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KNEE

Inverse kinematic alignment accommodates native coronal knee alignment better in comparison to adjusted mechanical alignment and restricted kinematic alignment

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Abstract

Purpose The purpose was to determine the proportion of native non-arthritic knees that fit within the target zones of adjusted mechanical alignment (aMA), restricted kinematic alignment (rKA), and inverse kinematic alignment (iKA), and to estimate adjustments in native coronal alignment to bring outlier knees within the respective target zones. The hypothesis was that the target zone of iKA, compared to the target zones of aMA and rKA, accommodates a higher proportion of native non-arthritic knees.

Methods The study used measurements obtained from a computed tomography (CT) scan database (SOMA, Stryker) of 972 healthy knees (Caucasian, 586; Asian, 386). Hip knee ankle (HKA) angle, medial proximal tibial angle (MPTA) and lateral distal femoral angle (LDFA) were used to estimate the proportions of knees within the patient-specific alignment target zones; and to estimate theoretical adjustments of MPTA, LDFA and soft tissue balance (HKA) to bring outlier knees within target zones. Theoretical adjustments to bring outlier knees within the alignment target zones of aMA, rKA and iKA were calculated by subtracting the native coronal alignment angles ($MPTA_{native}$, $LDFA_{native}$ and HKA_{native}) from angles on the nearest target zone border ($MPTA_{target}$, $LDFA_{target}$ and HKA_{target}).

Results Patients were aged 59.8 ± 15.8 years with a BMI of 25.0 ± 4.4 kg/m^2. The HKA angles were between 168° and 186°, MPTA between 78° and 98° and LDFA between 79° and 93°. Of the 972 knees, 81 (8%) were in the aMA target zone, 530 (55%) were in the rKA target zone, and 721 (74%) were in the iKA target zone. Adjustments of MPTA, LDFA and HKA angle to bring outlier knees within the target zones, were, respectively, 90, 91 and 28% for aMA, 45, 28 and 25% for rKA, and 25, 23 and 7% for iKA.

Conclusions There is considerable variability in native knee coronal alignment that corresponds to different proportions of the restricted patient-specific alignment target zones for TKA. Although extension of the MPTA and LDFA target zones with rKA accommodate native knee alignment better than aMA, up to 25% would require adjustment of native HKA angle. By also extending the HKA angle target zone into varus, iKA accommodates a greater proportion (93%) of native limb alignment.

Level of evidence IV.

Keywords Total knee arthroplasty · Coronal alignment · HKA angle · MPTA · LDFA · Adjusted mechanical alignment · Restricted kinematic alignment · Inverse kinematic alignment

Introduction

Total knee arthroplasty (TKA) has been aligned perpendicular to the mechanical axes—mechanical alignment—to achieve long-term survival. Hereby, the native alignment and soft tissue balance of a constitutional varus or valgus knee are changed, which could lead to dissatisfaction following TKA [25]. By aiming to restore native constitutional

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alignment—patient-specific alignment—a balanced TKA is achieved with a lower need for soft tissue releases [23].

Recent studies reported favourable clinical outcomes following TKA using patient-specific alignment techniques [2, 14, 29, 30], and some surgeons are therefore more comfortable in deviating from limits imposed by mechanical alignment [17]. Yet, there is no consensus on the 'safe zone' beyond which long-term survival could be compromised [3, 23, 25]. Instead of following an unrestricted patient-specific technique, e.g. kinematic alignment [13], some choose to apply restrictions defined as 'target zones', e.g. adjusted mechanical alignment (aMA) [29], restricted kinematic alignment (rKA) [3], or inverse kinematic alignment (iKA) [30].

Functional knee phenotypes [10–12, 19] that fall within the 'target zones' of restricted patient-specific alignment techniques will require little to no adjustment of their native femoral mechanical angle, tibial mechanical angle and/or hip knee ankle angle. The purpose of this study was to determine the proportion of native non-arthritic knees that fit within the target zones of aMA, rKA, and iKA, and to estimate adjustments in native coronal alignment to bring outlier knees within the respective target zones. The hypothesis was that the target zone of iKA, compared to the target zones of aMA and rKA, would accommodate a higher proportion of native non-arthritic knees. The present study presents the boundaries of three restricted patient-specific alignment techniques, and how they impact the number of outliers from the respective target zones.

Methods

Cohort

This study used measurements of HKA angle, medial proximal tibial angle (MPTA) and lateral distal femoral angle (LDFA), obtained from a computed tomography (CT) scan database of healthy knees (SOMA, Stryker, Mahwah, New Jersey) [27]. The SOMA database consists of over 25,000 bone models from over 3600 patients worldwide. The CT scans were acquired exclusively for medical indications such as polytrauma (20%), CT angiography (70%) and other reasons (e.g. total joint replacement) (10%) [20, 21]. From this database, 972 knees (Caucasians, 586; Asian, 386) without bone or joint abnormalities, evidence of substantial osteoarthritis or previous surgery were retrieved (Table 1).

