Original article

Differences in trochlear parameters between native and prosthetic kinematically or mechanically aligned knees

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ABSTRACT

Introduction: Kinematic (KA) and mechanical (MA) alignment techniques are two different philosophies of implant positioning that use the same TKA implants. This might generate differences in the resulting prosthetic trochleae parameters between the two techniques of alignment. Our study aim was to test the following hypotheses: (1) mechanically or kinematically aligned femoral implant understuffs the native trochlear articular surface and poorly restores the native groove orientation, and (2) the orientation of the prosthetic trochlear groove and trochlear fill are different between MA and KA.

Methods: Three-dimensional models of the femur were made from segmentation of preoperative Magnetic Resonance Imaging scans (MRIs) of ten subjects with isolated medial tibiofemoral osteoarthritis. In-house planning and analysis software kinematically and mechanically aligned a modern cruciate retaining femoral component and determined differences in parameters of the trochlear fit between native and prosthetic trochleae, and between KA and MA prosthetic trochleae.

Results: The MA prosthetic trochleae did not fill (understuffed) the entire length of the native medial facet and the proximal 70% of the native groove and lateral facet, and oriented the trochleae groove 8° more valgus than native. The KA prosthetic trochleae understuffed the proximal 70% of the native trochleae, and had a groove 6° more valgus than native. The KA trochleae understuffed the medial facet distally and oriented the groove 2° less valgus and 3° more internally rotated than the MA trochleae.

Conclusion: MA and KA prosthetic trochleae substantially understuff and create a prosthetic groove more valgus compared to native trochlear anatomy, and they also differed between each other regarding trochleae stuffing and groove alignment. Although randomized trials have not shown differences in patellofemoral complications between KA and MA, a femoral component designed specifically for KA that more closely restores the native trochlear anatomy might improve patient reported satisfaction and function.

Level of evidence: Level 2 controlled laboratory study.

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1. Introduction

The patella is a sesamoid bone that acts as a lever to facilitate knee extension, and increases the quadriceps moment arm. The native patella initially follows a circular path, which is guided by the circular trochlear groove of the femur, before articulating with the inner part of both the medial and the lateral condyles [1–3]. The function of the lateral facet is to prevent the patella from subluxing laterally in early flexion, and as flexion increases, the patella is guided by the floor of the groove and not the facets [3,4].

For decades, total knee arthroplasty (TKA) has tried, with the use of serial implants, to accommodate varying patients anatomy by systematically creating an almost similar “biomechanically friendly prosthetic knee” favouring long-term survivorship, rather than aiming at restoring the constitutional knee anatomy (either tibiofemoral or patellofemoral joint) which would have favour the functional outcomes [5]. To optimize the forces at the bone-implant interface with the aim of long-term implant survivorship, mechanical alignment (MA) technique for TKA aims at creating a straight limb with perpendicular tibiofemoral joint line. In general, the femoral implants in current use have trochlear grooves that are extended more proximally and oriented in more valgus compared to the native one. Also, prosthetic trochleae have a larger groove’s radius and a higher suclus angle, with the aim of ‘under-stuffing’ trochleae prosthetic surfaces relative to the native one.
These features result in a patella that is captured early in flexion, promoting stability without overly constraining the tracking [4,6–11]. This design rationale aims at minimizing patella instability, anterior knee pain from retinacular stretching [12] and accelerated component wear/loosening due to increased contact forces [13]. Clinical results suggest that this theory is translated into practice, with fewer patellofemoral complications with MA TKA [14,15]. However, patellofemoral complications after MA TKA unfortunately do occur despite computer assisted surgery, robotics and enhancements of implant design [16–19]. Those complications have been mostly attributed to abnormal patellar biomechanics [11,20], which has been shown to be influenced by implant positioning and design [21–24].

In order to improve the functional outcomes of total knee replacement, an alternative method of implant positioning, namely the kinematic alignment technique (KA), has been described [25–27]. This technique intends to restore native knee kinematics by restoring the pre-arthritic constitutional frontal and axial tibiofemoral joint line alignments and knee laxity. One step to achieve this goal is to align the femoral component both frontally and axially to the cylindrical (or trans-condylar) axis, about which the tibia flexes and extends around the femur [28]. This alternative philosophy of implant positioning has been found to be clinically effective [28–31]. However, functional assessment has been limited principally to the tibiofemoral joint. Reports of the impact of KA on the patellofemoral joint are limited. Because KA and MA techniques are two different philosophies of implant positioning, which are performed with similar TKA implants, the position and orientation of resulting prosthetic trochlea might differ from the native articular surface and between each other. Our study aims to test the following hypotheses: (1) mechanically or kinematically aligned femoral implant understuff the native trochlear articular surface and poorly restore the native groove orientation, and (2) the orientation of the prosthetic trochlear groove and trochlear fill are different between MA and KA.

