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Original article

Kinematic alignment technique for medial OXFORD UKA: An in-silico study

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ABSTRACT

Background: Mobile bearing unicompartmental knee arthroplasty (UKA) Oxford™ components are recommended to be systematically and mechanically aligned (MA) for restoring the constitutional lower-limb alignment. Good long-term clinical outcomes have been generated with the medially implanted MA Oxford™, but some sub-optimal biomechanical-related complications still remain. Kinematic Alignment (KA) is a personalised technique for anatomically and kinematically implanting components (total knee, fixed bearing partial knee, total hip) aimed at creating more physiological prosthetic joint biomechanics. Interestingly, for decades the principles for implanting fixed bearing UKA components were consistent with those promoted by the KA technique, but differently formulated. We initiated this computational study to assess the feasibility of this technique with the Oxford™ components, as we thought this more anatomical implantation may be clinically advantageous.

Hypothesis: We surmised that kinematically aligning the Oxford™ medial UKA would maximise the prosthesis-bone interface through maximising the implants' size used (question 1), and alter, within an acceptable limit, the components' orientation (question 2) compared to conventional mechanical alignment.

Methods: A cohort of 40 consecutive medial osteoarthritic knee patients scheduled for UKA had a preoperative CT scan that was segmented to create 3D knee bone models. MA and KA of medial UKA Oxford® components (Zimmer-Biomet, Warsaw, Indiana, USA) were simulated. Component sizing and positioning were compared between the two techniques.

Results: We found no difference in component size, but significantly fewer occurrences of borderline fit with the KA simulation. KA technique oriented the femoral component 3.6° more valgus (from 1° varus to 7° valgus) and the tibial component 2.9° more varus (from 8° varus to 0°) compared to the MA technique. The tibial component slope in KA simulation was 6.4° posterior (from 0 to 12°) compared to a systematic 7° posterior for MA positioning.

Discussion and conclusion: Kinematic alignment of the medial Oxford™ generated a different, albeit still acceptable (Oxford group recommendations), implant orientation, in addition to a likely better shape-fit between components and the supportive bone cut, compared to the MA technique. The potential to improve the implants' interaction and to restore a more physiological bone loading makes the KA of Oxford™ an attractive, potentially clinically beneficial option. Clinical investigations are needed to assess its true value.

Level of evidence: I, computational study.

1. Introduction

Unicompartmental knee replacement (UKA) has been shown to have many clinical advantages compared to total knee arthroplasty (TKA), whatever its anatomic fixed bearing or non-anatomic mobile bearing design. UKA aims at preserving bone, cruciate ligaments and the soft-tissue envelope, and at restoring constitutional knee alignment, laxity, and physiological knee kinematics,

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in order to provide higher knee function and allow easier revision surgery [1,2]. UKA has been shown to provide better knee function and gait [3,4], but higher revision rates when compared to TKA [5,6]. The main causes for revising a UKA are either unrelated (degeneration of other knee compartments) or related (mobile liner dislocation, residual pain related to proximal tibia plateau bone remodelling [7] and/or soft tissue impingement [8], periprosthetic tibial plateau fracture, or component loosening) to the implants [9,10]. Minimising those complications depends on a variety of factors, but proper component positioning is one of the most important determinants for good clinical outcome and implant survivorship.

In order to improve the reliability of positioning, implantation of the non-anatomic mobile bearing UKA Oxford™ components has been standardised, in that components are recommended to be mechanically implanted to reproduce the constitutional limb alignment (or hip-knee-ankle angle) [11,12]. While the Oxford™ femoral component is oriented in the coronal plane parallel to the femoral mechanical axis, the tibial component is frontally positioned perpendicular to the tibia mechanical axis and with a 7° posterior slope [11,12]. This conventional or 'mechanical' orientation of components enables restoration of the pre-arthritic femorotibial joint line level throughout the knee range of motion, but fails to recreate variable individual medial femoro-tibial compartment anatomy [13]. This may raise an issue in the case of those knees with severe joint line obliquity (JLO), when the mechanical alignment of components departs substantially from native condylar anatomy. It is probable this will affect components' interaction (or prosthetic biomechanics), generating a highly anistropic tibial bone interface (sclerotic bone peripherally and much less dense bone centrally) and a non-physiological loading of the supportive tibial bone, which may be clinically deleterious [14].