Measurements

The measurement protocol has been previously described and validated [15]. The HKA angle was measured between the mechanical axes of the femur (line connecting the femoral head centre to the knee centre) and tibia (line connecting the knee centre to ankle centre). The MPTA was measured between the tibial mechanical axis and the proximal tibial axis (line tangential to the medial and lateral tibial compartments). The LDFA was measured between the femoral mechanical axis and the distal femoral axis (line tangential with the most distal points on the medial and lateral femoral condyles). Measurements of HKA, MPTA, and LDFA were then profiled to each bone by automated software within < 2 mm and < 1° margin of error [21], and rounded to the nearest whole number.

Adjusted mechanical alignment

The aMA technique is an adjusted version of neutral mechanical alignment which aims to respect a patient's native coronal limb alignment, but within a target zone for HKA angles from 177° to 183° [24]. The native HKA angle is found by correcting the coronal limb alignment for cartilage wear and/or bony erosion, or by tensioning the extension gap. To balance the knee, aMA allows adjustments of LDFA to range from 87° to 90° in valgus knees, and from 90° to 93° in varus knees, while maintaining an MPTA of 90°. When still outside the HKA angle target zone of 177° to 183°, a medial or lateral soft tissue release may be performed (Fig. 1a).

Table 1 Cohort characteristics

	Combined cohort ($n=972$)		Caucasian ($n=586$)		Asian ($n=386$)		Caucasian versus Asian
	Mean ± SD	(Range)	Mean ± SD	(Range)	Mean ± SD	(Range)	p value
Age, years	59.8 ± 15.8	(18–92)	61.9 ± 14.8	(21–92)	56.6 ± 16.6	(18–88)	< 0.001
BMI, kg/m^2	25.0 ± 4.4	(14–42)	25.6 ± 4.6	(16–42)	23.3 ± 3.4	(14–33)	< 0.001
HKA angle, degrees	178.6 ± 2.8	(168–186)	178.9 ± 2.6	(170–185)	178.2 ± 3.0	(168–186)	0.005
MPTA, degrees	85.6 ± 2.3	(78–98)	86.2 ± 2.2	(78–92	84.9 ± 2.4	(78–98)	< 0.001
LDFA, degrees	85.9 ± 2.0	(79–93)	86.2 ± 1.9	(80–91	85.5 ± 2.2	(79–93)	< 0.001

SD standard deviation, *BMI* body mass index, *HKA* hip knee ankle, *MPTA* medial proximal tibial angle, *LDF*A lateral distal femoral angle

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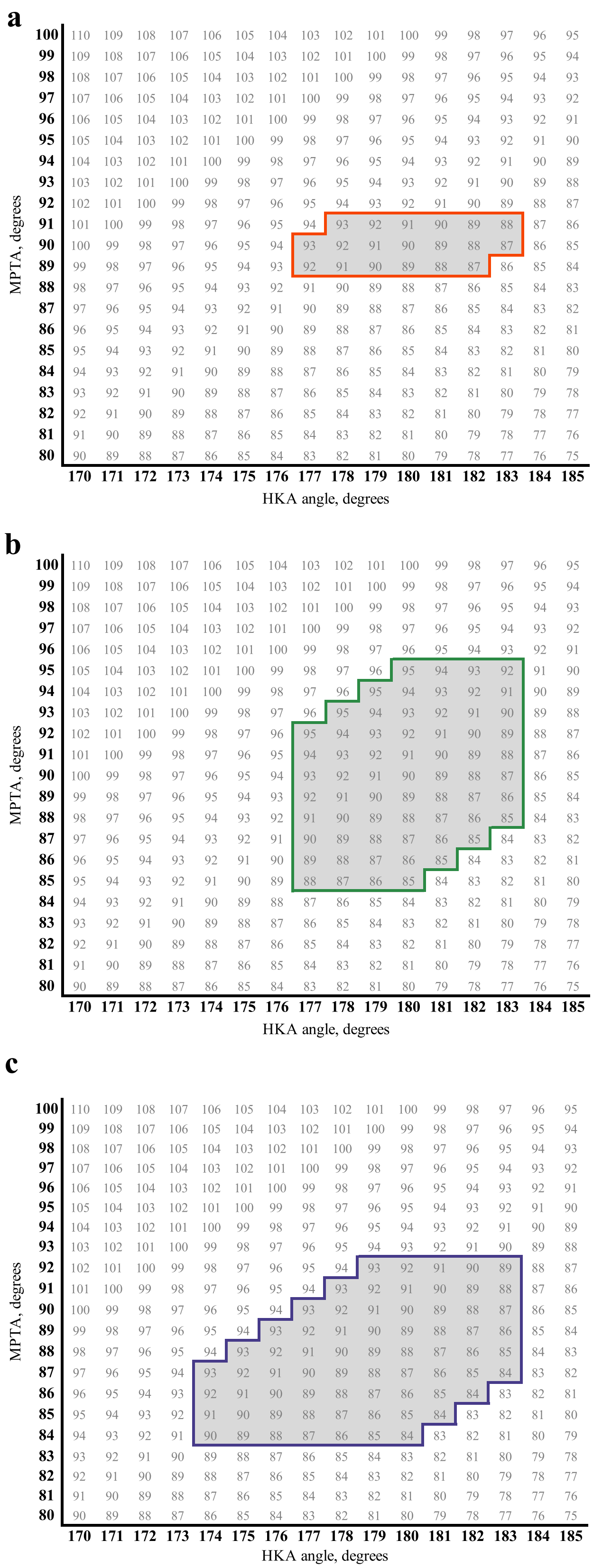

