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Technical note

Inverse Kinematic Alignment for Total Knee Arthroplasty

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ABSTRACT

Patient specific alignment might improve clinical outcomes in total knee arthroplasty (TKA). Different alignment concepts are described, each providing specific features with theoretical benefits or possible disadvantages. Inverse kinematic alignment (iKA) is a new patient specific alignment concept with excellent reported clinical outcome and patient satisfaction at short-term follow-up. iKA is a tibia-first, gap balancing technique restoring the native tibial joint line obliquity (JLO). In each patient, within boundaries, equal medial and lateral tibial resections are performed, compensating for cartilage and bone loss. We describe the surgical technique of iKA using a robotic assisted system (Mako, Stryker, Kalamazoo, USA). A case series of 100 consecutive iKA cases is assessed and the bony resections and resection angles are reported. Both in the coronal plane and axial plane, iKA might offer advantages over existing alignment strategies, possibly providing optimal clinical outcome and durable long-term survival, regardless of the alignment is varus, neutral or valgus.

Abbreviations

TKA	total knee arthroplasty
iKA	inverse kinematic alignment
JLO	joint line obliquity
MA	mechanical alignment
KA	kinematic alignment
rKA	restricted kinematic alignment
CT	computed tomography
SD	standard deviation
deg	degrees
HKA	Hip-Knee-Ankle
MPTA	medial proximal tibial angle
mLDFA	mechanical lateral distal femoral angle
PCA	posterior condylar axis
TEA	transepicondylar axis
JLCA	joint line congruency angle

1. Introduction

Total knee arthroplasty (TKA) has evolved from a vestigial surgical intervention with limited options to a complex and customizable procedure. Although this evolution in surgical techniques, implant geometry, implant fixation and multimodal perioperative surgical, anesthesiologic and rehabilitation protocols, 15-25% of patients report to be unsatisfied with their knee implant. [1] Knee biomechanics are a complex interplay between menisci, cruciate ligaments, collateral ligaments, knee capsule and muscles. [2,3] Also, there is a high interindividual difference in knee anatomy, mobility, stability, biomechanics and kinematics. [4–6] Last decade new assistive technology was introduced to enhance clinical outcome in TKA. To improve precision, different robotical systems were introduced [7], also in combination with highly specific load sensors [8]. However, the targeted alignment or optimal implant position is still debated.

Historically, in contrast to unicompartmental knee and hip replacement surgery, a patient specific position of the implant was not seen as necessary in TKA surgery. The optimal position of the knee implant was generally defined as mechanical alignment (MA). [9] Whether the patient's native knee alignment is varus, neutral or valgus, when following MA principles, perpendicular cuts to the

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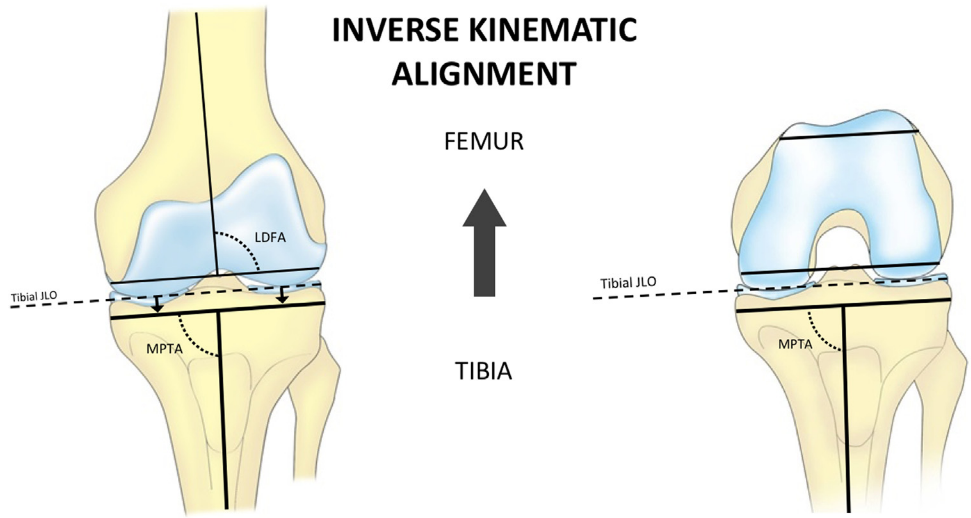

Fig. 1. Diagram showing principles of iKA. Equal bony resections medial and lateral on the tibial epicondyle are performed. Bony wear should be taken into account. Distal femoral cut is made by tensioning the ligaments in extension and making a parallel cut to the tibial cut. Posterior femoral cut is made by tensioning the ligaments in flexion and making a parallel cut to the tibial cut. Abbreviations: iKA, inverse kinematic alignment; MPTA, medial proximal tibial angle; LDFA, lateral distal femoral angle.

