec S Jr, Wulsschleger ME, Altmann M, Schuetz M (2017) 3D computer graphical anatomy study of the femur: a basis for a new nail design. Arch Orthop Trauma Surg 137(3):321–331. https://doi.org/10.1007/s00402-016-2621-7
2. Bao Z, Qiao L, Qin J, Xu J, Zhou S, Chen D et al (2017) The assessment of femoral shaft morphology in the sagittal plane in Chinese patients with osteoarthritis—a radiographic analysis. J Orthop Surg Res 12(1):127. https://doi.org/10.1186/s13018-017-0626-5
3. Chung BJ, Kang YG, Chang CB, Kim SJ, Kim TK (2009) Differences between sagittal femoral mechanical and distal reference axes should be considered in navigated TKA. Clin Orthop Relat Res 467(9):2403–2413. https://doi.org/10.1007/s11999-009-0762-5
4. Tang WM, Chiu KY, Kwan MF, Ng TP, Yau WP (2005) Sagittal bowing of the distal femur in Chinese patients who require total knee arthroplasty. J Orthop Res 23(1):41–45. https://doi.org/10.1016/j.jor.2004.06.015
5. Ko JH, Han CD, Shin KH, Nguku L, Yang IH, Lee WS et al (2016) Femur bowing could be a risk factor for implant flexion in conventional total knee arthroplasty and notching in navigated total knee arthroplasty. Knee Surg Sports Traumatol Arthrosc 24(8):2476–2482. https://doi.org/10.1007/s00167-015-3863-6
6. Minoda Y, Watanabe K, Iwaki H, Takahashi S, Fukui M, Nakamura H (2013) Theoretical risk of anterior femoral cortex notching in total knee arthroplasty using a navigation system. J Arthroplasty 28(8):1533–1537. https://doi.org/10.1016/j.arthro.2013.02.015
7. Chen X, Wang H, Cai Y, Zhu Q, Zhu J (2014) Sagittal component alignment is less reliable than coronal component alignment in a Chinese population undergoing navigated TKA. J Orthop Surg Res 6(9):51. https://doi.org/10.1186/s13018-014-0051-1
8. Shah MR, Patel JP, Patel CR (2020) Optimal flexion for the femoral component in TKR: a study of angle between mechanical axis and distal anatomic intramedullary axis using 3D reconstructed CT scans in 407 osteoarthritic knees studied in India. Indian J Orthop 54(5):624–630. https://doi.org/10.1007/s14435-020-00106-6
9. Shah SM, Sciberras NC, Allen DJ, Picard F (2019) Technical and surgical causes of outliers after computer navigated total knee arthroplasty. J Orthop 6(18):171–176. https://doi.org/10.1016/j.jor.2019.10.016
10. Cozzi Lepri A, Innocenti M, Matassa F, Villano M, Civinini R, Innocenti M (2019) Accelerometer-based navigation in total knee arthroplasty for the management of extra-articular deformity and retained femoral hardware: analysis of component alignment. Joints 7(1):1–7. https://doi.org/10.1055/s-0039-1697610
11. Jung SH, Cho MR, Song SK (2020) Appropriateness of the use of navigation system in total knee arthroplasty. Clin Orthop Surg 12(3):324–329. https://doi.org/10.4055/cios19159
12. Lee JH, Wang SI (2015) Risk of anterior femoral notching in navigated total knee arthroplasty. Clin Orthop Surg 7(2):217–224. https://doi.org/10.4055/cios.2015.7.2.217
13. Minoda Y, Kobayashi A, Iwaki H, Ohashi H, Takaoka K (2009) TKA sagittal alignment with navigation systems and conventional techniques vary only a few degrees. Clin Orthop Relat Res 467(4):1000–1006. https://doi.org/10.1007/s11999-008-4493-9
14. Ou YL, Li PY, Xia H (2020) Optimal sagittal insertion depth and direction of femoral intramedullary rod in total knee arthroplasty in Chinese osteoarthritis patients. Orthop Surg 12(4):1238–1244. https://doi.org/10.1111/os.12753
15. Chua KH, Chen Y, Lingaraj K (2014) Navigated total knee arthroplasty: is it error-free? Knee Surg Sports Traumatol Arthrosc 22(3):643–649. https://doi.org/10.1007/s00167-013-2641-6
16. Love GJ, Kinninmonth AW (2013) Training benefits of computer navigated total knee arthroplasty. Knee 20(4):236–241. https://doi.org/10.1016/j.knee.2012.09.012
17. Macdonald DJ, Clarke JV, Kinninmonth AWG (2011) Teaching benefits of navigation—a trainee’s perspective. Orthop Proc. 93:387–387
18. Ajued A, Smith C, Carlos A, Back D, Earnshaw P, Gibb P et al (2015) Saw cut accuracy in knee arthroplasty—an experimental case–control study. J Arthritis 4:144. https://doi.org/10.4172/2167-7921.1000144
19. Culp RW, Schmidt RG, Hanks G, Mak A, EstehaJI (1987) Supracondylar fracture of the femur following prosthetic knee arthroplasty. Clin Orthop 222:212–222
20. Antony J, Tetsworth K, Hohmann E (2017) Influence of sagittal plane component alignment on kinematics after total knee arthroplasty. Knee Surg Sports Traumatol Arthrosc 25(8):1686–1691. https://doi.org/10.1007/s00167-016-4098-x
21. Song SJ, Kang SG, Park CH, Bae DK (2018) Comparison of clinical results and risk of patellar injury between Attune and PFC Sigma knee systems. Knee Surg Relat Res 30(4):334–340. https://doi.org/10.5792/krr.18.020
22. D’Lima DD, Poole C, Chadha H, Hermida JC, Mahar A, Colwell CW Jr (2001) Quadriceps moment arm and quadriceps forces after total knee replacement with both prostheses in opposite knees. J Orthop Surg Res 6:18. https://doi.org/10.1186/s13018-000-00026
23. Fantozzi S, Catani F, Ensini A, Leardini A, Giannini S (2006) Femoral rollback of cruciate-retaining and posterior-stabilized total knee replacements: in vivo fluorescent analysis during activities of daily living. J Orthop Res 24(12):2222–2229. https://doi.org/10.1002/jor.20306
24. Carey BW, Harty J (2018) A comparison of clinical- and patient-reported outcomes of the cemented ATTUNE and PFC Sigma fixed bearing cruciate sacrificing knee systems in patients who underwent total knee replacement with both prostheses in opposite knees. J Orthop Surg Res 13(1):54. https://doi.org/10.1186/s13018-017-0575-6
25. Scott CEH, Clement ND, Yapp LZ, MacDonald DJ, Patton JT, Burnett R (2019) Association between femoral component sagittal positioning and anterior knee pain in total knee arthroplasty: a 10-year case–control follow-up study of a cruciate-retaining single-radius design. J Bone Joint Surg Am 101(17):1575–1585. https://doi.org/10.2106/jbjs.18.01096