Fig. 1 Definition of the restricted patient-specific alignment target zones. **a** aMA target zone, **b** rKA target zone, **c** iKA target zone

Restricted kinematic alignment

The rKA is a 'femur first' technique that aims to restore the pre-arthritic LDFA within a target zone from 85° to 95°, and the HKA angle within a target zone from 177° to 183° [3]. The native HKA angle is found by correcting the coronal limb alignment for cartilage wear and/or bony erosion, or by tensioning the extension gap. To balance the knee, the MPTA is adjusted within a target zone from 85° to 95°. When still outside the HKA angle target zone of 177° to 183°, a medial or lateral soft tissue release may be performed (Fig. 1b).

Inverse kinematic alignment

The iKA is a 'tibia first' technique that aims to restore pre-arthritic MPTA within a target zone from 84° to 92° and HKA angle within a target zone from 174° to 183° [30]. The native HKA angle is found by correcting the coronal limb alignment for cartilage wear and/or bony erosion, or by tensioning the extension gap. To balance the knee, the LDFA is adjusted within a target zone from 84° to 93°. When still outside the HKA angle target zone of 174° to 183°, a medial or lateral soft tissue release may be performed (Fig. 1c).

Analysis

Heat maps presented the proportions of knees within the aMA, rKA and iKA target zones. In aMA, a tolerance of ± 1° from neutral was used on the tibia, so the target zone for MPTA was defined as 89° to 91°. The analysis was done for the entire cohort of knees, and subgroup analyses were performed for Caucasian and Asian knees.

Knees outside the target zones were grouped in 8 outlier zones (Zones I to VIII) according to their phenotype values (HKA angle: HKA_{VAR}, HKA_{NEU}, HKA_{VAL}; MPTA: $MPTA_{VAR}$, $MPTA_{NEU}$, $MPTA_{VAL}$; LDFA: $LDFA_{VAR}$, $LDFA_{NEU}$, $LDFA_{VAL}$) (Fig. 2 & Supplementary Table A1). Theoretical adjustments to bring outlier knees within the alignment target zones of aMA, rKA and iKA were calculated by subtracting the native coronal alignment angles ($MPTA_{native}$, $LDFA_{native}$ and HKA_{native}) from angles on the nearest target zone border ($MPTA_{target}$, $LDFA_{target}$ and HKA_{target}). The estimated adjustments were quantified as required changes of MPTA ($MPTA_{native}$–$MPTA_{target}$), LDFA ($LDFA_{native}$–$LDFA_{target}$) and HKA (HKA_{native}–HKA_{target}). Finally, the authors assumed that knees outside the HKA target range could potentially require soft tissue release(s) to bring outlier knees within the target zone.

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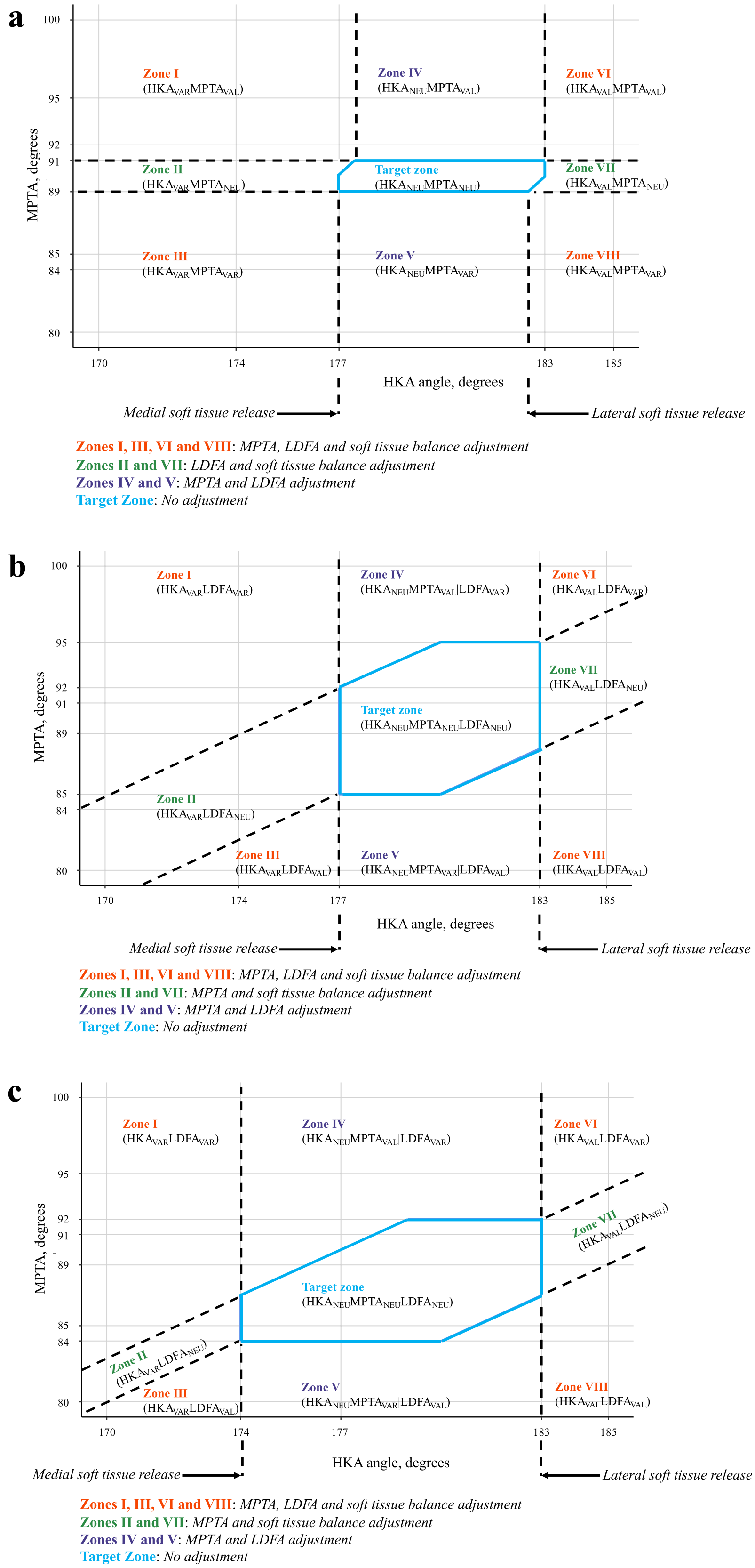