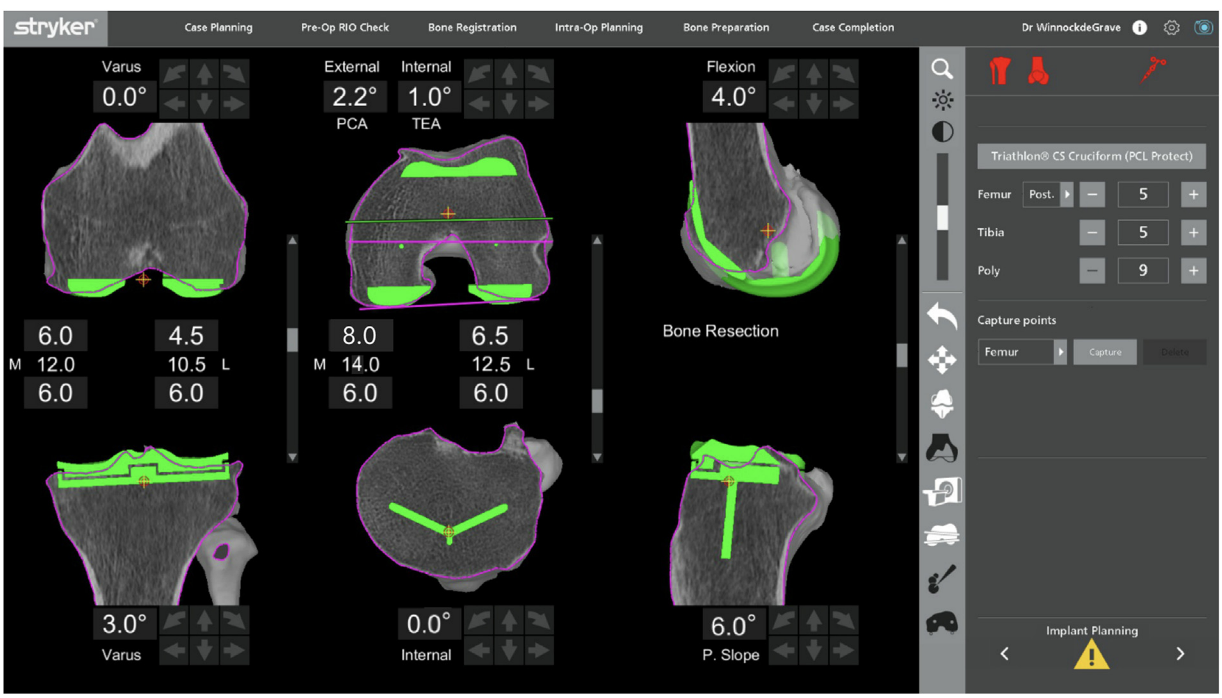

Fig. 2. Preoperative, provisional planning according iKA principles for the Triathlon CR knee. Femoral implant thickness is 8 mm. Bony resections: medial tibia: 6.0 mm, lateral tibia 6.0 mm, distal femur medial 6.0 mm, distal femur lateral 4.5 mm, posterior femur medial 8.0 mm, posterior femur lateral 6.5 mm. With these resections, calculated resection angles in this case: are: 3.0° varus (MPTA) on the tibia, 0.0° on the femur (LDFA) and 2.2° external rotation on the femur according to the PCA. Abbreviations: iKA, inverse kinematic alignment; CR, cruciate retaining; mm, millimeter; MPTA, medial proximal tibial angle; LDFA, lateral distal femoral angle; PCA, posterior condylar axis.

tibial and femoral mechanical axes are performed and by doing soft-tissue releases the native limb alignment is corrected to 180°. Proponents argue that merely the MA biomechanical properties warrant an optimal long-term survival. [10] In current literature, however, many reports on long term implant survival demonstrate that going off from MA, within certain boundaries, does not impact long-term survival. [11–14]

As an alternative to MA, kinematic alignment (KA) was first published in 2012. [15] KA is a patient specific alignment strategy. The femoral and tibial pre-arthritic joint surfaces are restored by removing bone and cartilage thicknesses corresponding with the implant thickness. In the presence of cartilage or bone loss, the resection thickness is adapted accordingly. The aim is to restore the patient's native soft tissue laxity. [16] To resolve tightness, no soft tissue releases are executed but modifications to the tibial cut are performed. Clinical outcomes of KA possibly outperform MA in the varus knee [17], yet KA outcomes might be less predictable in the valgus knee. [18] Meta-analyses are still indecisive, since clinical outcome in different trials with KA are not unequivocally better than MA [19,20]. A variant to KA is restricted kinematic alignment (rKA), applying boundaries to KA principles to prevent extreme implant positions in patients with atypical knee anatomy. [6,21]

Recently, a new patient specific alignment concept, inverse kinematic alignment (iKA), was introduced [22]. In iKA, the native

Table 1
Guidelines for component- and overall alignment according iKA principles.