2. Methods

2.1. Material

Ten preoperative magnetic resonance imaging (MRI) scans (3.0 Tesla) of arthritic patients were segmented using Mimics® software (Materialize, Belgium). Patients had end-stage medial tibiofemoral osteoarthritis without significant patellofemoral arthritis (<Iwano stage 2 [32]). MRI included “hip, knee, and ankle areas”, and therefore ten 3-dimensional bone models (cartilage not segmented), including complete femoral head plus knee and distal tibial plafond, were created. Because images and clinical data were anonymized, their use was not subject to approval by our institutional review board.

Simulation of implant positioning and comparison of native and prosthetic trochlear articular surfaces (Fig. 1). Following a method previously published [25,33], 3-dimensional models of cruciate retaining Persona femoral component (Zimmer Biomet, Warsaw, USA) were mechanically and kinematically positioned on every bone model (Fig. 1), and a software was used to compare native and prosthetic articular surfaces through cutting planes revolving around the patella axis. Because the prosthetic trochleae extend more proximally than the native one, this extension was assessed via cutting planes translating proximally from the apex of the native trochlea at 1 mm increments. To account for the difference in angular sweep between trochleae, degrees of rotation were converted to a percentage rotation, and measurements were taken at 20% increments across the length of the groove, where 0% and 100% were defined as the most proximal and distal point on the native groove, respectively (Fig. 1). Based on published data [34–36], measurements of native trochlea surfaces were compensated for cartilage thickness by 2 mm for the groove and the distal parts of the trochlea facets (≥80% of revolving process – corresponding to the transition zone with extension facets of femoral condyles), and 1 mm for the proximal part of trochlea facets (<80% of revolving process). Trochlear parameters measured were: varus-valgus and internal-external groove orientations (valgus and externally rotated groove orientations are represented as positive value), mediolateral groove translation, heights of the groove and facets (Fig. 2). Based on previously reported data [12,37], an ideal fit was defined as a difference value less than 2 mm; if the value was larger than 2 mm, overstuffing or understuffing was therefore considered.

2.2. Statistical analysis

To enable comparison of geometric parameters across different sized femora, radial heights were normalized to the mean groove radius and mediolateral translation was normalized to the mean transepicondylar width. The data were determined to be normally distributed by a Shapiro-Wilk test (p > 0.05), so the results were analyzed with a repeated measures analysis of variance (Anova) and post-hoc paired t-tests. A Bonferroni correction for multiple comparisons was performed, and the significance level (p-value) was set at 0.02. Results are presented as mean (SD, min to max). The reliability of measurements was tested by measuring three variables (native and prosthetic groove height at 40° and native coronal plane orientation) in four randomly selected knees (for each group) by two observers (intra- and inter-observer reliability) using the intraclass correlation coefficient (ICC). The ICC was calculated as a one-way random effects model of single measures for each variable, and resulting ICC indicated good agreement (0.71 to 0.84). All statistical analyses were performed with SPSS™ Statistics V22.0 (IBM, Armonk, NY, USA).

3. Results

Results for MA and KA prosthetic trochlea stuff relative to the native articular surfaces are illustrated in Fig. 3. Figs. 4 and 5 illustrate two cases with different distal femoral joint line (DFJL) obliquity.

Fig. 1. In-house analysis software. Cutting plane revolves around the patellar axis.

Fig. 2. Measured trochlear parameters. Axial (B) and frontal (C) groove rotations are assessed relative to the cylindrical axis. Lateral (b) and medial (c) facets heights, and groove height (a) are assessed relative to the patella axis. Mediolateral groove translation (d), external groove rotation (ER), internal groove rotation (IR), Valgus and externally rotated groove orientations are represented as positive value.

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Fig. 3. Trochlear stuffing differences between native and MA and KA trochleae. Blue (*) and red (•) asterisks indicate significant difference between native trochleae and MA and KA trochleae, respectively. Black asterisk (*) indicates significant difference between MA and KA trochleae.

Fig. 4. Illustration of the substantial difference between MA (grey implant) and KA (blue implant) trochleae. The distal femur has a distal joint line with 5° valgus obliquity.