Fig. 2 Classification of the outlier zones (Zones I to VIII) based on the coronal alignment phenotypes, **a** aMA target zone, **b** rKA target zone, **c** iKA target zone

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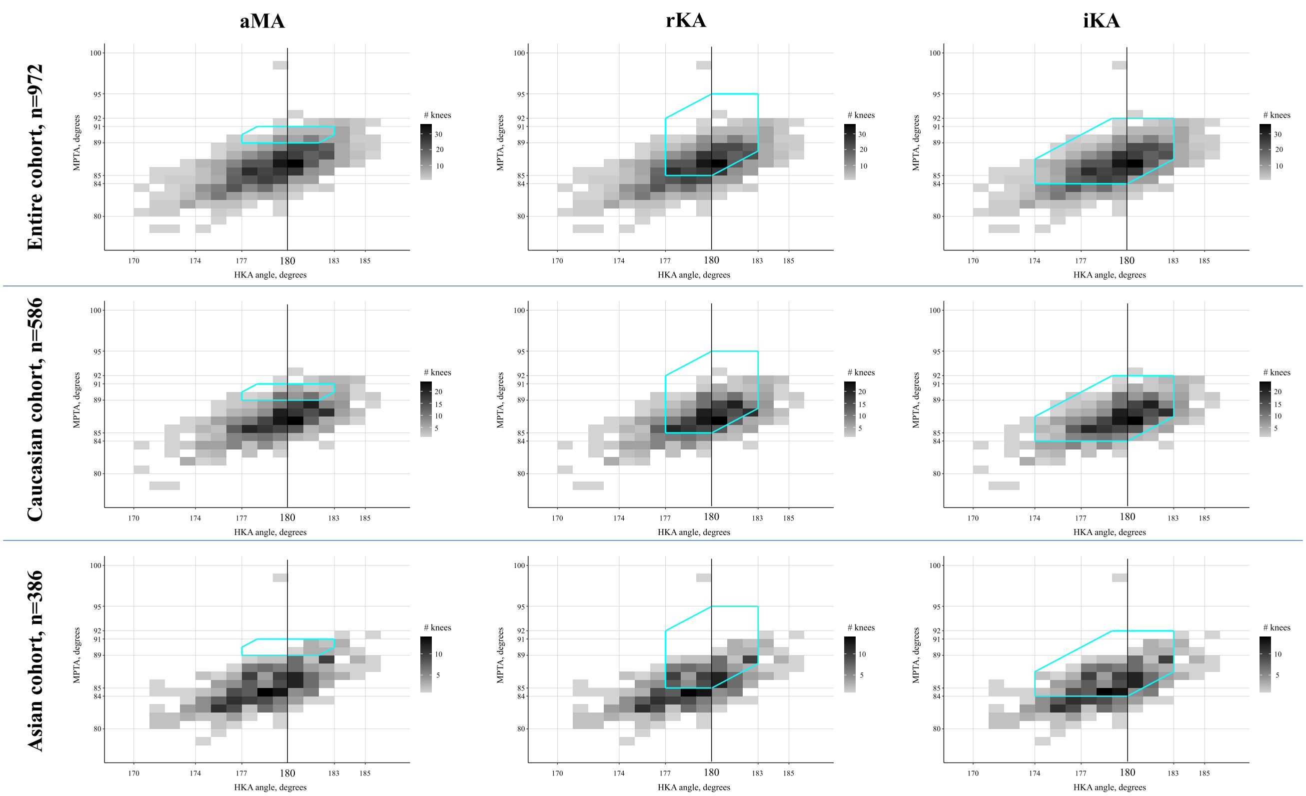