Tibia	
Coronal(varus/valgus)	Parallel to the native tibial joint line
	Equal bone resections, taking into account bony wear when present
	Boundary: MPTA (deg): 84 - 92
Sagittal(slope)	Parallel to native slope of medial tibial plateau in posterior cruciate retaining design
	Reduced slope in cruciate sacrificing design
Femur	
Coronal(varus/valgus)	Parallel to the tibial resection, with soft tissue envelope tensioned in extension (10° flexion)
	Equal gaps medial and lateral in extension
	Medial resection according implant thickness
	Boundary: mLDFA (deg): 84 - 93
Axial(rotation)	Parallel to the tibial resection, with the soft tissue envelope tensioned in flexion (90° flexion)
	Equal gaps medial and lateral in flexion, or slight more loose lateral gap
	Medial resection according implant thickness
Overall	*Boundary: HKA (deg): 174 - 183*

tibial anatomy is restored by removing bone and cartilage corresponding with the implant thickness on the medial and lateral tibial condyle (Fig. 1) so that the native tibial joint line obliquity (JLO) is restored. After this patient specific, anatomical tibial cut, the rest of the procedure is the same as a conventional, gap balancing technique: balancing the extension and flexion gap by adapting the femoral cuts, as a well-balanced knee is the goal. No soft tissue releases are performed, within the boundaries of hip-knee-ankle (HKA) angle between 174° and 183°. The difference between KA and iKA is that in KA the knee is balanced by changing the orientation of the tibial cut while in iKA the knee is balanced by changing the orientation of the femoral cuts.

We describe the iKA surgical technique and report resection angles and thicknesses of 100 consecutive, robotically assisted cases.

2. Surgical Technique

A preoperative computed tomography (CT) scan of the hip, knee and ankle is uploaded to the TKA application platform for segmentation of a subject-specific three-dimensional model of the knee. The robotic system (MAKO, Stryker, Kalamazoo, MI, USA) is set up and calibrated following the standard protocol [23].

Preoperatively, the implant is virtually positioned according iKA settings (resections and angles) provisionally, as detailed in Fig. 2 and the Video. With iKA, the aim is to restore the native medial proximal tibial angle (MPTA), by performing equal bony resections medial and lateral on the tibial plateau. Resection thicknesses are measured from the middle of the medial and the middle of the lateral tibial condyle at 2/3rd posterior, usually the deepest point on the plateau where the contact point with the femoral condyle is. The native MPTA is restored within the boundaries of 84° (varus) and 92° (valgus) preventing extreme implant positions. Postoperative varus beyond 3° from neutral [12,13], and up to 6° varus [11] have shown no deleterious effect on implant survival. These boundaries represent native tibial alignment in 93% of Caucasian knees. [24] The tibial slope is set parallel to the native medial tibial slope. During surgery, the tibial resection angle (MPTA) is not changed anymore. On the femoral side, the femoral component is provisionally positioned to restore the medial joint line height, resulting in MCL isometry and preventing mid-flexion instability [25].

The patient is positioned supine on a regular operation room (OR) table. A far medial subvastus approach is performed [26]. Once the approach is finished, the tourniquet is deflated for the remainder of the surgery. Tibial and femoral navigation trackers are fixed

Table 2
Guidelines for balancing during TKA surgery according iKA principles.

Extension - Flexion		
Tight	Extension & flexion	Recut tibia
	Extension	Recut distal femur Or: recut tibia and posteriorize femoral component
	Flexion	Anteriorize femoral component Or: recut tibia and distalize femur
Loose	Extension & flexion	Cut less tibia Or: use thicker insert
	Extension	Distalize femoral component Or: cut less tibia and anteriorize femoral component
	Flexion	Posteriorize femoral component Or: cut less tibia (or use thicker insert) and proximalize femoral component
Medial - Lateral		
Extension	Tight medial & loose lateral	Add varus to distal femur
	Loose medial & tight lateral	Add valgus to distal femur
Flexion	Tight medial & loose lateral	Add external rotation to femoral component
	Loose medial & tight lateral	Add internal rotation to femoral component
Soft tissue release		
	HKA angle > 6° varus	Medial release
	HKA angle > 3° valgus	Lateral release

TKA: total knee arthroplasty; iKA: inverse kinematic alignment; HKA: hip-knee-ankle.

Table 3
Patient demographics of 100 consecutive TKA patients.