Kinematic alignment (KA) is an alternative, personalised technique for implanting total knee arthroplasty (TKA), successfully promoted over the last decade in order to improve knee outcomes when compared to the conventional mechanical alignment (MA) technique [15,16]. The principles are to anatomically position (true resurfacing) and kinematically align (cylindrical femoral and antero-posterior (AP) tibial axes [17]) the components, in order to restore the highly inter-individually variable native knee's articular surface and improve prosthetic interaction (or biomechanics). Interestingly, for decades the principles for implanting fixed bearing UKA components were consistent with those promoted by the KA technique, but differently formulated (Fig. 1) [18]. Personalising the Oxford™ components' orientation by performing kinematic alignment would reproduce the individual condylar anatomy and potentially be clinically advantageous by reducing the aforementioned complications, through optimizing the interactions between bone and prosthesis (more physiological loading of the supportive bone), and between bearing surfaces [13].

We therefore initiated this study to assess the feasibility of kinematically aligning the Oxford™ components on the medial femoro-tibial compartment. We surmised that kinematically aligning the Oxford™ medial UKA would maximise the prosthesis-bone interface by maximising the implants' size used (question 1), and alter, within an acceptable limit, the components' orientation (question 2) compared to conventional mechanical alignment.

2. Methods

2.1. Material

Forty adult patients (23 males; mean age of 58, ranging from 31 to 76) with unilateral (19 right knee) low-grade primary medial

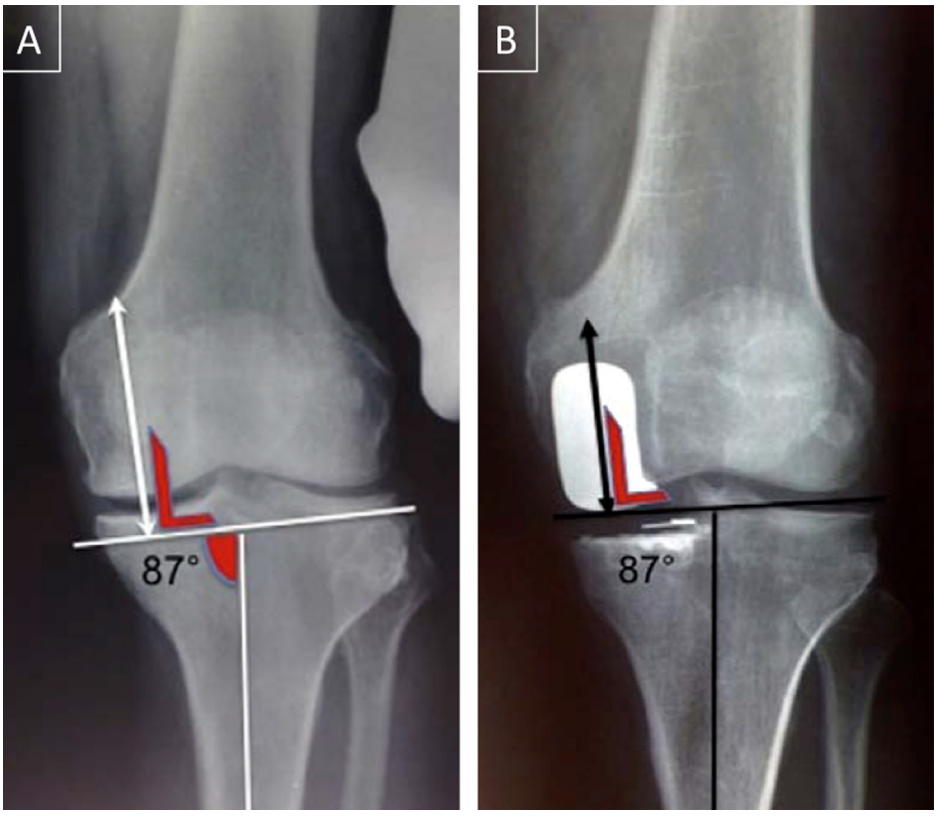

Fig. 1. Antero-posterior knee radiographs illustrating preoperative planning (A) and implantation (B) of an anatomically (or kinematically) positioned fixed bearing UKA. *Image courtesy of Deschamps et al. [18].*

Table 1
Anatomical characteristics of the 3D bony models.

	Mean	SD	Min	Max
Leg length (mm)	810	51	661	892
Tibial mechanical axis length (mm)	369	24	297	408
Femoral mechanical axis length (mm)	437	29	363	487
Hip-knee-ankle angle (valgus +)	−0.46°	3.48°	−7.1°	6.4°
Medial femoral flexion facet radius (mm)	20.3	1.71	16.9	23.7
Lateral femoral flexion facet radius (mm)	21.39	1.77	17.4	26
DFJLO (90-LDFA) (valgus +)	3.76°	1.87°	−0.1°	8°
PTJLO (90-MPTA) (varus +)	2.76°	2.48°	−2°	8°

tibiofemoral osteoarthritis (Ahlback grade ≤ 2) had their preoperative knee CT scan segmented using Mimics® software (Materialize, Belgium) to generate tri-dimensional bony knee models (cartilage not segmented). Anthropomorphic data of 3D bony models are illustrated in Table 1. 3D femoral and tibial Oxford® mobile-bearing medial UKA implants (Zimmer-Biomet, Warsaw, Indiana, USA) were then virtually mounted both kinematically and mechanically, using an in-house planning software, on each preoperative 3D bony model. As images were anonymised, no institutional review board approval was needed.

