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Sexual and ethnic polymorphism result in considerable mismatch between native trochlear geometry and off-the-shelf TKA prostheses

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Abstract

Purpose To determine if trochlear morphology in healthy knees depends on sex and ethnicity, and to compare it to off-the-shelf TKA prostheses.

Methods Three retrospective series of CT angiograms from France (female, 124; male, 135), China (female, 122; male, 137) and South Africa (female, 21; male, 62) were used to digitize osseous landmarks at the level of the femoral epicondyles. Sulcus angle, trochlear rotation, lateral trochlear inclination, trochlear asymmetry ratio, and trochlear depth index were quantified for each knee and for 10 total knee arthroplasty (TKA) models. Univariable regression analyses were performed to determine associations of the five trochlear parameters with sex and ethnicity. Interquartile ranges (IQR) of native trochlear parameters were compared to the trochlear parameters of 10 off-the-shelf TKA prostheses.

Results Compared to French knees, Chinese knees had greater sulcus angle ($\beta = 6.3°$, $p < 0.001$), trochlear rotation ($\beta = 0.8°$, $p = 0.004$) and trochlear depth index ($\beta = 1.60$, $p < 0.001$). Conversely, South African knees had greater trochlear rotation ($\beta = 1.9°$, $p < 0.001$) and lateral trochlear inclination ($\beta = 3.7°$, $p < 0.001$). Female knees had smaller trochlear asymmetry ratios ($\beta = -0.03$, $p = 0.05$) but greater trochlear rotation angles ($\beta = 0.7$, $p = 0.005$). Considerable mismatches in trochlear morphology were revealed between native knees and off-the-shelf TKA prostheses.

Conclusions The findings suggest that thresholds used in the diagnosis of patellofemoral instability should be adapted to patient sex and ethnicity, and that standard off-the-shelf TKA may not restore native trochlear parameters in all patients.

Level of evidence III, retrospective comparative.

Keywords Trochlear groove · Polymorphism · Sulcus angle · Trochlear rotation · Lateral trochlear inclination · Trochlear asymmetry ratio · Trochlear depth index · TKA · Custom TKA · Off-the-shelf TKA

Introduction

Patellofemoral complications remain among the main reasons for patient dissatisfaction after total knee arthroplasty (TKA) [5, 23, 29]. Quantification of trochlear morphology is the foundation for investigating differences between healthy, pathological, and prosthetic knees [7]. Both sex and ethnicity account for differences in distal femoral anatomy [3, 13, 14]. Furthermore, the normal range of trochlear parameters is unknown and likely more variable than expected [9], thereby highlighting the need for further investigation.

Trochlear morphology is quantified from geometric ratios based on landmarks detected on radiographs [22], computed tomography (CT) [14] or magnetic resonance images (MRI) [18]. Ratios are classified according to thresholds based on Western populations and TKA designs are based on principles from the 1960s and 1970s [25], with little information on trochlear geometry [5].

Off-the-shelf TKA prostheses do not cover the wide spectrum of ethnic tibiofemoral morphotypes [14]. Mismatch in sulcus angles between prostheses and native knees have been demonstrated [5, 14, 23], but it is uncertain to what extent this is true for other patellofemoral ratios. The purposes of

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this study were therefore: (i) to quantitatively assess trochlear morphology in healthy knees and to determine whether it depends on sex and ethnicity, and (ii) to compare trochlear morphology of healthy knees to off-the-shelf TKA. The hypotheses were that: (1) Chinese trochleae would be shallower than French and South African trochleae, and (2) the anterior trochlear line would be more externally rotated in native knees than in TKA prostheses.

Materials and methods

Three series of CT angiograms of healthy knees from France (female, 124; male, 135), China (female, 122; male, 137) and South Africa (female, 21; male, 62) were retrospectively used to digitize osseous landmarks at the level of the femoral epicondyles. All patients had provided informed consent for the use of their data and images for study and publication purposes. Institutional review board (IRB) approvals were obtained in advance (Nos. 01–0415, 01–0416 and 01–0417).

The CT scans were acquired at the three centres using Sensation 16 Scanners (Siemens, Erlangen, Germany) with 16 × 1.5 mm collimation (120 kV, 80 mA; light speed 16) and an image matrix of 512 × 512 pixels. Knees were scanned in a supine position while extended and relaxed. The femoral mechanical axis was assumed to be aligned within ± 10° to the longitudinal axis of the scanner, which would result in negligible errors in measurements made on the transverse CT slices (maximum error = 1 − cos 10° = 1.5%). Digital imaging and communications in medicine (DICOM) files from the CT scanner were processed and analysed using Amira® version 4.1.1 (FEI Visualization Sciences Group, Bordeaux, France).