	Mean ± SD	(Min-Max)
Age (years)	68,0 ± 8,5	(52–94)
BMI (kg/m^2)	29,5 ± 5,0	(19,6–44,7)
Women/Men	59/41	
Preoperative HKA angle (deg)		
Varus knees (< 177°)	51	(168–176)
Neutral knees (177° to 183°)	38	(177–183)
Valgus knees (> 183°)	11	(184–190)

TKA: total knee arthroplasty; SD: standard deviation; deg: degrees; BMI: body mass index; HKA: hip-knee-ankle.

to the bones, and femur and tibia registration is done. Next, the status of the soft-tissue envelope is incorporated in the robotic platform: after removal of the osteophytes, the knee ligaments are tensioned in extension (10° flexion) and flexion (90° flexion, patella in place) by holding the leg manually, or by using a ligament tensioner or spoons. The gap sizes are assessed and recorded with the navigation. By doing this, the medial and lateral gap sizes in extension and flexion, according to the preoperative, provisional implant planning are known. As a well-balanced knee is the goal, adjustments to the implant position are now made, until equal medial and lateral gap sizes both in extension and flexion are reached. Since iKA is defined by the restoration of the native tibial joint line obliquity, the preset tibial resection angle is never changed. Mainly the position of the femoral component is adjusted. Guidelines for implant positioning and balancing according iKA principles are detailed in Table 1, Table 2 and the Video. Once the knee is virtually balanced, all resections are executed using the robotic arm. Trial implants are put in place and the stability, alignment and range of motion are assessed both conventionally and by using the navigation system. At this point, adjustments (ie. recuts and/or soft tissue

Table 4
Intraoperative measurements of iKA settings and bony resections categorized according to preoperative HKA angle (Varus: < 177°; Neutral: 177° to 183°; Valgus: > 183°).

	Varus (n = 51)			Neutral (n = 38)			Valgus (n = 11)		
	Mean	±SD	(min-max)	Mean	±SD	(min-max)	Mean	±SD	(min-max)
Angles									
HKA angle									
Preoperative (deg)	173,2	±1,7	(168–176)	178,6	±2,1	(177–183)	185,1	±1,5	(184–190)
Postoperative (deg)	177,0	±1,6	(174–180)	179,5	±1,0	(176–183)	181,4	±1,0	(180–183)
Net change (deg)	3,8	±0,9	(2–8)	0,9	±2,0	(0–4)	-3,7	±1,4	(-7–-2)
MPTA									
Preoperative (deg)	86,0	±1,3	(82,0–89,5)	87,4	±1,1	(83,0–90,5)	89,6	±2,1	(87,0–95,5)
Postoperative (deg)	86,3	±1,2	(84,0–89,5)	87,7	±1,0	(84,0–90,5)	89,3	±1,6	(87,0–92,0)
Net change (deg)	0,3	±0,6	(0,0–2,5)	0,3	±0,3	(0,0–2,0)	-0,5	±0,8	(0,0–-3,5)
mLDFA									
Preoperative (deg)	88,0	±1,2	(85,5–91,0)	87,0	±1,1	(83,5–88,5)	86,1	±1,5	(82,5–89,0)
Postoperative (deg)	89,3	±1,3	(86,0–92,0)	88,2	±1,0	(84,0–89,5)	87,9	±1,3	(84,0–89,0)
Net change	1,4	±0,9	(0,0–2,5)	1,2	±0,6	(0,0–3,0)	1,8	±0,8	(0,5–4,0)
Femoral rotation from PCA (deg; - internal)	2,0	±1,2	(-1,0–4,6)	1,9	±1,2	(-0,5–4,1)	1,3	±1,3	(-1,0–4,0)
Femoral rotation from TEA (deg; - internal)	-0,8	±1,8	(-4,1–3,3)	-1,0	±1,4	(-3,5–2,4)	-1,8	±1,4	(-4,0–3,0)
Tibial Slope (deg)	6,0	±0,7	(4,2–7,9)	5,7	±0,5	(4,0–7,3)	5,0	±1,0	(3,1–7,2)
Resections (bone)									
Tibia									
Medial (mm)	6,1	±0,7	(3,0–8,5)	6,0	±0,6	(3,0–8,0)	5,5	±0,8	(3,5–7,5)
Lateral (mm)	6,3	±0,6	(4,0–8,5)	6,1	±0,6	(3,5–7,5)	5,5	±0,9	(3,0–7,5)
Femur									
Distal medial (mm)	6,0	±0,8	(3,5–7,5)	6,1	±0,6	(4,0–7,5)	6,3	±1,2	(3,5–8,0)
Distal lateral (mm)	4,6	±1,3	(3,0–7,0)	4,8	±1,2	(3,0–6,5)	4,1	±1,4	(2,5–6,5)
Posterior medial (mm)	8,0	±1,0	(5,5–9,5)	7,6	±0,8	(5,5–9,0)	7,1	±0,9	(5,0–8,5)
Posterior lateral (mm)	6,3	±1,0	(3,5–8,0)	6,1	±0,9	(3,0–8,0)	6,5	±0,7	(4,5–8,0)

iKA: inverse kinematic alignment; SD: standard deviation; deg: degrees; HKA: Hip-Knee-Ankle; MPTA: medial proximal tibial angle; mLDFA: mechanical lateral distal femoral angle; PCA: posterior condylar axis; TEA: transepicondylar axis.

releases) can be made but are rarely (<5%) necessary. [22] The surgery is continued by resurfacing the patella and determining the tibial rotation.

