

Differences in trochlear groove based on morphometric measurements of three-dimensional reconstruction models between native knees and five different femoral component designs in Chinese subjects

shi chang chen (✉ chenshch05@126.com)

Batibo District Hospital <https://orcid.org/0000-0002-2228-1769>

Hua Xu

Shanghai Baoshan Hospital of Integrated Traditional Chinese and Western Medicine

Shaohua Gong

Shanghai Baoshan Hospital of Integrated Traditional Chinese and Western Medicine

Research article

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Abstract

Background: The prosthetic trochlear design is important in postoperative patellofemoral kinematics and knee function. However, little research has been conducted on the differences in trochlear groove between native and prosthetic knees. We aimed to investigate the differences between Chinese native knees and prosthetic knees of five different femoral component designs using three-dimensional computerized quantification of the entire trochlear length.

Methods: Virtual total knee arthroplasty was performed using three-dimensional models of 42 healthy Chinese knees matched to the femoral components of five different prosthetic systems by mechanical alignment. The deepest points of the trochlear groove were marked in multiple cross sections for both the native and prosthetic knees. Taking the lower extremity mechanical axis as reference line, the differences in the mediolateral location of the trochlear groove were analyzed between the native and prosthetic knees.

Results: From the proximal to the distal end, the native trochlear groove started from 0° cross section and extended laterally and then medially, with its turning point located at 69° cross section. The prosthetic trochlear groove showed a similar medial orientation and extended more proximally, but varied in mediolateral location and the length extending to the intercondylar notch. Compared with the proximal portion of the native trochlear groove, the prosthetic knees extended along a paradoxical orientation and started from a more proximal and lateral position to 3.2 mm in the 0° cross section, with maximal discrepancy. Distally, the prosthetic trochlear grooves were located significantly medial to 2.4 mm in the 69° cross section, with maximal discrepancy.

Conclusion: The prosthetic trochlear design varied among the different types and did not conform to the native knee in terms of shape, orientation, and location, which may cause soft tissue tension imbalance and abnormal patellofemoral biomechanics during knee flexion. This study may provide useful information for creating prosthetic trochlear designs that conform with the native knee anatomy to optimize patellofemoral biomechanics and reduce the risk of patellofemoral complications.

Background

Despite the current success of total knee arthroplasty (TKA), patellofemoral complications are a common postoperative problem and one of the causes of revision surgery [1]. The bearing geometry and kinematic pattern of different guided-motion prosthetic designs can influence the clinical and functional outcomes and complications of TKA [2,3]. The prosthetic trochlear groove design is considered the main determinant [2-6]. The exact prosthetic morphological parameters vary with respect to the trochlear groove location, groove angle, groove depth, groove length, and condylar height [7-10].

The various characteristics of the femoral trochlear designs of different prosthetic systems have been reported. In a study by Dejour et al., the differences in the trochlear designs of 14 different femoral grooves (0°, 15°, 30°, and 45°), in which the sulcus angle,

trochlear groove orientation, lateral facet height, and mediolateral groove location were evaluated. The study showed that some femoral components exhibit characteristics of trochlear dysplasia [11]. A comparative study of one type of prosthetic femoral component in 21 knees found that the trochlear groove of prosthetic knees was more lateral than that of native knees, while it was medial relative to its position in the native knees [8]. The patellofemoral anatomical morphology changed postoperatively, and the patellar motion followed an unphysiological trochlear groove. Compared with designs with a neutral or symmetrical trochlear groove (a symmetrical groove does not turn medially or laterally), the currently used femoral components with an asymmetrical trochlear groove (“patella-friendly” design, with trochlear grooves that extend more proximally and orient more valgus than the native one) are believed to favor early patella capture and promote patellofemoral stability; however, the physiological patellofemoral kinematics, patellar tracking, and stability have not been provided [5,7,8,12,13]. Some biomechanical studies have shown that when influential factors such as component positioning, alignment, soft tissue balancing, and patellar resurfacing are controlled, the patellofemoral biomechanics is not fully restored to the normal anatomy [8,12].