Eight osseous landmarks used in anthropometry [1, 15] were digitized on the native transverse CT slice where the epicondyles are most prominent: the medial and lateral epicondyles, the most posterior points on the medial and lateral condyles, as well as the deepest and highest points of the trochlea. From these, three trochlear angles and two ratios were quantified for each knee: sulcus angle (Fig. 1a) [18], trochlear rotation (Fig. 1b) [27], lateral trochlear inclination (Fig. 1c) [18], trochlear asymmetry ratio (Fig. 1d) [18], and trochlear depth index (Fig. 1e) [8].

Equivalent points were digitized on ten explanted TKA femoral components and then analysed as per a previous study (Fig. 2) [14]. The points were extracted from a transverse plane parallel to the distal resection plane passing through the most posterior margin of the prosthetic condyles. This was assumed to be close to the level of the native femoral epicondyles, which enabled comparison between the prostheses and native knees on the basis of sulcus angle, trochlear rotation, lateral trochlear

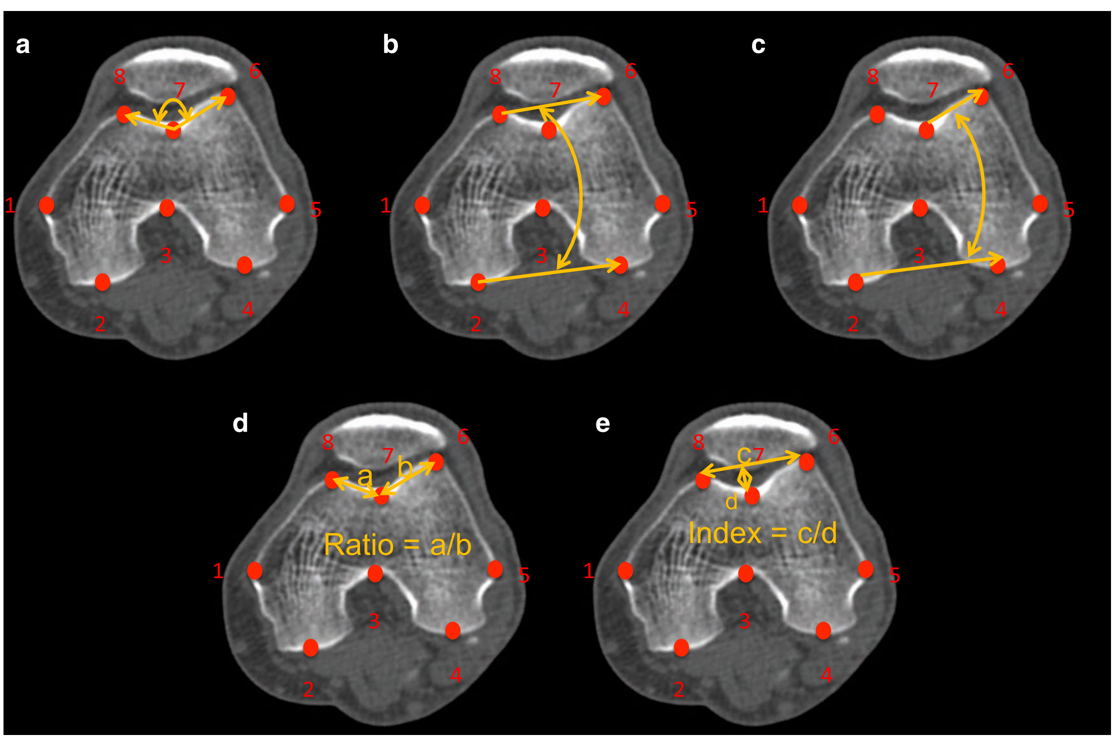

Fig. 1 Schematic illustration of the trochlear ratios. **a** Sulcus angle; **b** trochlear rotation; **c** lateral trochlear inclination; **d** trochlear asymmetry ratio; **e** trochlear depth index