3. Results

The final implant position using iKA principles a single surgeon continuous series of 100 consecutive, robotically assisted TKA surgeries over 1 year period were assessed. Inclusion criteria was multicompartmental osteoarthritis (OA) of the knee with at least grade 4 OA in 1 compartment. Exclusion criteria was posttraumatic OA. Patient demographics are detailed in Table 3. The Triathlon knee system and Mako robotic system (Stryker, Kalamazoo, USA) was used in all cases. Triathlon femoral implant thickness is 8,5 mm. Resection thicknesses and resections angles were defined, recorded and executed by the robotic system. All surgeries were performed according the iKA positioning and balancing protocol, as detailed in Table 1 and Table 2. The posterior cruciate ligament was retained in all cases. Implants were fully cemented. In all cases a 9 mm polyethylene was used. No intra-operative complications occurred.

Population was categorized according the preoperative HKA angle into 3 groups: varus (<177°), neutral (177° to 183°) and valgus (>183°). The mean implant positions are detailed in Table 4.

In the varus subgroup (n=51), the mean postoperative HKA angle was 177,0° with a mean MPTA of 86,3° and a mean mLDFA of 89,3°. In the neutral subgroup (n=38), the mean postoperative HKA angle was 179,5° with a mean MPTA of 87,7° and a mean mLDFA of 88,2°. In the valgus subgroup (n=11), the mean postoperative HKA angle was 181,4° with a mean MPTA of 89,3° and a mean mLDFA of 87,9°.

The mean femoral and tibial resections of bone for the 3 subgroups are displayed in Table 4.

The mean medial tibial resection of bone varies between 5,5 and 6,1 mm. The mean lateral tibial bony resection varies between 5,5 and 6,3 mm. The mean distal resection on the medial femoral condyle varies between 6,0 and 6,3 mm. The mean distal resection on the lateral femoral condyle varies between 4,1 and 4,8 mm. The mean posterior resection on the medial femoral condyle varies between 7,1 and 8,0 mm. The mean posterior resection on the lateral femoral condyle varies between 6,1 and 6.5 mm.

A varus, neutral and valgus case are demonstrated in Fig. 3, Fig. 4 and Fig. 5.

4. Discussion

The study on this robotically assisted TKA series report the tibial and femoral resections when following iKA principles. iKA is a tibia first technique whereby the native tibial joint line obliquity is restored (Table 4), within boundaries (Table 1). Subsequently, medial and lateral, extension and flexion gaps are virtually tensioned, and parallel cuts on the femur are made. In comparison with mechanical alignment, more bone is resected on the lateral condyle, resulting in a better restoration of the native femoral valgus angle, and less external rotation of the femoral implant. By preserving the native tibial joint line, less femoral anatomy modifications will be produced by the gap balancing intervention, which was shown to translate in better clinical outcomes, compared to MA. [27,28] One-year clinical outcome of iKA is reported indicating a higher patient satisfaction with iKA, compared to MA. [22]

Performing a tibia first technique such as iKA could offer potential benefits, in comparison to a femur first technique, such as KA. In the coronal plane, generally, a lower LDFA is measured in the valgus knee. [29] In a femur first technique, equal resections are performed on the distal femur resulting in a significant valgus cut. Therefore, a parallel yet excessive tibial varus cut in a generally neutral tibia is performed, sacrificing important medial tibial bone stock. Overresection of medial tibial bone should be avoided when aimed for optimal long-term survival. [30,31] As the mean