2.2. Simulation of medial UKA

2.2.1. Implant sizing

Method for component sizing is described in Table 2 and illustrated in Fig. 2. The method followed the same rules for MA and KA simulation: The femoral component size was selected to best fit the pre-arthritic femoral condyle by reproducing the most distal and posterior condylar points after compensation of 2 mm for cartilage (not segmented), and by obtaining a 2-mm postero-superior overhang from the posterior bony condyle. If there was any doubt between sizes, the closest size to the medium size was chosen. The tibial component size was selected to obtain maximum bone coverage, without anterior overhang, or greater than 2 mm posterior and/or medial overhang, or tibial spine violation beyond the medial ridge. For each simulation (MA and KA) we defined the proportion of components with "borderline sizing" as a situation where the selected implant size was at the limit of acceptable (Oxford group and Zimmer-Biomet guidelines [11]), and resulted in a compromise between optimal bony-coverage and acceptable component overhang. A borderline implant size may be clinically inferior than a non-borderline one (good "implant fit to the bone cut"), as it could cause pain related to soft-tissue irritation and/or bone remodeling and/or implant loosening [7,8]. We considered borderline implant size situations to be 1 to 2 mm implants' overhang (antero-medially, posteriorly and/or medially for the femoral and tibial components, respectively) and/or supra-millimetric medial tibial bone undercoverage in its third anterior, medial, and posterior parts (Fig. 2). Anterior tibial component overhang and implant overhang greater than 2 mm in abovementioned areas were considered unacceptable and were never simulated. Measurements for implant overhang and bone undercoverage were made by using our planning software, which enables fine-tuning of implant positioning with a precision of 0.5 mm.

2.2.2. Implant positioning

The method for component positioning and position measuring is described in Table 2 and illustrated in Fig. 3. The mechanical simulation followed the guidelines proposed by the Oxford group [11,12], with the exception of the tibial component axial rotation, which was set at the same as the KA simulation due to software limitations (impossible to target the femoral head centre). In brief, the femoral component was oriented parallel (coronal plane) and with 5° flexion (sagittal plane) relative to the femoral mechanical axis; the tibial component was frontally positioned perpendicular to the tibia mechanical axis and with a 7° posterior slope. The kinematic simulation followed similar rules to the KA technique for TKA [15], with the reproduction of the prearthritic articular surfaces by only considering intra-articular knee landmarks, and aligning components with the knee kinematic axes [17]. The KA femoral component was therefore frontally and axially aligned with the cylindrical (or trans-condylar) axis, and the KA tibial component was axially aligned with the AP tibial axis and reproduced the individual frontal and sagittal medial tibial plateau slope. Tibial bone cut thickness followed the same rules for MA and KA simulation; accounting for an average of 2 mm of cartilage thickness and to

Table 2
Method for sizing and orienting components.

	Mechanical positioning	Kinematic positioning
Femoral component		
Implant size	Position the femoral component 2 mm more distal and more posterior than the most distal and posterior points of the bony condyle, respectively; and with 2 mm of postero-superior overhang	
Medio-Lateral translation	Centre line (or central third) of the femoral condyle with potential antero-medial implant overhang always ≤ 2 mm	
Frontal rotation (valgus +)	Parallel to mechanical axis	Perpendicular to cylindrical axis
Sagittal rotation (flexion +)	5° flexion relative to sagittal femoral mechanical axis	
Axial rotation (internal +)	Perpendicular to cylindrical axis	
Tibial component		
Implant size	Maximum bone coverage without antero-medial overhang, with ≤ 2 mm postero-medial and/or posterior overhang, without tibial spine resection beyond the medial ridge (fig)	
Cranio-caudal translation	Adjusted in order to obtain a 5 mm resection depth	
Frontal rotation (valgus +)	Perpendicular to mechanical axis	Parallel to medial plateau (Cartier angle)
Sagittal rotation (slope)	7° posterior	Parallel to native medial plateau slope
Axial rotation (internal +)	Parallel to the AP axis of the tibia [23]	