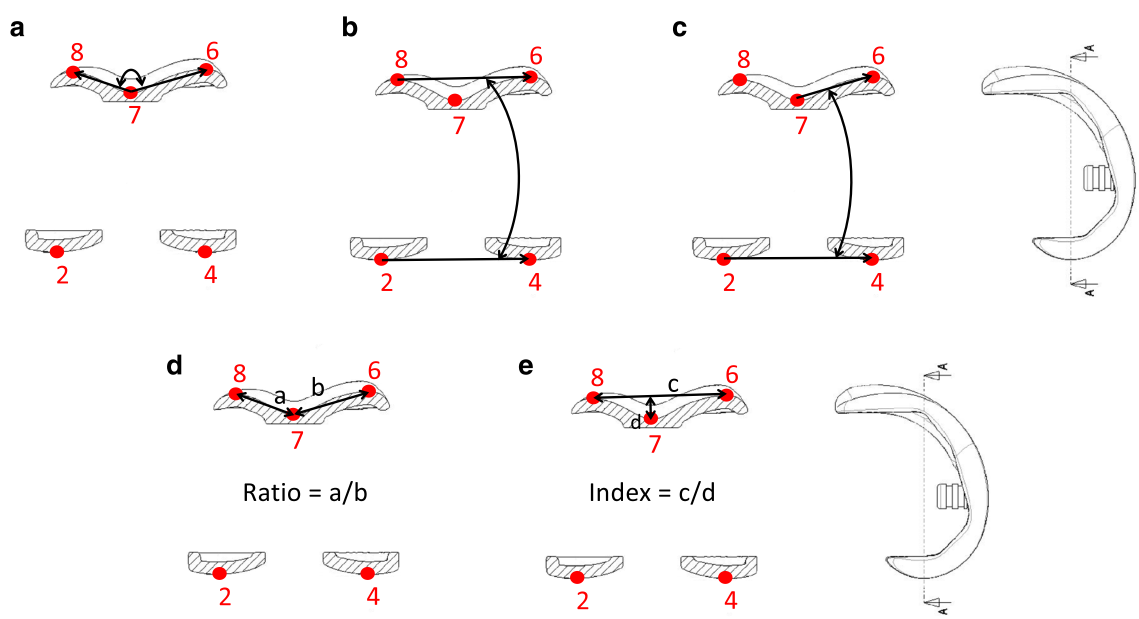

Fig. 2 Schematic illustration of the 5 corresponding points on a TKA from which the trochlear ratios are calculated for comparison to the native trochlear ratios. **a** Sulcus angle; **b** trochlear rotation; **c** lateral trochlear inclination; **d** trochlear asymmetry ratio; **e** trochlear depth index

inclination, trochlear asymmetry ratio and trochlear depth index.

Statistical analysis

Data was summarised using descriptive statistics, and normality assessed using Shapiro–Wilk tests. For non-Gaussian quantitative data, differences between groups were evaluated using the Wilcoxon-rank-sum test (Mann–Whitney *U* test). Univariable regression analyses were performed to determine associations of the five trochlear parameters with sex and ethnicity. Considering the findings of Li et al. [14] who reported the mean sulcus angle for knees from France (136.7° ± 8.8°), and to determine whether a difference of 4° in sulcus angle is statistically significant, a priori sample size calculation indicated that a minimum of 81 knees per group is necessary to achieve a power of 80% (G*Power 3.1, Heinrich-Heine-Universität Düsseldorf, Germany). To ascertain detection of effects of two variables independently (ethnicity and sex), the sample size used for the present study was adequate, with 259 from France, 295 from China and 83 from South Africa. Measurements were performed by two observers (KL and EC), and inter- and intra-observer reliability tests revealed percentage errors for each landmark to be < 5% [14]. Statistical analyses were performed using R version 3.6.1 (R Foundation for Statistical Computing, Vienna, Austria). p values < 0.05 were considered statistically significant.

Results

Trochlear morphology

Sulcus angle was smallest in French knees, marginally greater in South African knees and greatest in Chinese knees (Table 1). The differences were significant between French and Chinese ($p < 0.001$) and between South African and Chinese knees ($p < 0.001$). Compared to women men showed significantly smaller sulcus angles ($p = 0.026$).

External trochlear rotation was lowest in French knees, greater in Chinese knees and greatest in South African knees. The differences were significant among all three groups (French vs. Chinese, $p = 0.017$; French vs. South African, $p < 0.001$; Chinese vs. South African, $p = 0.013$). External trochlear rotation was also significantly lower in men ($p = 0.008$) compared to women.

Lateral trochlear inclination was similar in French knees and Chinese knees but was significantly greater in South African knees (both $p < 0.001$). It was equivalent in men and women for all three ethnicities (n.s.).

Trochlear asymmetry was similar among the three ethnicities (n.s.), as well as between men and women (n.s.). Trochlear depth index was similar in French and South African knees (n.s.), but the trochleae were significantly shallower in Chinese (both $p < 0.001$).