26. Kang KT, Koh YG, Son J, Kwon OR, Park KK (2019) Flexed femoral component improves kinematics and biomechanical effect in posterior stabilized total knee arthroplasty. Knee Surg Sports Traumatol Arthrosc 27(4):1174–1181. https://doi.org/10.1007/s00167-018-5093-1

27. Huang YF, Gao YH, Ding L, Liu B, Liu JG, Qi X (2020) Influence of femoral implant design modification on anterior knee pain and patellar crepitus in patients who underwent total knee arthroplasty without patella resurfacing. BMC Musculoskelet Disord 21(1):364. https://doi.org/10.1186/s12891-020-03391-2

28. Ranawat CS, White PB, West S, Ranawat AS (2017) Clinical and radiographic results of Attune and PFC Sigma knee designs at 2-year follow-up: a prospective matched-pair analysis. J Arthroplasty 32(2):431–436. https://doi.org/10.1016/j.arth.2016.07.021

29. Nakahara H, Matsuda S, Okazaki K, Tashiro Y, Iwamoto Y (2012) Sagittal cutting error changes femoral anteroposterior sizing in total knee arthroplasty. Clin Orthop Relat Res 470(12):3560–3565. https://doi.org/10.1007/s11999-012-2397-1

30. Hamai S, Miura H, Matsuda S, Shimoto T, Higaki H, Iwamoto Y (2010) Contact stress at the anterior aspect of the tibial post in posterior-stabilized total knee replacement. J Bone Joint Surg Am 92(8):1765–1773. https://doi.org/10.2106/jbjs.i.00479

31. Banks SA, Harman MK, Hodge WA (2002) Mechanism of anterior impingement damage in total knee arthroplasty. J Bone Joint Surg Am 84(Suppl 2):37–42. https://doi.org/10.2106/00004623-200200002-00004

32. Moon YW, Kim HJ, Ahn HS, Park CD, Lee DH (2016) Comparison of soft tissue balancing, femoral component rotation, and joint line change between the gap balancing and measured resection techniques in primary total knee arthroplasty: a meta-analysis. Medicine 95(39):e5006. https://doi.org/10.1097/md.0000000000005506

33. Heesterbeek PJ, Jacobs WC, Wymenga AB (2009) Effects of the balanced gap technique on femoral component rotation in TKA. Clin Orthop Relat Res 467(4):1015–1022. https://doi.org/10.1007/s11999-008-0539-2

Publisher’s Note
Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

---

Ready to submit your research? Choose BMC and benefit from:

- fast, convenient online submission
- thorough peer review by experienced researchers in your field
- rapid publication on acceptance
- support for research data, including large and complex data types
- gold Open Access which fosters wider collaboration and increased citations
- maximum visibility for your research: over 100M website views per year

At BMC, research is always in progress.
Learn more biomedcentral.com/submissions