Fig. 3 Heat maps illustrating the proportion of knees that are within the aMA (column 1), rKA (column 2) and iKA target zones (column 3). Row 1 represents the entire cohort of 972 knees, row 2 the Caucasian cohort of 586 knees and row 3 the Asian cohort of 386 knees. Darker grey represents a higher density, and light grey represents a lower density

Statistical analysis

Descriptive statistics were used to summarise the data. Shapiro–Wilk tests were used to determine the normality of distributions: differences among datasets were evaluated with the student *t* test (normally distributed) or the Wilcoxon rank sum tests (Mann–Whitney *U* test, non-Gaussian). Values for $p < 0.05$ were considered statistically significant. All statistical analyses were performed using R version 4.1.0 (R Foundation for Statistical Computing, Vienna, Austria).

Ethical aspects

All scans were obtained per local legal and regulatory requirements which included ethics board approval and informed patient consent [21]. The SOMA database was constituted after local ethical approval and informed patient consent for the use of their data in future studies. The present study was approved by the local institutional review board (IRB#: B1172022000030).

Results

Knees within the alignment target zones

Of the 972 knees, 81 (8%) were in the aMA target zone, 530 (55%) were in the rKA target zone, and 721 (74%) were in the iKA target zone (Fig. 3). Of the 586 Caucasian knees, 65 (11%) were in the aMA target zone, 384 (66%) were in the rKA target zone, and 494 (84%) were in the iKA target zone. Of the 386 Asian knees, 16 (4%) were in the aMA target zone, 146 (38%) were in the rKA target zone, and 227 (59%) were in the iKA target zone.

Estimated adjustments in coronal alignment

For aMA, adjustments of MPTA, LDFA and HKA angle were required in, respectively, 90, 91 and 28% of knees (Table 2). For rKA, adjustments of MPTA, LDFA and HKA angle were required in, respectively, 45, 28 and 25% of knees. For iKA, adjustments of MPTA, LDFA and HKA angle were required in, respectively, 25, 23 and 7% of knees.

For aMA in Caucasian knees, adjustments of MPTA, LDFA and HKA angle were required in, respectively, 86, 88 and 25% (Table 3). For rKA in Caucasian knees, adjustments

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Table 2 Comparison of estimated coronal alignment adjustment for knees of the entire cohort that are outside the target zones of aMA, rKA and iKA

	aMA			rKA			iKA			*p* values		
	n (%)	Mean ± SD	(Range)	*n* (%)	Mean ± SD	(Range)	*n* (%)	Mean ± SD	(Range)	aMA vs rKA	aMA vs iKA	rKA vs iKA
All knees	972			972			972					
MPTA adjustment, deg	872 (90%)	3.9 ± 2.0	(1–11)	433 (45%)	2.1 ± 1.4	(1–9)	242 (25%)	1.8 ± 1.2	(1–8)	< 0.001	< 0.001	< 0.001
LDFA adjustment, deg	881 (91%)	3.4 ± 1.6	(1–9)	273 (28%)	1.5 ± 0.8	(1–4)	222 (23%)	1.6 ± 0.9	(1–6)	< 0.001	< 0.001	n.s.
Soft tissue release, deg	276 (28%)	2.2 ± 1.5	(1–9)	247 (25%)	2.3 ± 1.5	(1–9)	64 (7%)	2.1 ± 1.7	(1–9)	n.s.	n.s.	n.s.
Varus outliers[a]	224			224			41					
MPTA adjustment, deg	222 (99%)	5.7 ± 1.9	(1–11)	224 (100%)	2.8 ± 1.6	(1–9)	41 (100%)	3.1 ± 1.6	(1–8)	< 0.001	< 0.001	n.s.
LDFA adjustment, deg	214 (96%)	3.4 ± 1.9	(− 3 − 8)	62 (28%)	1.6 ± 0.9	(1–4)	24 (59%)	1.2 ± 1.4	(− 2 − 4)	< 0.001	< 0.001	n.s
Soft tissue release, deg	224 (100%)	2.3 ± 1.6	(1–9)	224 (100%)	2.3 ± 1.6	(1–9)	41 (100%)	2.4 ± 2.0	(1–9)	n.s.	n.s.	n.s
Neutral[b]	696			725			908					
MPTA adjustment, deg	615 (88%)	3.3 ± 1.7	(− 7 – 9)	195 (27%)	1.4 ± 0.8	(− 4 – 4)	187 (21%)	1.5 ± 1.0	(− 6 − 6)	< 0.001	< 0.001	n.s.
LDFA adjustment, deg	615 (88%)	3.3 ± 1.7	(− 7 – 9)	195 (27%)	1.4 ± 0.8	(− 4 – 4)	187 (21%)	1.5 ± 1.0	(− 6 − 6)	< 0.001	< 0.001	n.s.
Soft tissue release, deg												
Valgus outliers[c]	52			23			23					
MPTA adjustment, deg	35 (67%)	1.9 ± 0.8	(1–3)	14 (61%)	0.1 ± 1.3	(− 2 – 2)	14 (61%)	− 0.9 ± 0.9	(− 2 − 1)	0.024	< 0.01	n.s.
LDFA adjustment, deg	52 (100%)	2.8 ± 1.4	(1–6)	16 (70%)	2.1 ± 1.0	(1 –4)	11 (48%)	1.6 ± 0.7	(1–3)	n.s.	0.043	n.s.
Soft tissue release, deg	48 (92%)	− 1.5 ± 0.9	(− 4 − 1)	23 (100%)	− 1.5 ± 0.7	(− 3 − 1)	23 (100%)	− 1.5 ± 0.7	(− 3 − 1)	n.s.	n.s.	n.s.