Ethnic differences in knee morphology have been proven. The Chinese femoral anatomy is different from that of the Caucasian [14,15]. Studies that evaluate the trochlear groove between Chinese subjects and imported prostheses are rare, establishing the need for the present study. We hypothesized that the morphological characteristics of the trochlear groove in Chinese native knees differed from those of imported prosthetic femoral components in terms of shape, orientation, and location.

Methods

Subjects

We collected the data of 42 healthy Chinese adults (11 men and 31 women) from our previous study [16]. This study was approved by the ethical committee of our institute, and informed consent was obtained from all the subjects. The participants had a mean (range) age of 45.8 years (34-57 years), height of 161.4 cm (150-179 cm), body mass index of 23.7 kg/m² (16.5-29.6 kg/m²), and mechanical axis of the lower limb of 179.7° 174.7-184.4°. None of the subjects had experienced a trauma or previous knee surgery, or had a clinical record of osteoarthritis-related knee pain. This was verified with a clinical examination and computed tomography (CT) images.

Five TKA prosthetic systems, namely the Advance Medial-Pivot (MP) Knee System, Advance Stature Knee System (MicroPort Orthopedics Co., Arlington, TN), Triathlon Knee System (Stryker Co., Kalamazoo, MI), NRG Knee System (Stryker Co., Mahwah, NJ), and NexGen Complete Knee Solution (Zimmer Inc., Warsaw, IN), were evaluated in the present study. The Stature femoral component is a morphology-specific knee implant designed based on the standard MP implant and accommodates the femora in men or women with a relatively narrower femoral condyle. For a given anteroposterior dimension, the mediolateral dimension of the Stature femoral component was 5 mm smaller than that of the MP

The 42 subjects were selected from previous database, and had similar distal femur anteroposterior dimensions (the distance between the anterior femoral cortex and the posterior surface of the condyle: 56.9 ± 1.5 mm). Based on the anteroposterior dimension of the distal femur and femoral component [-17], size 3 of the MP (56.5 mm) and Stature (56.1 mm), size 7+ of the Triathlon (57.0 mm) and NRG (55.8 mm), and size E of the NexGen (56.9 mm) most closely matched the sizes of the distal femurs and were evaluated in the present study (Fig. 1).

Data Scanning

Three-dimensional (3-D) knee models were reconstructed using CT images (Light speed 16, GE Medical System, Milwaukee, WI), with a slice thickness of 0.625 mm and resolution of 512×512 pixels. The entire length of the femur was included in the scanned images. A 3-D laser scanner (KLS-171; Kreon Technologies, Limoges, France) was used to create 3-D models of the right femoral metal components. We then introduced the scanned data into the Geomagic Studio 10.0 software (Geomagic, Morrisville, NC, USA) for use in the 3-D reconstruction of the right femur and femoral components.

Virtual Femoral Component Implantation

The femur model was aligned as follows: the mechanical axis was defined as a line connecting the center of the femoral head and the center of the knee (the midpoint of the femoral transepicondylar axis). The coronal plane was parallel to the mechanical axis and was externally rotated at 3° relative to the posterior condylar line. The sagittal plane was perpendicular to the coronal plane and passed through the mechanical axis. The horizontal plane was perpendicular to both the coronal and sagittal planes.

In the coronal plane, the femoral component was aligned perpendicular to the mechanical axis. The rotational alignment of the femoral component was set parallel to the coronal plane. In the sagittal plane, we positioned the femoral component parallel to the anterior cortex of the distal femur [-18]. The femoral component was then shifted as posteriorly as possible, without notching the anterior cortex of the distal femur, and shifted transversely until the mediolateral center of the component reached the sagittal plane. The medial distal surfaces of the femoral components were consistent (Fig. 2).

Measurements and Statistical Analyses

A cylinder was established with its axis parallel to both the coronal and transverse planes, and its radius was adjusted to allow the cylindrical surface to closely fit the trochlear groove; its axis represented the trochlear groove axis. The 0° cutting plane passed through the trochlear groove axis, and parallel to the transversal plane. Then with 3° increments, we created cutting planes that rotated around the trochlear

groove axis toward the proximal (negative direction, negative angle) and distal ends (positive direction, positive angle) of the trochlear groove. We marked the deepest points of the trochlear groove on the surfaces of the native and prosthetic knee models in each cross section (Fig. 3A). The distance (mediolateral location) from the deepest point of the trochlear groove to the mechanical axis was measured. If the point was located at the medial side of the mechanical axis, the value was positive (d); otherwise, the value was negative (-d) (Fig. 3B).