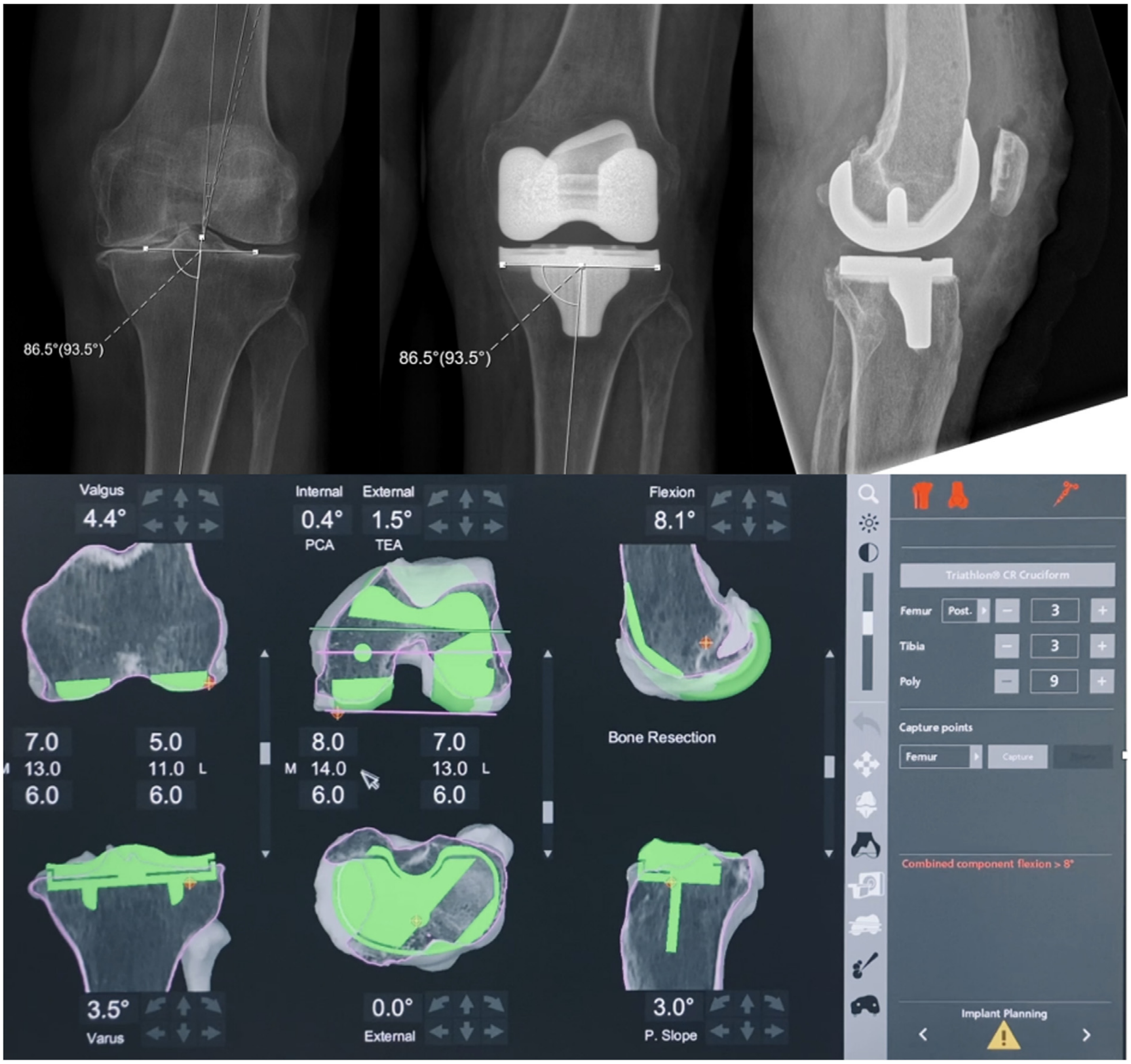

Fig. 3. 68 years old female with medial and patellofemoral grade 4 osteoarthritis. Preoperative alignment of 2° varus (HKA angle 178°). Native MPTA of 3,5° varus (86,5°). Postoperative MPTA of 3,5° varus (86,5°), LDFA of 4,5° valgus (85,5°) and overall postoperative alignment of 1° valgus (HKA angle 181°). Final resections and resection angles are shown on the robotic platform. Abbreviations: MPTA, medial proximal tibial angle; LDFA, lateral distal femoral angle; HKA, hip knee ankle.

joint line congruency angle (JLCA) in non-arthritic knees reported in literature is 2° [32,33], the mean postoperative JLO in iKA will be 2° less oblique compared to KA, possibly enhancing long-term survival.

For the patellofemoral tracking, with iKA, the femoral implant is positioned in the axial plane with a mean external rotation around 2° compared to the PCA (Table 4). In the coronal plane, a mean varus position of 2° compared to the native LDFA, which corresponds with the reported alignment and position of the sulcus angle in literature [34,35]. Moreover, trochlear anatomy is correlated to the MPTA [36] which is nicely exemplified in practice by this tibia-first, iKA technique. Furthermore, iKA possibly favors optimal patellofemoral tracking which might be a benefit regarding the current use of off-the-shelf implants.

Accordingly, in most cases the native surfaces of the lateral femoral condyle are changed with iKA. The effects on the native femorotibial kinematics and kinetics are currently investigated with extensive biomechanical analysis during gait and functional movements (ClinicalTrials.Gov: NCT04912973), comparing iKA and MA, with healthy controls.