MPTA medial proximal tibial angle, *LDFA* lateral distal femoral angle, *aMA* adjusted mechanical alignment, *rKA* restricted kinematic alignment, *iKA* inverse kinematic alignment, *SD* standard deviation, *n.s.* not significant

[a]HKA angle < 177° for aMA and rKA and < 174° for iKA (Zones: I, II, III)

[b]HKA angle between 177° to 183° for aMA and rKA, and between 174° to 183° for iKA (Zones: IV, V, Target Zone)

[c]HKA angle > 183° for aMA, rKA and iKA (Zones: VI, VII, VIII)

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Table 3 Comparison of estimated coronal alignment adjustment for Caucasian and Asian knees that are outside the target zones of aMA, rKA and iKA

	aMA			rKA			iKA			*p* values		
	n (%)	Mean ± SD	(Range)	*n* (%)	Mean ± SD	(Range)	*n* (%)	Mean ± SD	(Range)	aMA vs rKA	aMA vs iKA	rKA vs iKA
	Caucasian cohort											
All knees	586			586			586					
MPTA adjustment, deg	506 (86%)	3.4 ± 1.8	(1–11)	199 (34%)	1.9 ± 1.2	(1–7)	88 (15%)	1.6 ± 1.0	(1–6)	< 0.001	< 0.001	0.010
LDFA adjustment, deg	514 (88%)	3.0 ± 1.4	(1–7)	106 (18%)	1.4 ± 0.6	(1–4)	75 (13%)	1.4 ± 0.7	(1–4)	< 0.001	< 0.001	n.s.
Soft tissue release, deg	144 (25%)	1.9 ± 1.3	(1–7)	121 (21%)	2.1 ± 1.4	(1–7)	29 (5%)	1.6 ± 0.9	(1–4)	n.s.	n.s.	n.s.
Varus knees[a]	109			109			17					
MPTA adjustment, deg	107 (98%)	5.0 ± 1.9	(1–11)	109 (100%)	2.4 ± 1.5	(1–7)	17 (100%)	2.8 ± 1.6	(1–6)	< 0.001	< 0.001	n.s.
LDFA adjustment, deg	102 (94%)	3.0 ± 1.6	(− 1 – 6)	18 (17%)	1.2 ± 0.4	(1–2)	7 (41%)	2.4 ± 0.8	(2–4)	< 0.001	n.s.	< 0.001
Soft tissue release, deg	109 (100%)	2.2 ± 1.4	(1–7)	109 (120%)	2.2 ± 1.4	(1–7)	17 (100%)	1.8 ± 1.0	(1–4)	n.s.	n.s.	n.s.
Neutral knees[b]	442			465			557					
MPTA adjustment, deg	377 (85%)	2.9 ± 1.5	(− 1 – 7)	81 (17%)	1.4 ± 0.6	(1–4)	63 (11%)	1.3 ± 0.6	(1–3)	< 0.001	< 0.001	n.s
LDFA adjustment, deg	377 (85%)	2.9 ± 1.5	(− 1 – 7)	81 (17%)	1.4 ± 0.6	(1–4)	63 (11%)	1.3 ± 0.6	(1–3)	< 0.001	< 0.001	n.s
Soft tissue release, deg												
Valgus knees[c]	35			12			12					
MPTA adjustment, deg	22 (63%)	1.9 ± 0.8	(1–3)	9 (75%)	0.0 ± 1.2	(− 1 – 2)	8 (67%)	− 1.0 ± 0.9	(− 2 – 1)	0.002	< 0.001	n.s
LDFA adjustment, deg	35 (100%)	2.4 ± 1.2	(1–5)	7 (58%)	1.9 ± 0.7	(1–3)	5 (42%)	1.2 ± 0.4	(1–2)	n.s.	n.s.	n.s.
Soft tissue release, deg	35 (100%)	− 1.2 ± 0.5	(− 3 – 1)	12 (100%)	− 1.3 ± 0.5	(− 2 – 1)	12 (100%)	− 1.3 ± 0.5	(− 2– 1)	n.s	n.s	n.s
	Asian cohort											
All knees	386			386			386					
MPTA adjustment, deg	366 (95%)	4.6 ± 2.1	(1–11)	234 (61%)	2.3 ± 1.5	(1–9)	154 (40%)	1.9 ± 1.3	(1–8)	< 0.001	< 0.001	0.039
LDFA adjustment, deg	367 (95%)	4.0 ± 1.7	(1–9)	167 (43%)	1.6 ± 0.8	(1–4)	147 (38%)	1.7 ± 0.9	(1–6)	< 0.001	< 0.001	< 0.001
Soft tissue release, deg	132 (34%)	2.4 ± 1.7	(1–9)	126 (33%)	2.4 ± 1.7	(1–9)	35 (9%)	2.5 ± 2.1	(1–9)	n.s.	n.s.	n.s.
Varus knees[a]	115			115			24					
MPTA adjustment, deg	115 (100%)	6.3 ± 1.7	(2–11)	115 (100%)	3.1 ± 1.7	(1–9)	24 (100%)	3.3 ± 1.6	(1–8)	< 0.001	< 0.001	n.s.
LDFA adjustment, deg	112 (97%)	3.9 ± 2.1	(− 3 – 8)	44 (38%)	1.7 ± 0.9	(1–4)	17 (71%)	0.7 ± 1.4	(− 2 – 2)	< 0.001	< 0.001	0.022
Soft tissue release, deg	115 (100%)	2.5 ± 1.7	(1–9)	116 (101%)	2.5 ± 1.7	(1–9)	24 (100%)	2.8 ± 2.4	(1–9)	n.s.	n.s.	n.s.
Neutral knees[b]	254			260			351					
MPTA adjustment, deg	238 (94%)	3.9 ± 1.9	(− 7 – 9)	114 (44%)	1.4 ± 0.8	(− 4 – 4)	124 (35%)	1.6 ± 1.2	(− 6 – 6)	< 0.001	< 0.001	< 0.001
LDFA adjustment, deg	238 (94%)	3.9 ± 1.9	(− 7 – 9)	114 (44%)	1.4 ± 0.8	(-4 – 4)	124 (35%)	1.6 ± 1.2	(− 6 – 6)	< 0.001	< 0.001	< 0.001
Soft tissue release, deg												
Valgus knees[c]	17			11			11					
MPTA adjustment, deg	13 (76%)	1.8 ± 0.9	(1–3)	6 (55%)	0.2 ± 1.6	(− 2 – 2)	6 (55%)	− 0.8 ± 1.0	(− 2 – 1)	0.001	0.002	n.s.
LDFA adjustment, deg	17 (100%)	3.5 ± 1.5	(1–6)	9 (82%)	2.3 ± 1.1	(1–4)	6 (55%)	2.0 ± 0.6	(1–3)	n.s.	0.045	n.s.
Soft tissue release, deg	17(100%)	− 2.1 ± 1.1	(− 4 – 1)	11 (100%)	− 1.8 ± 0.9	(− 3 – 1)	11 (100%)	− 1.8 ± 0.9	(− 3 – 1)	n.s.	n.s.	n.s.