To minimize measurement error, all the measurements were performed by three physicians (CSC, XH, and GSH). CSC and XH measured all the samples first. After an interval of 1 day, GSH measured the samples again. Reliability measurements were assessed using intraclass correlation coefficients (ICCs). The agreement between CSC and XH was good (Cohen's unweighted $\kappa = 0.91$). The agreement between the first measurements and the retest by GSH was also good (Cohen's unweighted $\kappa = 0.93$). All the measurements were demonstrated to be reliable (ICC > 0.90). The CT measurements had a precision value of 0.1 mm.

A paired *t* test was performed to determine if the difference in the mediolateral location of the trochlear groove was significantly different between the native and prosthetic knees. A *p* value of less than 0.05 was considered statistically significant. Based on the mean and standard deviation of the trochlear groove location of recruited subjects, a priori power analysis ($\alpha = 0.05$) indicated that 12 subjects will have >90% power to detect the differences between the native and prosthetic knees. The sample size of the present study was sufficient to detect morphological differences.

Results

For the native trochlear groove, the mean angle span was $-0.3^\circ \pm 6.2^\circ$ to $107.8^\circ \pm 5.3^\circ$ from the proximal to the distal end. For the femoral components of the MP, Stature, Triathlon, NRG, and NexGen prostheses, the angle spans were from -51° to 110° , from -45° to 110° , from -42° to 60° , from -39° to 66° , and from -45° to 78° , respectively. From the proximal to distal end, the native trochlear groove consisted of the laterally oriented proximal portion and medially oriented distal portion, with the turning point located at the 69° cross section.

The prosthetic trochlear groove showed a similar medial orientation and extended more proximally, but varies in the mediolateral location and the length extending to the intercondylar notch. Compared with the proximal portion of the native trochlear groove, the prosthetic knees extended along an opposite orientation with its starting point located more proximal and lateral. Distally, the prosthetic trochlear grooves were still located significantly medial (Fig. 4A). A significant difference in mediolateral location was observed between the native and prosthetic trochlear grooves ($p < 0.05$), except between 27° - 36° (MP and Stature), 18° - 24° (Triathlon and NRG), and 39° - 48° (NexGen) cross sections, respectively. The mean differences in 0° cross section for MP, Stature, Triathlon, NRG, and NexGen were 2.5, 2.0, 2.1, 1.7, and 3.2 mm, respectively; distally, the prosthetic trochlear groove was more medial, and the corresponding mean differences in 60° cross section were 1.8, 1.8, 2.3, 2.4, and 1.2 mm. For Triathlon and NRG, the trochlear

groove was set at 0 mm when the difference in the 69° cross section was analyzed. Furthermore, distally, Triathlon, NRG, and NexGen (the angle spans extended to 60°, 66°, and 78°, respectively) had shorter trochlear grooves than the native knees, and MP and Stature (with angle spans both extended to 110°) showed similar trochlear groove lengths as the native knees.

Discussion

In the present study, the geometry of the trochlear groove in the native and prosthetic knees was evaluated. Our results were consistent with the findings of previous research studies, showing that the native trochlear groove followed a path that could be approximated by two consecutive straight lines, a bilinear approximation, composed of a laterally oriented proximal portion, and a medially oriented distal portion [19,20]. The prosthetic trochlear groove was relatively consistent and smooth among different types, showed a proximal-lateral to distal-medial orientation throughout the length of the trochlea, and had a prolonged proximal part compared to the native knees.

Unlike in TKA with a symmetrical component in which the trochlear groove does not turn medially or laterally, in TKA with an asymmetrical component with a laterally orientated trochlear groove (more parallel to the orientation of the quadriceps force) and asymmetrical trochlear flanges, patellar “capture” and a more stable and physiological patellar tracking could be expected during the early stage of flexion (0°-30°; the supracondylar pouch/anterior flange) [5,7,12,21]. However, both symmetrical and asymmetrical TKAs have altered physiological patellofemoral kinematics. When compared with a symmetrical prosthesis, the asymmetrical component did not provide better patellar stability and improvement in the non-physiological tracking of the patella [5,12]. This indicated that the groove of the prosthetic trochlea may still be different from that of the normal trochlea [7,8].