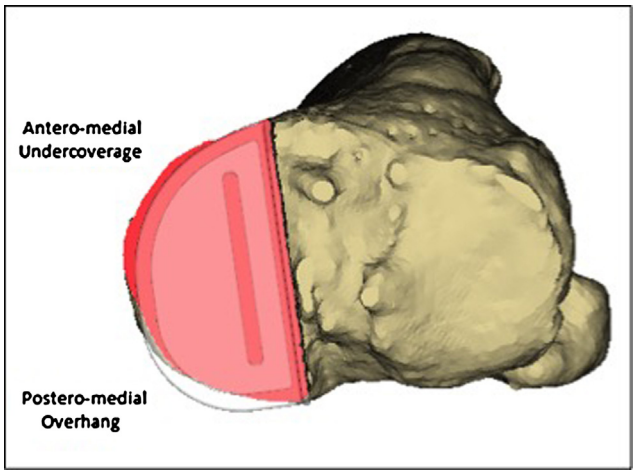

Fig. 2. Determination of borderline component size.

accommodate a 4-mm thick polyethylene bearing, the tibial component (3 mm thick) was always positioned 5 mm below the bony surface of the medial tibia plateau's central part. Both component positioning philosophies aim to reproduce the constitutional limb alignment (or hip-knee-ankle angle).

2.3. Statistical analysis

Descriptive statistics were used to represent the characteristics of the patients; continuous variables were expressed as mean ± standard deviation and categorical data in terms of absolute numbers. The *t*-test for paired samples for quantitative data and the Wilcoxon rank test for qualitative data were used to analyse the differences in positioning parameters between the two simulations. The level of statistical significance was set at 0.05. By using the intraclass correlation coefficient (ICC), the two methods of simulation were found to be reliable, with a repeatability and reproducibility of > 0.99 for each of the parameters of comparison. All statistical analyses were performed using IBM SPSS 18 software.

Table 3
Comparisons of implant size and orientation between mechanical and kinematic alignment simulation. Mean ± SD [min–max].

	MA simulation	KA simulation	*p*-value
Femoral component			
Implant size			
XS	3	3	1.000
S	12	12	
M	15	15	
L	9	9	
XL	1	1	
Frontal orientation (valgus +)	0 ± 0° [0–0°]	3.6 ± 2° [−1–7°]	< 0.001
Axial rotation (internal +)	0 ± 0° [0–0°]	0 ± 0° [0–0°]	1.000
Sagittal orientation (flexion +)	5 ± 0° [5–5°]	5 ± 0° [5–5°]	1.000
Tibial component			
Implant size			1.000
AA	0	0	
A	1	1	
B	7	7	
C	10	10	
D	16	16	
E	5	5	
F	1	1	
Frontal orientation (valgus +)	0 ± 0° [0–0°]	−2.9 ± 2.1° [−8–0°]	< 0.001
Axial rotation (internal +)	3.3 ± 2.8° [0–12.5°]	3.3 ± 2.8° [0–12.5°]	1.000
Posterior slope (flexion +)	7 ± 0° [7–7°]	6.4 ± 2.5° [0–12°]	0.145

3. Results

3.1. Question 1

Component size was the same on the femoral side, and two simulations had a one-size difference on the tibia side, although

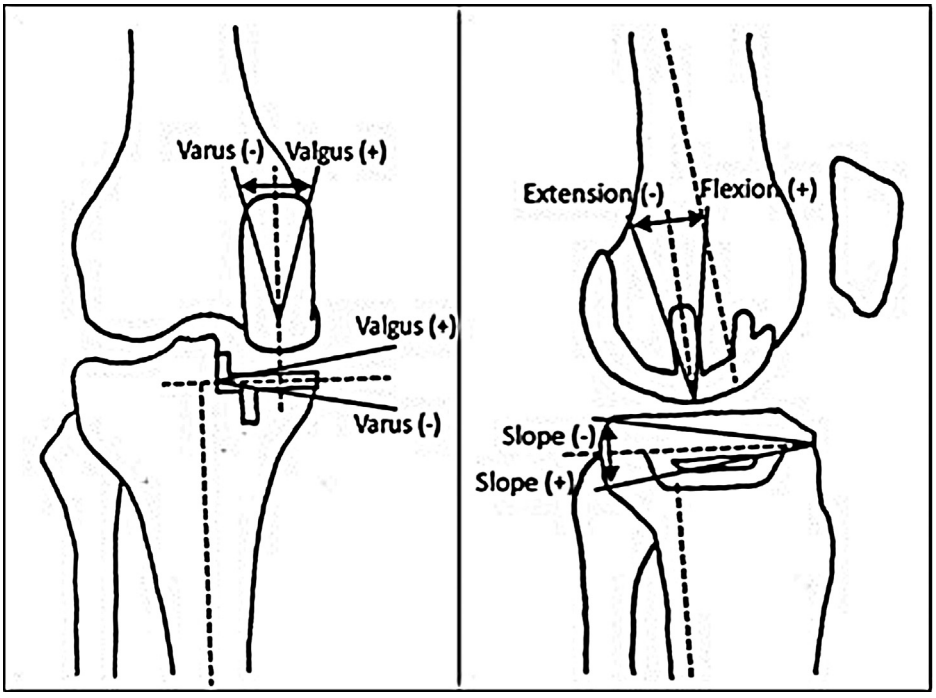

Fig. 3. Nomenclature for components' position.