3.1. Native versus MA trochleae

The MA prosthetic trochleae understuffed the whole native medial facet and the proximal 70% of the native groove and lateral facet (p < 0.01). Throughout the revolving process, the prosthetic trochleae understuffed the native medial facet by 2.3 mm (1.8, −6 to 0.2) (p = 0.003) and a trend of overstuffing the native groove and lateral facet. The MA groove was 8° (4.7°, 1° to 17°) more valgus than the 2° valgus (3.2°, −3° to 8°) of the native groove (p < 0.001). The MA groove was 2° (SD 2.74) externally rotated and 1 mm (SD 0.725) medially located, which were not different from the native trochleae (p = 0.074 and 0.05, respectively).

3.2. Native versus KA trochleae

The KA prosthetic trochleae significantly understuffed the proximal 70% of the native groove, medial facet, and lateral facet. Compared to native groove, the KA prosthetic groove significantly understuffed the proximal part till 70% of the revolving process, overstuffed the distal part at 100% of the revolving process by 3 mm (SD 1.79) (p < 0.001), was 6° (4°, 1° to 14°) more valgus (p < 0.001) and 2 mm (0.8 mm, 0.4 to 3) more medially translated (p < 0.001). The slight internal rotation of the prosthetic groove (1°, SD 1.44) did not reach significance (p = 0.4).
3.3. KA trochleae vs. MA trochleae

The KA medial facet overstuffed the MA medial facet at 90 and 100% of the revolving process ($p < 0.001$). The KA groove was 2° (SD 1.2°) less valgus ($p < 0.001$), 3° more internally rotated ($p < 0.001$), and 1.6 mm (SD 0.9) more medially located ($p < 0.001$).

4. Discussion

Because KA and MA techniques for TKA are performed with same conventional femoral implants, their resulting prosthetic trochleae might differ from the native trochlea and between each other. The present study showed that neither approach to prosthesis orientation restored native trochlear anatomy, and differed a little between each other regarding trochlea stuffing and groove alignment.

4.1. Native versus prosthetic trochleae

The MA and KA prosthetic trochleae only poorly reproduced the native trochlea anatomy, with notably a substantial understuffing of the proximal articular surface and a groove that is oriented in more valgus and, for the KA groove, slightly mediailized. This poor restoration of the native anatomy was worst with MA positioning, as the distal part of the trochlea and the groove alignment were closer to the native anatomy after KA simulation.

Regarding MA positioning, these findings were expected as MA of TKA implants aims rather at a biomechanical goal of early patella capture and low-constraining patella tracking [4,10] than preventing pain from stretching of retinacular ligaments [12]. Varadarajan et al. [9] also found MA TKA (NeXGen®, Zimmer, Warsaw, USA) to substantially understuff the proximal part of the whole native trochlea. In our study, the MA prosthetic medial facet revealed even more understuffing. This is because our simulation tries to reproduce real surgical practice (no cartilage thickness compensation on the distal medial condyle) while above-mentioned authors used healthy knees, which has led to a femoral component more distally positioned, thus reducing proximal trochlea understuffing. Also, Varadarajan et al. [9] found the MA TKA positioning to generate a distal lateral facet overstufing; in our study the difference we observed failed to reach significance, this is likely to represent an error type 2.

Regarding KA positioning, this poor anatomic restoration could have deleterious effect on the clinical outcomes of KA TKA. Indeed, KA technique aims at achieving the best knee kinematics and function [5], which goal should be likely to be best achieved by a proper restoration of the knee anatomy, that is the tibiofemoral and the patellofemoral joints [3]. Because it has been shown the native frontal groove alignment tends towards being perpendicular to the DFJL [1], which has highly variable inter-individual obliquity [38,39], current femoral implants, which generally display a built-in valgus oriented groove, are therefore condemned to replicate the native trochlear alignment only poorly when kinematically aligned. Also, the substantial KA proximal trochlea understuffing should be balanced against the dangers of patella instability, as excessively slack patella ligaments and low constrained trochlea are well-known risk factor for this complication [40]. This risk of patella maltracking/instability with KA technique could be theoretically higher than the one after MA technique as patients with valgus knee have their constitutional limb alignment reproduced, and also because KA femoral component positioning rarely reaches the target of closely restoring the native groove orientation. Computational studies having simulated kinematic positioning of TKA on a restricted number of anatomic knee models have shown KA positioning may affect the patellofemoral biomechanics in early knee flexion but result in a more physiologic one in deeper flexion [41,42]. To achieve a soft patella engagement, KA TKA should probably reproduce the individual (patient-specific) groove orientation, which has been shown to often not be the case in this study. However, KA does not have an increased incidence of mid-term patellofemoral complications when compared to MA [29–31,43–45]. Even better, current clinical evidence has shown KA TKA might reduce the incidence of anterior knee pain [30]. In order to better estimate the clinical impact of current implant designs, and to define if specific implants for KA technique (improving patella capture and tracking) have to be developed, investigations have to be pursued.