In the present study, when compared with the proximal portion of the native trochlear groove, the prosthetic trochlear groove extended along an opposite orientation, with its starting point located more proximal and lateral, with maximal discrepancy of 3.2 mm in the 0° cross section. One limitation of the present study was that it was based on CT-scanned knee models that neglected the geometry of the articular cartilage. Although the difference in the location between the osseous and cartilaginous grooves was small (<1 mm) [22], the effect of the articular cartilage on the morphology of the trochlear groove should not be neglected. Previously, Varadarajan et al. compared the trochlear groove morphology of NexGen cruciate retaining femoral components and 21 knee models, including the bone and articular cartilage, using virtual TKA. Proximally, between 43.5% and 58.7% of the trochlear length, the prosthetic groove was more lateral than the native trochlear groove (difference, 0.6–3.5 mm; mean, 2.0 mm; $p < 0.034$) [8]. The study of Stoddard et al. on TKA fresh-frozen knees with a resurfaced patella showed that the asymmetrical design (Triathlon) did not provide more anatomical patellar kinematics and stability than the symmetrical design [12]. The researchers found that soft tissue had an overriding influence, and the patella was disengaged from the trochlea by the medial patellofemoral ligament in the native knee near extension [12,23]. Thus, the prosthetic patellar initial position and engagement area might differ

from those of the native patella, which might affect early stage patellar tracking and contribute to changes in the patellofemoral kinematics after TKA [12,24].

Patellar tracking and patellofemoral kinematics could be affected by changes in the groove location after TKA [25,26]. During knee flexion, a patellar medial shift might lead to patellar periphery soft tissue imbalance and patellar lateral tilt, which may cause pain impingement on the lateral edge of the trochlea (in the case of a non-resurfaced patellar) and a laterally directed force on the patella [27,28]. A biomechanical study by Barink et al. showed that an unsurfaced TKA patella was significantly displaced at high flexion angles, by approximately 3 mm more medially at 80°-90° of flexion, compared with the intact knees [5]. In the present study, the distal trochlear groove of the prosthetic knees was more medial than that of the native knees, with a maximal discrepancy of 2.4 mm at the 69° cross section. Individual variability should be taken into account in prosthetic designs. The standard deviation of the native knee measurements can be regarded as the trochlear groove variability between the different subjects [7]. Besides, the mediolateral position of the femoral and patellar button and how the surgeon should judge the best mediolateral position may also affect the groove position and patellar tracking [12,25].

In the present study, distally, Triathlon, NRG, and NexGen (the angle spans extended to 60°, 66°, and 78°, respectively) had shorter trochlear grooves than the native knees, MP and Stature (with both angle spans extended to 110°) showed similar trochlear groove length as the native knees. Femoral components with a shorter trochlea appear to have increased incidence of patellar clunk syndrome, which has been associated with posterior stabilized TKA [29-31]. In the study of Maloney et al., the prevalence of patellar clunk was 3.9% in 179 consecutive patients who underwent Insall-Burstein II posterior stabilized TKA. With a longer trochlear groove extended distally, no patellar clunk developed in the patients with Advanced posterior stabilized TKA [29]. In a recently published series, an incidence of 2.76% was observed with a modern posterior stabilized implant, whereas an incidence of 6% was found with the use of a different posterior stabilized design [31]. Lengthening the trochlea groove distally makes it more difficult for a nodule to develop and become entrapped [29]. Additionally, patella baja or alta, abnormal patellar tracking, anterior placement of the tibial tray, and increased degree of postoperative knee flexion have also been associated with the development of patellar clunk syndrome [31,32].