Table 4
Comparisons of implant fitting between mechanical and kinematic alignment simulation.

	MA simulation	KA simulation	*p*-value
Femoral antero-medial overhang	10	2	0.005
Tibial postero-medial and/or posterior overhang	2	2	1
Tibial undercoverage			
1/3 posterior	0	0	0.083
1/3 medium	3	0	
1/3 anterior	0	0	
Total of borderline anatomical component fit	15	4	0.009

this difference fails to reach significance (Table 3). We found KA simulation to have less (4 versus 15) borderline component sizings (Table 4). Specifically in the KA simulation, there was less femoral component antero-medial overhang ($p = 0.005$) and a trend for less tibia bony under-coverage in its middle third part ($p = 0.083$).

3.2. Question 2

Using KA, the femoral component was oriented in 4° more valgus (ranging from 1° varus to 7° valgus), but had the same axial and sagittal positioning in comparison to the MA femoral component ($p < 0.001$) (Table 3 and Fig. 4). Using KA, the tibial component was 3° more varus (ranging from 8° varus to 0°) in comparison to the MA tibial component ($p < 0.001$) (Fig. 4). Tibial component slope in KA simulation (6.4° posterior slope — ranging from 0° to 12°) was more dispersed than the systematic 7° posterior of the MA simulation, but this difference failed to reach significance ($p = 0.145$) (Fig. 4). Frontal KA femoral and tibial component positioning very strongly correlated with distal femoral JLO (DFJLO) ($r = 0.92$, $p < 0.001$) and proximal tibial JLO (PTJLO) ($r = 0.68$, $p < 0.001$), respectively (Fig. 5).

4. Discussion

Mechanically aligned Oxford™ medial UKAs have shown excellent long-term outcomes despite a few remaining complications that could be secondary to non-physiological tibial bone loading and poor components' interaction, especially in situations of severe knee JLO. As the KA technique aims at aligning knee components based upon the kinematic knee axes in order to improve prosthetic joint biomechanics and bone loading [15], KA of the Oxford™ medial UKA might potentially be clinically advantageous. We found the KA positioning of Oxford™ components to significantly differ from that of MA, whilst remaining within the recommended limits for positioning [11,12]. KA simulation led to femoral components with more valgus orientation, tibial components with more varus orientation, and with both components likely to have a better shape-fit to the supportive bone cut, compared to MA simulation.

4.1. Question 1

The technique of alignment significantly influences component sizing, not by changing the choice of implant size (only 2 differences in tibial component size out of 40 cases), but by altering the incidence of borderline fit. In our simulation, the KA implants were much easier to plan compared to the MA implants, with less compromise needed between component overhang and bony under-coverage (borderline fit). This better fit between the bone cut surface and the tibial implant shape could potentially be clinically beneficial by improving long-term implant fixation (better bone coverage), and by reducing pain related to soft-tissue impingement and/or antero-medial tibial bone-remodelling (reduced implant overhang) [7,8].

4.2. Question 2

Our results were anticipated as KA and MA positioning logically differ from each other by aiming for two different goals: a patient-specific versus systematic mechanical implantation [15],