As a conclusion, iKA is a tibia first, gap-balancing, alignment strategy restoring the native tibial joint line obliquity, trochlear

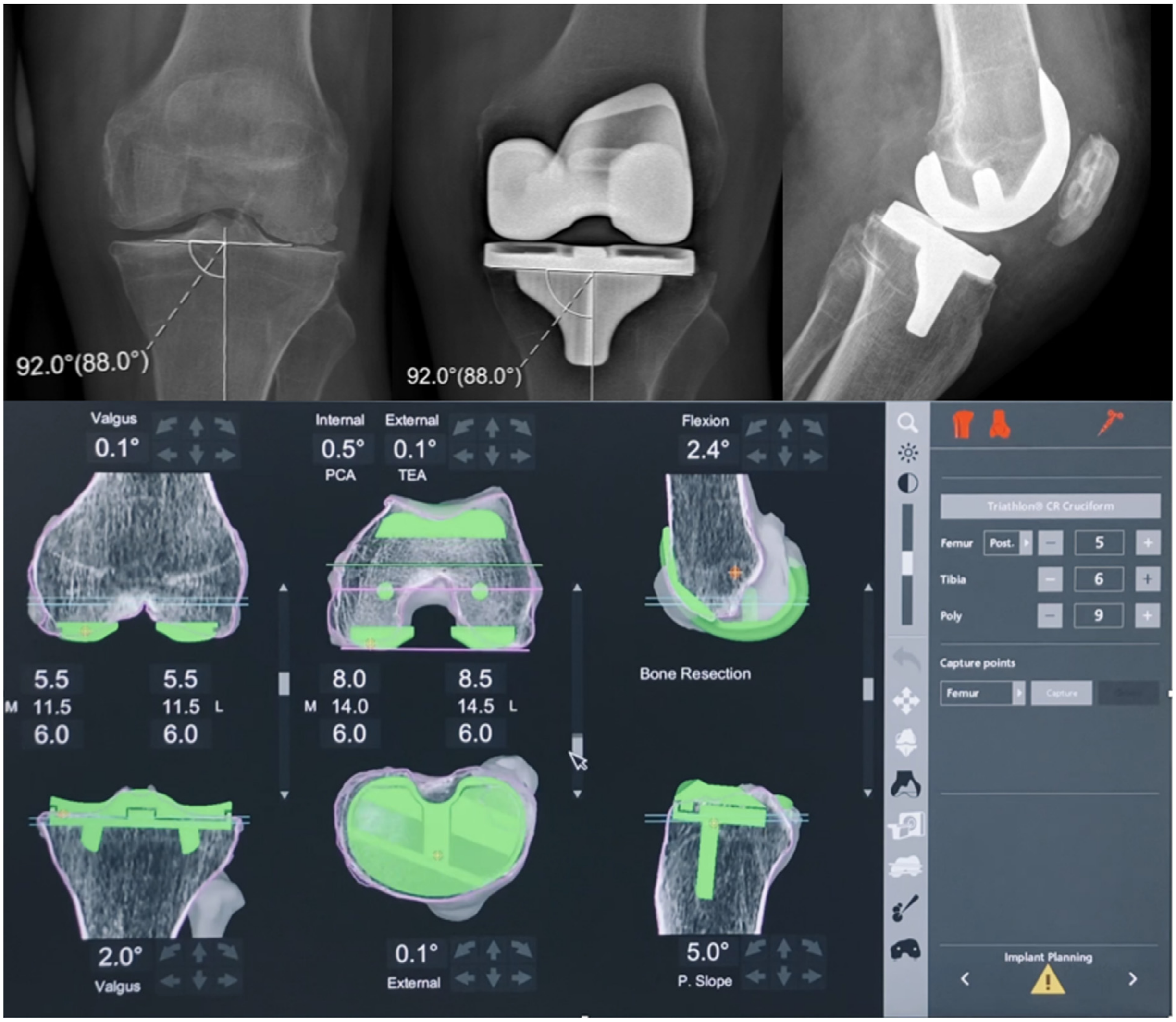

Fig. 4. 75 years old male with lateral and patellofemoral grade 4 osteoarthritis. Preoperative alignment of 6° valgus (HKA angle 186°). Native MPTA of 2° valgus (92°). Postoperative MPTA of 2° valgus (92°), LDFA of 0° valgus (90°) and overall postoperative alignment of 2° valgus (HKA angle 182°). Final resections and resection angles are shown on the robotic platform. Abbreviations: MPTA, medial proximal tibial angle; LDFA, lateral distal femoral angle; HKA, hip knee ankle.