The knee joint is a well-balanced system, and good function relies on coordination and cooperation of the femur, tibia, patella, and soft tissue during dynamic motion. A main limitation of the study was the static analysis of the femoral trochlea was performed separately. The present study did not provide evidence to support the use of one prosthetic design over another but showed the differences of the trochlear groove between various prosthetic systems and between the native and prosthetic knees. Owing to the sensitivity of ligaments and tendons to applied tensile loads such that stretching of these structures at very low loads may induce major changes in the response of their sensory receptors [33], better patellofemoral function may be expected from a femoral component designed with physiological values of the trochlear groove; however, further studies are needed. Another limitation was that physiological features (e.g. the width and height of the lateral and medial femoral condylar facets, and the trochlear bisector angle),

osthesis and patellofemoral kinematics were not evaluated

[8,11]. Further studies are needed to explore these parameters. Third, only a relatively small sample of Chinese subjects and implants were recruited for this study; thus, the results might not be generalizable.

Conclusions

Our study revealed variations in trochlear design parameters among different types, and the current prosthetic trochlear design does not conform to the native knee. The prosthetic trochlear groove was different from the native trochlear groove in terms of shape, orientation, and location, which may cause soft tissue tension imbalance during knee flexion and lead to abnormal patellofemoral biomechanics. This study may be useful for the development of a prosthetic trochlear design that conforms with the native anatomy to optimize patellofemoral biomechanics and decrease the risk of patellofemoral complications.

Abbreviations

TKA: Total knee arthroplasty; CT: Computed tomography; MP: Medial-Pivot

Declarations

Ethics approval and consent to participate

This study was approved by the ethics committee of Shanghai Baoshan Hospital of Integrated Traditional Chinese and Western Medicine, and written informed consent for participation was obtained from all subjects.

Consent to publish

Not applicable.

Availability of data and materials

The dataset used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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No funding was obtained for this study.

Authors' contributions

CC designed the study, performed the measurements, analyzed the data, and wrote and revised the manuscript. HX designed the study, performed the measurements, and reviewed the manuscript. SG designed the study, performed the measurements, and reviewed the manuscript. All authors read and approved the final manuscript.

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Author details

Department of Orthopaedics Surgery, Shanghai Baoshan Hospital of Integrated Traditional Chinese and Western Medicine, 181 YouYi Road, Shanghai 201999, China.