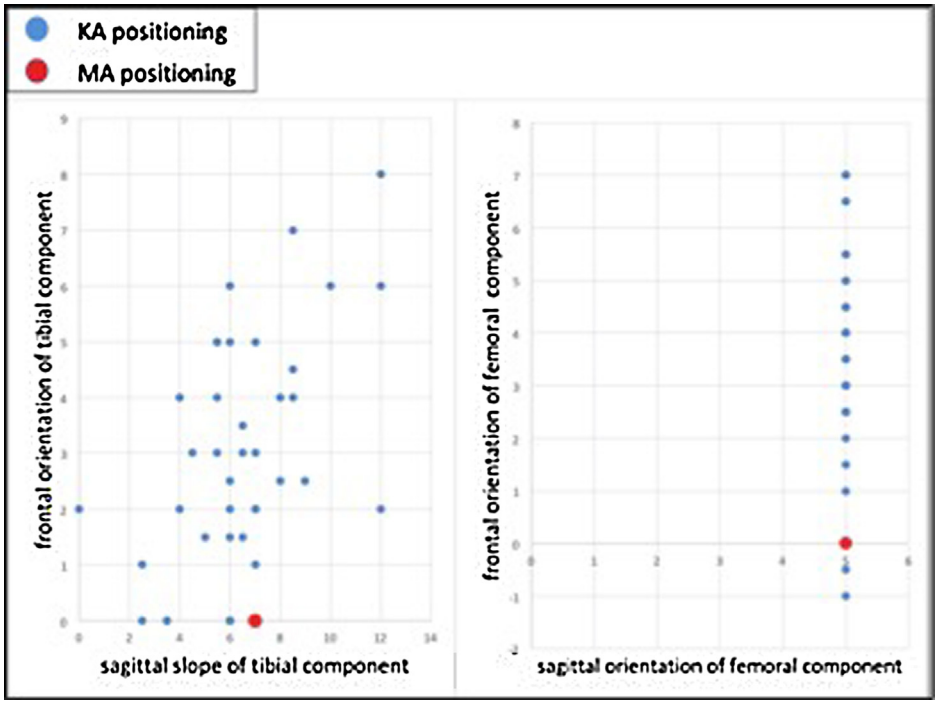

Fig. 4. Comparison of KA (blue) and MA (red) tibial (left graph) and femoral (right graph) components' positioning.

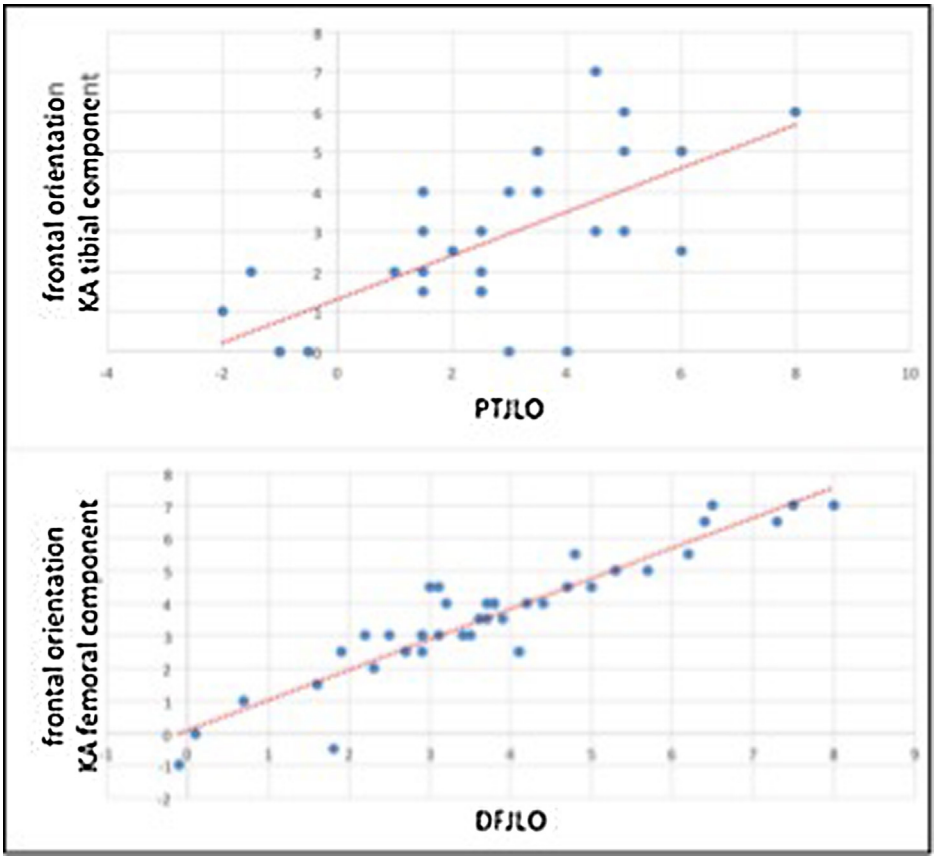

Fig. 5. Relationship between the distal femoral (DFJLO, $r = 0.92$–above graph) and proximal tibial (PTJLO, $r = 0.68$–below graph) joint line orientation and frontal orientations of KA femoral and tibial components.