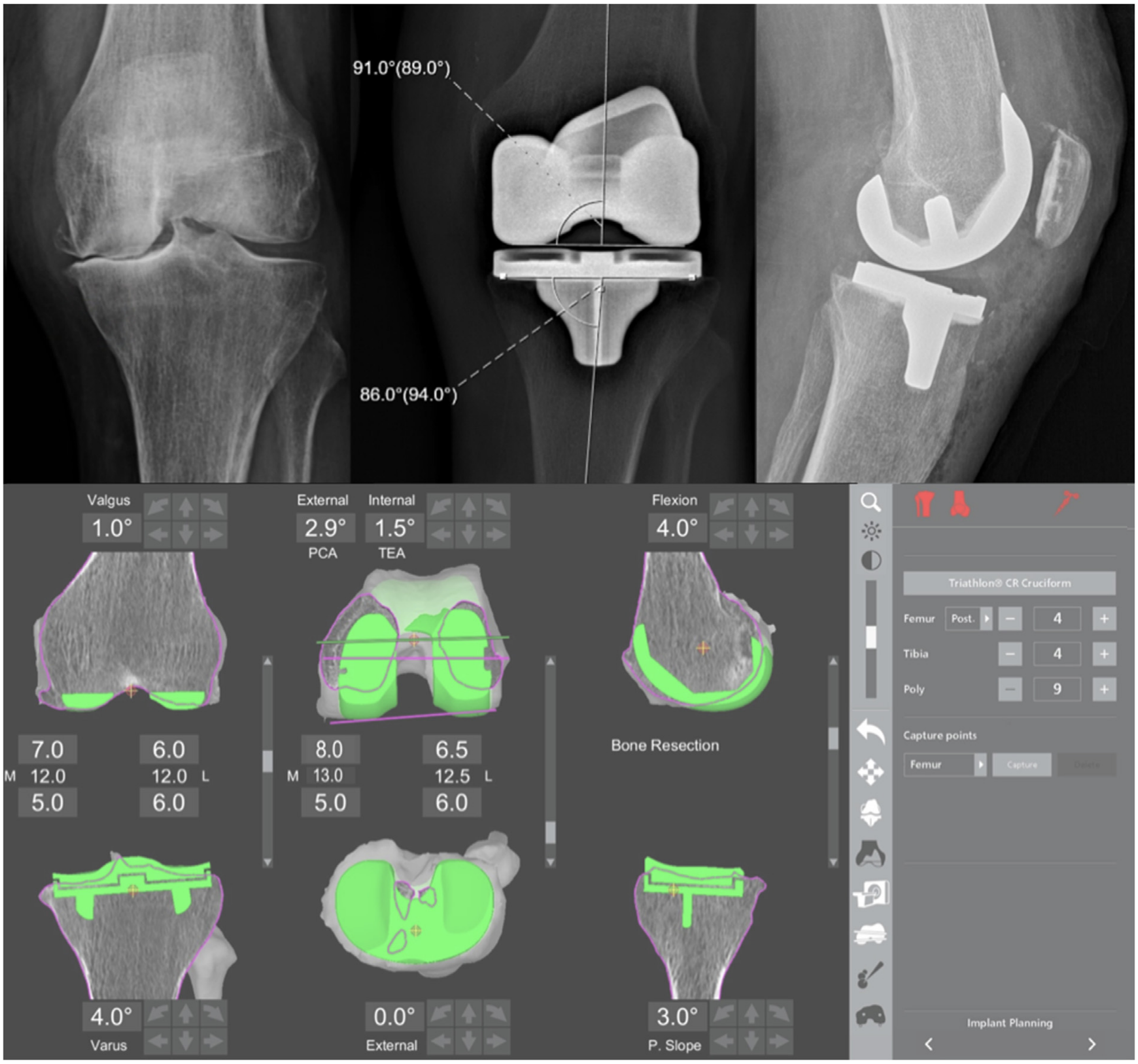

Fig. 5. 78 years old female with medial grade 4 and patellofemoral grade 3 osteoarthritis. Preoperative alignment of 8° varus, with some medial bony wear. Postoperative MPTA of 4° varus (86°), LDFA of 1° valgus (89°) and an overall postoperative alignment of 3° varus (HKA angle 177°). Final resections and resection angles are shown on the robotic platform. Abbreviations: MPTA, medial proximal tibial angle; LDFA, lateral distal femoral angle; HKA, hip knee ankle.

anatomy and femoral anatomy close to native. Both in the coronal plane and the axial plane, iKA might offer advantages over existing alignment strategies, possibly providing optimal clinical outcome and durable long-term survival, regardless of whether the alignment is varus, neutral or valgus. However, further studies are needed to validate the clinical benefits and long-term outcomes.

Disclosure of interest

The authors declare that they have no competing interest.

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None

Contribution

PWDG: design of the technique, design of the study, collecting and analyzing data, writing the manuscript, making the video

JK: collecting the data

TL, TT, FL, KC: editing the manuscript

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.otsr.2022.103305.

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