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Figures

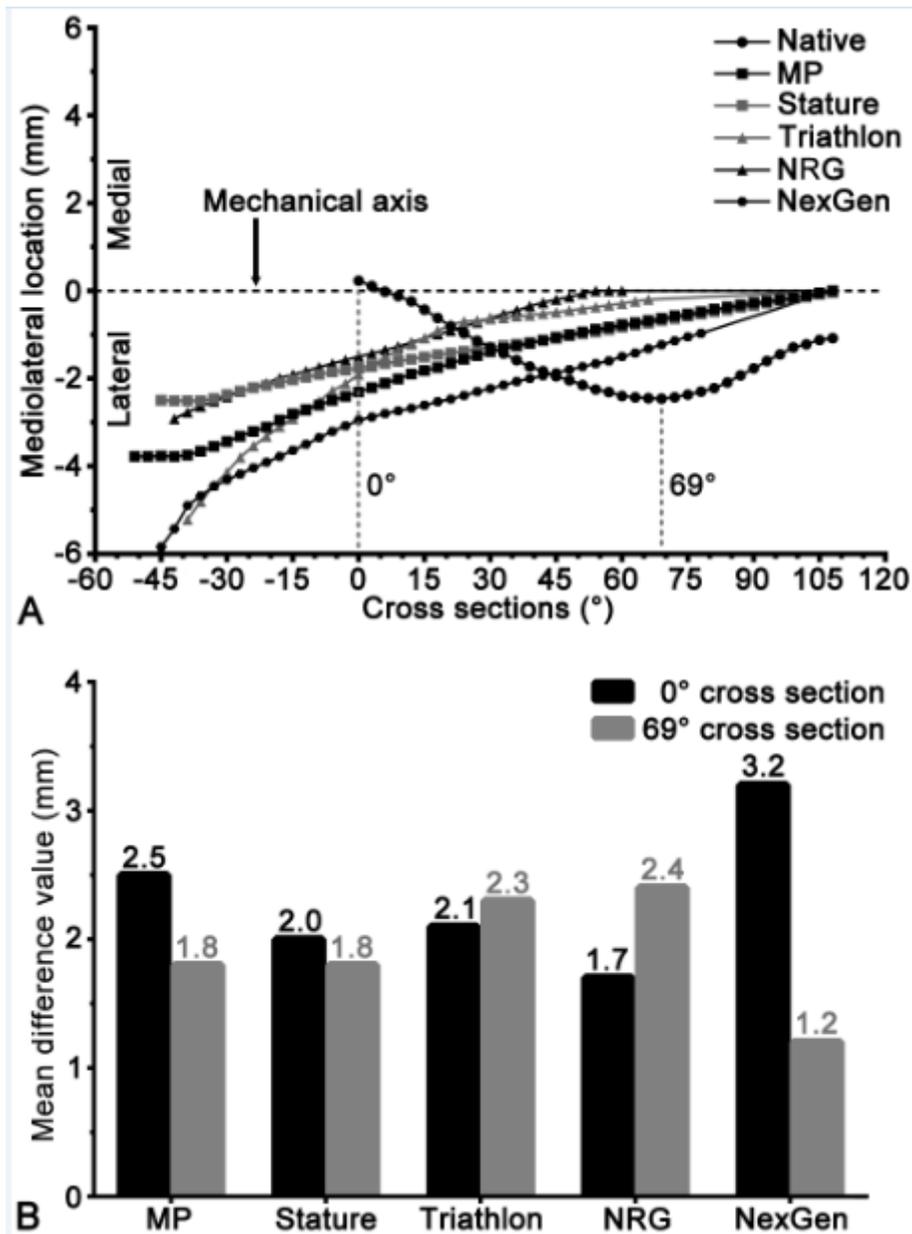


Figure 1

Differences of the trochlear grooves between the native and prosthetic knees. A. Difference in the mediolateral location of the entire trochlear groove length between the native and prosthetic knees. B. Mean difference in the mediolateral location between the native and prosthetic knees in the 0° and 69° cross sections