respectively. As the medial knee condyle was found similarly frontally oriented when compared to the knee epiphyses (distal femur and proximal tibial), KA of medial UKA implants tends towards valgus orientation for the femoral, and varus orientation for the tibial components, similar to kinematic positioning of TKA components [19]. Compared to MA, our KA simulation often seemed to improve the components' interaction (Fig. 6) by optimising their surface contact area as the femoral and tibial components were often in more contiguous and convergent positions on the extended knee simulation (Fig. 6), thus potentially reducing polyethylene wear, and preventing risks of liner dislocation and soft-tissue impingement. Nonetheless, it is important to acknowledge that the design of the highly congruent Oxford mobile bearing UKA prevents accelerated polyethylene wear, even in situations of significant non-contiguity and convergence between femoral and tibial implants, thus KA component positioning is probably not a game-changer with regards to the rate of polyethylene wear. Varus positioning of the tibial component would probably (1) reduce shear stress on the bone-implant fixation interface, as the tibial component would be almost parallel to the ground in functional standing/walking positions [20,21], and (2) result in a more physiological loading of the supportive bone, as the KA tibial component would be more perpendicularly positioned to the subchondral trabeculae [22]. Dai et al. [20] found that slight varus inclination of the mobile bearing tibial component was acceptable, as it reduces the peak stress on the medial cortex, better distributes the stress to the supporting cancellous and cortical bone, and avoids a rise in stress between the tip of the keel and the medial tibial cortex.

A few authors [23,24] have reported good mid-term clinical outcomes of MA Oxford^{TM} medial UKAs displaying unintentional dispersion of the components' positioning (relative to the long bone mechanical axes), similar to what we found in our KA simulation. Clarius et al. [21] found the MA tibial Oxford^{TM} components to be varus aligned 4.4° (range 3° valgus to 13° varus), and Lee et al. [23] found the MA femoral Oxford^{TM} components to be on average 2.34° valgus oriented (range 8.49° valgus to 3.72° varus). In contrast to those reports mentioned, the dispersion of the KA positioning observed in our computational study is intentional and results from reproduction of the individual medial condylar anatomy [13].

Rotationally aligning the tibial component parallel to the AP tibia axis, which approximates the axis of the lateral wall of the medial femoral condyle when knee flexing [25], has been shown to better respect the insertion of cruciate ligaments, to generate more reliable positioning, and to reduce the risk of polyethylene liner spinning/dislocation, when compared to the conventional MA technique for rotation (ASIS, femoral head) [25–27]. In addition, using the axial wall of the medial femoral condyle creates a tibial bone cut suitable to fit commercially available Oxford® tibial component sizes [27]. Our study also confirms that using the lateral condylar wall enables one to set the tibial axial rotation parallel to the AP tibial axis; this is due to (1) the fact the AP tibial axis is perpendicular to the cylindrical femoral axis and the DFJL [17], and (2) we found a very strong correlation between the frontal positioning of the femoral component (set parallel to the axial wall of femoral medial condyle) and the DFJLO ($r = 0.92$). One of the senior authors (JC) uses the anatomic tibial axis, a published method for setting the tibial component axial rotation [28], which can be simply simulated and is widely used.

Kinematically aligning the Oxford^{TM} UKA could raise concerns over the accuracy of implant positioning, with the risk of generating clinically deleterious aberrant component positioning, as general belief is that referencing the long bone mechanical axis is