MPTA medial proximal tibial angle, *LDFA* lateral distal femoral angle, *aMA* adjusted mechanical alignment, *rKA* restricted kinematic alignment, *iKA* inverse kinematic alignment, *SD* standard deviation

[a]HKA angle < 177° for aMA and rKA and < 174° for iKA (Zones: I, II, III)

[b]HKA angle between 177° and 183° for aMA and rKA, and between 174° and 183° for iKA (Zones: IV, V, Target Zone)

[c]HKA angle > 183° for aMA, rKA and iKA (Zones: VI, VII, VIII)

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of MPTA, LDFA and HKA angle were required in, respectively, 34, 18 and 21%. For iKA in Caucasian knees, adjustments of MPTA, LDFA and HKA angle were required in, respectively, 15, 13 and 5%.

For aMA in Asian knees, adjustments of MPTA, LDFA and HKA angle were required in, respectively, 95, 95 and 34% (Table 3). For rKA in Asian knees, adjustments of MPTA, LDFA and HKA angle were required in, respectively, 61, 43 and 33%. For iKA in Asian knees, adjustments of MPTA, LDFA and HKA angle were required in, respectively, 40, 38 and 9%.

Discussion

The most important finding of the study was the considerable variability in native knee alignment, with different proportions that corresponded to the three restricted patient-specific alignment target zones. The iKA target zone accommodated the greatest proportion of knees (74%), followed by the rKA target zone (55%), whereas the aMA target zone accommodated the smallest proportion (8%). Adjustments of HKA angle (and potential additional adjustments needed) were required most frequently for aMA (28%), followed by rKA (25%) and least for iKA (7%). These findings, therefore, support the hypothesis that the target zone of iKA accommodates a higher proportion of native non-arthritic knees.

Recent studies found deviation from the neutral alignment strategy for TKA to be beneficial, as slight under-correction in varus knees yielded greater improvements in clinical and functional scores [26, 29], while no difference in revision rates at 20 years were observed among neutral versus what were considered “mal-aligned” knees [1]. Reports on clinical outcomes using different alignment techniques are increasing [3], but few studies investigate the association between postoperative coronal alignment and native knee morphology [9]. Hirschmann et al. [12] analysed the native anatomy of 308 non-osteoarthritic knees, and revealed in accordance with the present study that 8.9% were within the aMA target zone, but that 76.0% were within the rKA target zone compared to the 55% in the present study. Almaawi et al. [3] analysed the native anatomy of 4884 knees scheduled for TKA, and found that 51% were within the rKA target zone, and that after adjustment of MPTA and/or LDFA, 68% were within the rKA target zone. The remaining 32% (25% in the present study) had HKA angles outside the 177° to 183° range, requiring further adjustment in MPTA. Blakeney et al. [6] simulated rKA in 1000 CT scans of knees scheduled for TKA, and found that 45% would require adjustment of MPTA only, 15% would require adjustment of LDFA only, and 10% would require adjustment of both MPTA and LDFA when performing the rKA technique. Finally, Winnock de Grave et al. [30] performed TKA by iKA in 40 knees, of which native anatomy in 32 knees (93%) were found to be within the MPTA target zone, and 38 knees (96%) within the HKA target zone.