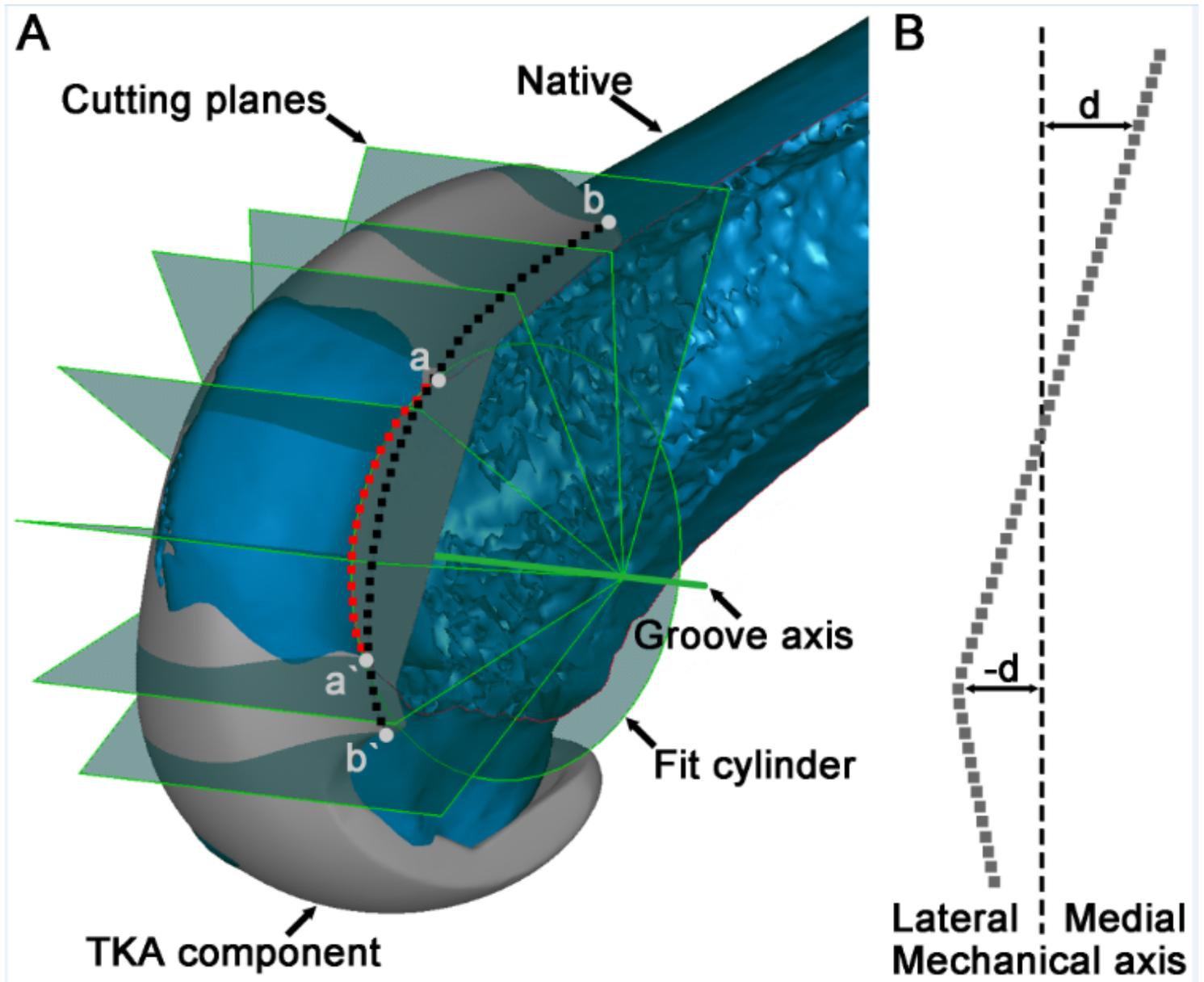


Figure 2

The cutting planes and measurement of the mediolateral location of the trochlear groove. A. A cylinder was established to allow the cylindrical surface to closely fit the trochlear groove; its axis represented the trochlear groove axis. Cutting planes rotating around the trochlear groove axis were created throughout the arc of the groove, with 3° increments. The red and black dash lines indicate native and prosthetic trochlear grooves, respectively. Dots *a* and *b* indicate the proximal ends of the native and prosthetic trochlear grooves, respectively; dots *a'* and *b'* indicate the distal ends of the native and prosthetic trochlear grooves, respectively. B. A positive *d* value (*d*) indicates that the point was located at the medial

side of the mechanical axis; a negative d value (-d) indicates that the point was located at the lateral side of the mechanical axis