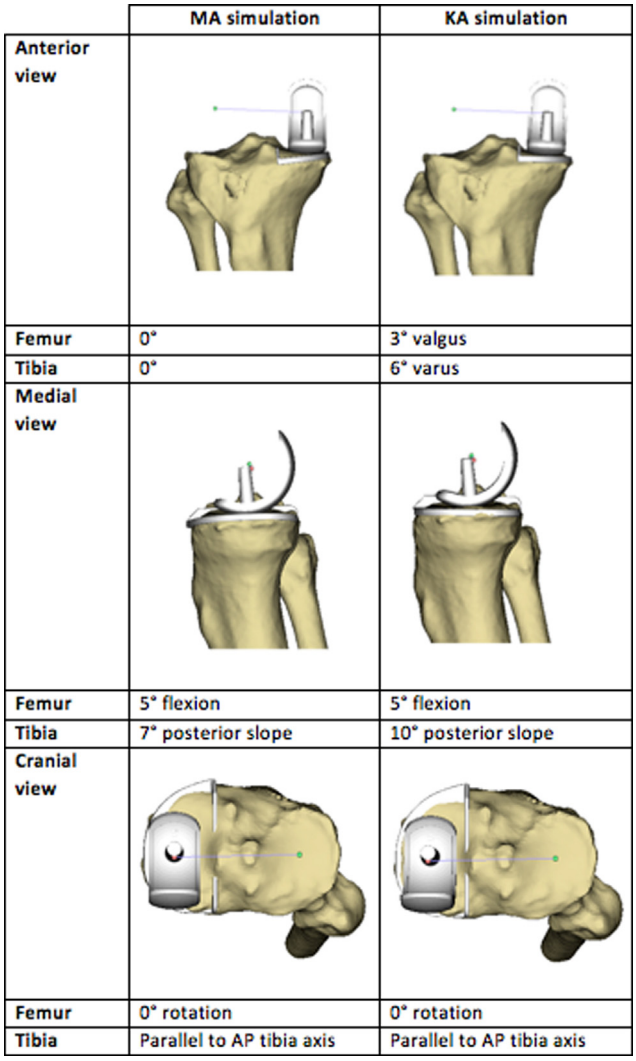

Fig. 6. Comparison of implants' interaction between mechanically and kinematically aligned medial UKA. The 3D bone model had a 6° varus HKA, 3° valgus LDFA, and 5° varus MPTA. Components size was the same for both MA and KA simulation.

more reliable. This concern should be lowered by the fact that (1) most fixed bearing UKA designs have been kinematically implanted for decades and with excellent long-term outcomes [18], (2) technological tools aimed at improving surgical accuracy (navigation, robotics, PSI) may help in lowering this risk, and (3) the ultra-congruent design of the Oxford™ components provides a high tolerance for component positioning that should help to palliate some imprecisions in positioning [23]. While it may seem counter-intuitive, exclusively following intra-articular bony landmarks and estimating the articular surfaces' wear appears to be reliable for implanting UKA components [23,24]. It is important to be aware that extrapolation of the current recommendation (Oxford Group) for mechanical component positioning to KA positioning would not necessarily apply as the two positioning philosophies significantly differ from each other, and thus their safe zone for aligning components will probably also differ. Kinematically positioned fixed bearing UKA physiologically loads the supportive bone, but has a low tolerance for suboptimal component positioning (poor component interaction causing complications related to edge-loading). In contrast, mechanically aligned Oxford™ mobile bearing UKA poorly loads the supportive bone but is highly tolerant to imprecise implantation, thanks to the high congruency between components. By kinematically positioning the Oxford™ mobile bearing UKA, we probably have the best from both worlds.

A few limitations should be discussed that may affect the generalisation of the findings. Firstly, this is only an in-silico (or in-vitro or computational) study that prevents extrapolation to any clinical outcomes. Secondly, our data are only valid for a single design (Oxford™) and on a single (medial) femorotibial compartment. Thirdly, we could not compare the axial rotation of KA and MA tibial components as they were both kinematically planned (parallel to AP tibial axis). This is because our planning software did not allow adjustment of the tibial component rotation by targeting the femoral head or the ASIS (MA technique), as recommended by the Oxford Group. However, this traditionally recommended method has been shown to be inconsistent, often leading to iatrogenic posterior cruciate ligament injury (violation of PCL fossa), in addition to polyethylene liner spinning [26], as well as being inferior to the method setting tibial rotation parallel to AP tibial axis [25,27]. Fourthly, for the same reasons as the third limitation, the assessment of the "tibial implant fit to the bone cut" in the MA simulation has probably been affected. Fifthly, we only assessed 40 knees, which could be considered insufficient to generate a reliable overview of the multiple anatomies encountered in osteoarthritic knee population. This has probably resulted in us missing some severe pathoanatomy that could lie outwidth the recommended limits for implanting the Oxford UKA. Lastly, we lacked statistical power for some of our tests; an obvious illustration remains in the comparison of the tibia component sagittal slope, which is patient-specific for the KA simulation and must differ (but not statistically in our study) from the systematic 7° posterior slope for the MA simulation.

5. Conclusion

KA technique of the Oxford™ medial UKA generated a different, albeit still acceptable (considering recommendations from the Oxford group), implant orientation as well as a likely better shape-fit between components and the supportive bone cut, compared to the MA technique. The potential to improve the implants' interaction (or biomechanics), to restore more physiological bone loading, and to reduce the risk of borderline implant fit, make the KA technique for mobile bearing UKA an attractive, potentially clinically beneficial option. Clinical investigations are needed to assess its true value.

Disclosure of interest

The authors declare that they have no competing interest.

Outside the current study Charles Rivière declares being a paid-consultant for Medacta and having been a paid-speaker for Corin Tornier, and Justin Cobb declares being consultant for Biomet-Zimmer, Mathortho, and to receive a fee from Microport.

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None.

Authors' contribution

C.M.: data acquisition, data analysis, reviewing manuscript.
C.H.: data acquisition, data analysis, reviewing manuscript.
A.L.: data acquisition, reviewing manuscript.
J.C.: reviewing manuscript.
C.R.: protocol, data acquisition, writing manuscript.

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