A ‘femur first’ technique maintains the femoral joint line obliquity granted there is only cartilage wear without any bone loss, and the tibial joint line will be aligned with the femoral joint line in a balanced TKA. A ‘tibia first’ technique maintains the tibial joint line obliquity granted there is only cartilage wear without any bone loss, and the femoral joint line will be aligned with the tibial joint line in a balanced TKA. In non-arthritic varus knees, the non-weight bearing joint line congruency angle is $1.3° \pm 1.1°$ [21], while in arthritic varus knees, the weight bearing joint line congruency angle is $3° \pm 2°$ [28]. Therefore, a tibial component could be 1° to 3° more oblique (varus) if following a “femur first” technique as opposed to a “tibia first” technique for TKA in varus knees. In valgus knees, the femur is hypoplastic on the lateral side, and therefore, a “femur first” technique could result in maintaining the hypoplastic LDFA. Moreover, because a ‘femur first’ technique maintains the LDFA within the limits of the target zone, it could result in exacerbated medial translation of the prosthetic trochlear groove causing postoperative patellofemoral problems. This is supported by a recent study that found patients with a preoperative valgus limb axis, suffered from patellofemoral pain following kinematic aligned TKA ("femur first” technique) [25]. Finally, new restricted patient-specific alignment techniques encompass wider “safe zones” for MPTA, LDFA and HKA, but there remains a lack of evidence on whether these expansions translate into improved clinical outcomes and implant survival [25].

Two recent meta-analyses revealed considerable variability in femoral [5] and tibial [4] geometric ratios among knees can potentially cause substantial bone–implant mismatch. Although bone–implant fit may largely be dependent on the patient knee morphology and implant design, the effect of the surgical technique should not be underestimated [7]. Analyses in the present study revealed a large proportion of knees that required adjustment of the MPTA and LDFA. Moreover, compared to Caucasian knees, Asian knees required a greater degree and number of modifications in MPTA and LDFA. A number of studies [8, 16, 22, 31] highlighted the risk of bone–implant mismatch in Asian knees, which could be further increased by modifications in MPTA and/or LDFA to bring knees within alignment target zones.

The present study compared the extent to which three current restricted patient-specific alignment techniques accommodate native coronal alignment. However, the findings of this analysis should be interpreted with the following limitations in mind. First, the database of 972 knees contained only basic demographic data—age and BMI. Second, the database consisted of CT scans of patients in a non-weight bearing supine position from which MPTA, LDFA and HKA

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angles were derived to estimate the overall coronal alignment. Third, estimation of theoretical soft tissue releases was only based on the modification of HKA angles, and it was not possible to take the physiological tissue laxity, surgical approach, removal of menisci and one or both cruciate ligaments into account; however, a recent randomised controlled trial revealed that restoring a patient's constitutional alignment during TKA result in better quantitative soft tissue balance when compared with conventional methods that aim for neutral alignment [18]. Finally, this study only took coronal alignment into account and did not consider rotational and sagittal alignment. The findings of this study provide an overview of how well aMA, rKA and iKA represented native knee anatomy and provide estimates of adjustments in bone resections and soft tissue releases to bring outlier knees within the target zones of each.

Conclusion

There is considerable variability in native knee coronal alignment that corresponds to different proportions of the restricted patient-specific alignment target zones for TKA. Although extension of the MPTA and LDFA target zones with rKA accommodate native knee alignment better than aMA, up to 26% would require adjustment of the native HKA angle. By also extending the HKA angle target zone into varus, iKA accommodates a greater proportion (93%) of native limb alignment.

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Data availability The authors will consider providing access to raw data upon reasonable request.

Declarations

Conflict of interest PWdG reports consultancy for Stryker, Lima and Mathys. TL reports consultancy for Stryker, Lima and Corin. TvC, JHM, BO, EvE and KC have nothing to disclose. SL is employed by Stryker with stocks or stock options, is on the editorial or governing board of Journal of Orthopaedic Research, is on the board or a committee member of Penn State University Center for Biodevices, is on the board or a committee member of Stryker/ORS Women's Research Fellowship, has a family member that is employed by Onkos Surgical. AF is employed by Stryker with stocks or stock options.

Ethical approval All scans were obtained per local legal and regulatory requirements which included ethics board approval and informed patient consent. The SOMA database was constituted after local ethical approval and informed patient consent for the use of their data in future studies. The present study was approved by the local institutional review board (IRB#: B1172022000030).

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