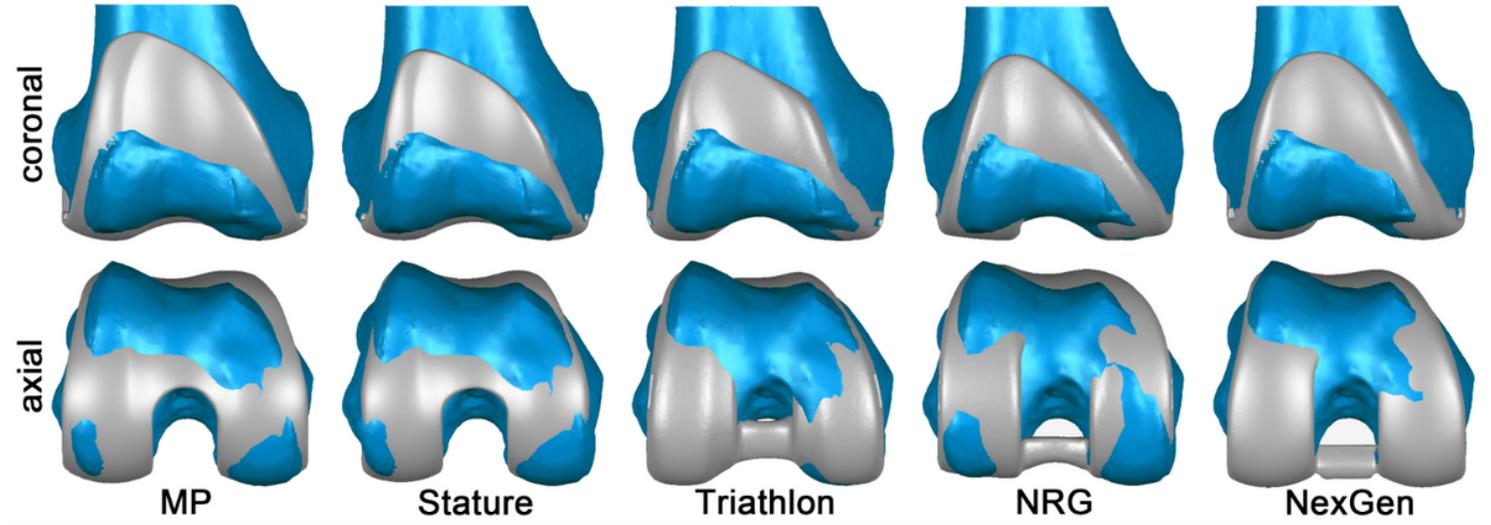


Figure 3

Coronal and axial views of the knee after virtual total knee arthroplasty

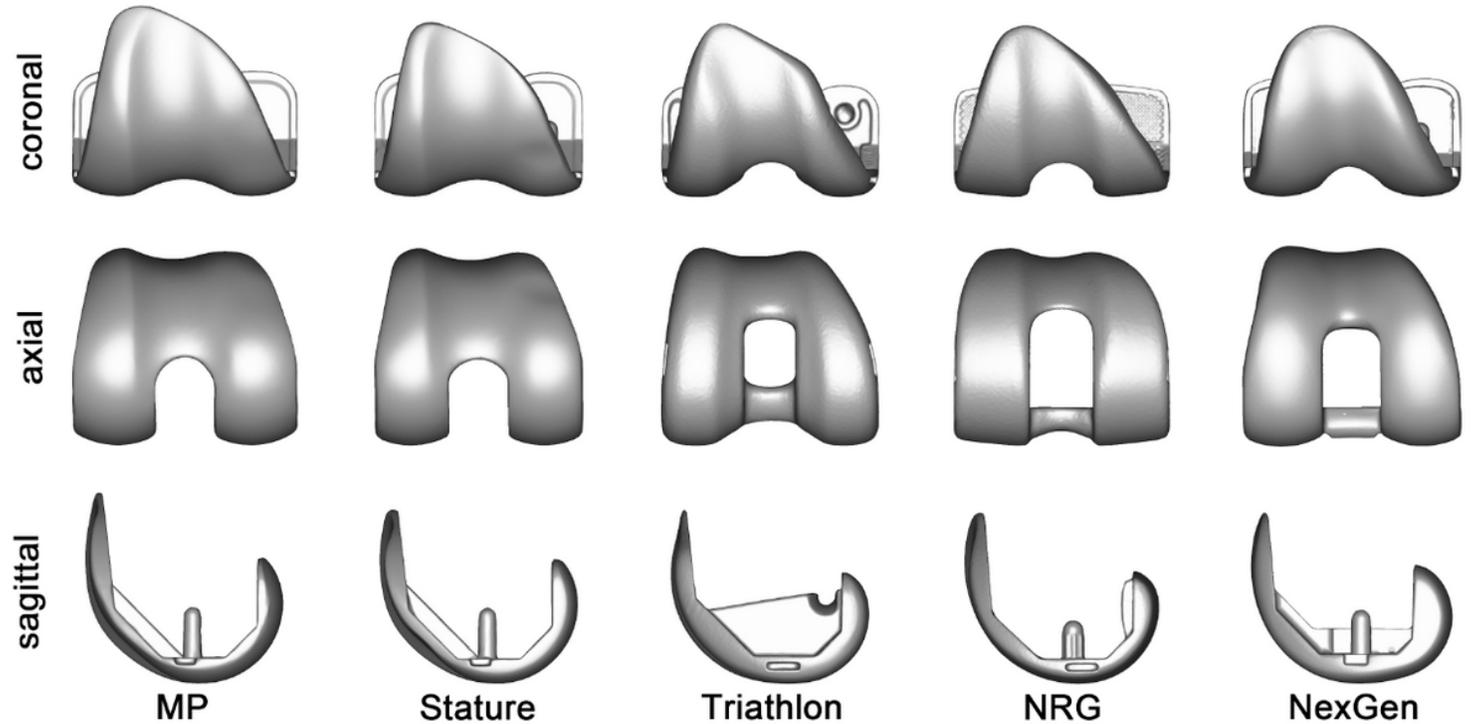


Figure 4

The femoral components used in this study