4.2. KA versus MA prosthetic trochleae

Regarding the groove alignment, we found the KA femoral implant positioning to mainly affect the alignment (less valgus by 2.1°) and the mediolateral location (more medial by 1.6 mm) of the groove, when compared with MA trochlea. This correlates with results from Brar et al. [46] who found KA TKA to reduce the lateral reach of the most proximal point of the trochlea (by 3 mm) when compared to MA TKA. This reduction of valgus groove orientation after KA technique was expected because KA technique restores the constitutional DFJL, which is on average 3° valgus [38].

Regarding the trochlea stuffing, we found KA medial facet to overstuff MA medial facet in their distal portion. This is probably because the distal medial condyle is a reference landmark to set distal femoral cut for both techniques, but only KA technique compensates for the 2 mm of distal condylic cartilage wear, thus reducing the distal understuffing of the KA medial facet. We were surprised to find that KA and MA techniques almost similarly understuff the proximal native trochlea, with notably the proximal part of the lateral facet heights to be very similar and the distal part to differ but without statistical significance. The former is probably mainly explained by the fact the proximal part of the lateral facet is understited in the MA technique by the 3° of femoral component external rotation, while it is also understuffed with KA technique because the physiologic valgus obliquity of the DFJL is restored. The latter is probably the consequence of the low power of our study and therefore is likely to represent a type 2 error. In order to quantify the mechanical effect of the trochlear understuffing, we estimated roughly the decrease in the extensor moment of the quadriceps at 90° knee flexion. We based our calculations on the assumption that the centre of rotation of the native knee is the same as post-TKA, and used the values for moment arm and quadriceps force from the available literature [47,48] to make these calculations. We thus calculated a 5 mm decrease in the extensor moment for 5 mm decrease in the lever arm, a decrease of 13%. An 8 mm decrease in the lever arm would yield an extensor moment decrease of 25%. The implication of this would be that the patient would have to generate more quadriceps force in order to extend their knee, potentially leading to inferior functional outcomes and patella component at risk of failure (loosening, wear) secondarily to the increase of joint reaction force. Unfortunately, we were unaware of any studies reporting the clinical effects of trochlea understuffing.

Before interpreting the results of this study, it is important to acknowledge some limitations. First, with only 10 knees assessed and level of significance adjusted at 0.02, our study is likely to be underpowered for the testing of our second hypothesis, specially the comparison of lateral facet stuffing. As KA and MA techniques aim a different frontal femoral component positioning, it is probable the stuffing of the distal part of lateral trochlea facet be
different between them, which was not found in our study and therefore is likely to be an error type 2. Second, we did not segment cartilage on the MRI and therefore we assumed its thickness on femoral condyles and trochlea. However, because cartilage thickness has been shown to be slightly variable between patients [28,34–36], this limitation should be likely to have no significantly affected our in silico TKA planning, estimation of native trochlear articular surface, and therefore results regarding comparison between prosthetic and native trochlear stuffling. This low impact is even more likely considering the large highly statistically significant difference observed. In contrast, native groove alignment measurements are likely to not be affected by this limitation. Third, measurement of the native trochlea parameters are prone to imprecision as knees had some amount of patellofemoral osteoarthritis, which has potentially generated trochlea bone remodelling. However, this limitation does not affect results for comparison between MA and KA trochlea, and is likely to have a negligible effect on results for our hypotheses 1 and 2 as patients had very little patellofemoral arthritis (≤ Iwano stade 2). Last, the study evaluated one femoral implant design with symmetric femoral condyles, which was chosen to be representative of modern TKA implants that are known to incorporate a similar design rationale of the trochlea. Different femoral implants may differ in their designs of course, and the impact of altering their position and orientation between MA and KA are unknown. We suspect however that the magnitude of the differences will be similar.

5. Conclusion

Compared to native articular surfaces, MA and KA techniques for positioning TKA create prosthetic trochlea that is understuffed and with a groove more valgus oriented. MA and KA prosthetic trochlea also differed between each other regarding trochlea stuffling and groove alignment, but the KA trochlea is closer to the native patient-specific anatomy. Although randomized trials have not shown differences in patellofemoral complications between KA and MA, new femoral component specifically designed for KA positioning and aiming at improving patellofemoral biomechanics in early knee flexion might be beneficial.

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Disclosure of interest

The authors declare that they have no competing interest. Outside the current study Charles Rivière declares having been consultant for Depuy, Sébastien Parratte declares being consultant for Zimmer-Biomet, Arthrex, Craftys, and Adler Ortho, and to receive royalties from Euros, and Justin Cobb declares being consultant for Biomet-Zimmer, Mathortho, and to perceive fee from Miroport.

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