Table 1 Cohort demographics and morphometric data

	n	Age Mean ± SD (range)	Sulcus angle (°) Mean ± SD (range)	Trochlear rotation (°) Mean ± SD (range)	Lateral trochlear inclination (°) Mean ± SD (range)	Trochlear asymmetry ratio Mean ± SD (range)	Trochlear depth index Mean ± SD (range)
French							
Male	135	58.1 ± 14.2 (18.0–85.0)	136.7 ± 8.8 (120–168)	3.3 ± 2.4 (0–12)	18.2 ± 6.2 (1–37)	0.73 ± 0.16 (0.39–1.59)	5.59 ± 1.86 (3.48–19.63)
Female	124	56.3 ± 15.9 (14.0–87.0)	138.6 ± 9.7 (110–164)	3.9 ± 2.8 (0–13)	18.7 ± 6.4 (2–34)	0.70 ± 0.16 (0.37–1.24)	5.96 ± 1.83 (2.97–15.03)
Chinese							
Male	137	53.3 ± 17.0 (21.0–80.0)	143.4 ± 11.3 (117–169)	3.8 ± 2.8 (0–12)	17.9 ± 5.3 (2–31)	0.74 ± 0.16 (0.45–1.57)	7.18 ± 3.36 (3.19–21.34)
Female	122	52.2 ± 17.4 (20.0–80.0)	144.5 ± 10.2 (117–174)	5.0 ± 3.2 (0–17)	18.6 ± 5.3 (3–30)	0.71 ± 0.19 (0.37–1.64)	7.57 ± 4.44 (3.63–38.66)
South African							
Male	62	44.1 ± 16.6 (21.0–85.0)	138.7 ± 8.8 (121–162)	5.2 ± 2.9 (0–11)	21.9 ± 4.4 (9–32)	0.70 ± 0.13 (0.48–1.25)	5.87 ± 1.74 (3.67–13.74)
Female	21	44.0 ± 16.0 (21.0–69.0)	138.5 ± 10.6 (123–161)	6.2 ± 4.1 (1–16)	22.8 ± 5.2 (13–34)	0.72 ± 0.14 (0.53–1.03)	5.98 ± 2.32 (3.88–12.25)

n Sample size, *SD* standard deviation

Regression analysis

Univariable analysis revealed that, compared to French knees, Chinese knees had greater sulcus angle ($\beta = 6.3°$, $p < 0.001$), shallower ($\beta = 1.60$, $p < 0.001$), and more externally rotated ($\beta = 0.8°$, $p = 0.004$) trochleae (Table 2). Moreover, South African knees also had more externally rotated trochleae ($\beta = 1.9°$, $p < 0.001$) and greater lateral trochlear inclination angles ($\beta = 3.7°$, $p < 0.001$). Compared to men, women had smaller trochlear asymmetry ratios ($\beta = -0.03$, $p = 0.05$) with more externally rotated trochleae ($\beta = 0.7°$, $p = 0.005$).

Commercially available TKA

Comparing the geometries of the 10 commercially-available TKA femoral components to the interquartile ranges (IQR) of the ratios and angles measured from patient CT scans revealed considerable mismatches (Fig. 3). The sulcus angle was too high in 5 TKAs and too low in 1 TKA (Vanguard). Trochlear rotation angle was too low in 6 TKAs; only the Persona (Zimmer), Scorpio (Stryker), Journey (Smith & Nephew) and LCS (DePuy) fell inside the IQR of all ethnicities. The lateral trochlear inclination of the Noetos (Tornier) and Journey (Smith & Nephew) were too low for French and Chinese knees, whereas only the Persona (Zimmer) and LCS (DePuy) fell inside the IQR for South African knees. The lateral trochlear inclination of the Vanguard (Biomet) was too high for all ethnicities. Finally, the trochlear depth index of all TKAs were within the IQR for all ethnicities, except for the Journey (Smith & Nephew).

Discussion

The most important finding of the present study was that 4 of the 5 trochlear morphometric parameters measured depended significantly on ethnicity, while only 2 of these parameters depended on sex. Furthermore, comparing the geometries of 10 commercially-available TKA revealed considerable mismatches with native knees. Chinese knees had shallower trochleae (confirms hypothesis 1) that were oriented more externally. Trochleae of South African knees were more externally rotated with higher lateral trochlear inclination. Women had higher lateral trochlear inclination, but smaller trochlear asymmetry ratios. Compared to native knees, TKA prostheses had shallower trochleae which were rotated less externally (confirms hypothesis 2), with smaller lateral facet slopes and larger trochlear asymmetry ratios.

The clinical relevance of these findings is that classifying native trochlear geometry of different ethnicities should be done with caution. For instance, the thresholds for normal

Table 2 Univariable regression analysis to determine associations between morphometric data and patient ethnicity or sex

	n	Sulcus angle (°)			Trochlear rotation (°)			Lateral trochlear inclination (°)			Trochlear asymmetry ratio			Trochlear depth index		
		β	95% CI	*p* value	*β*	95% CI	*p* value	*β*	95% CI	*p* value	*β*	95% CI	*p* value	*β*	95% CI	*p* value
Ethnicity																
French	259	Reference			Reference			Reference			Reference			Reference		
Chinese	259	6.3°	4.6–8.0	**<0.001**	0.8°	0.2–1.3	**0.004**	− 0.2°	− 1.2 to 0.8	0.675	0.01	− 0.02 to 0.04	0.470	1.60	1.09–2.10	**<0.001**
South African	83	1.0°	− 1.4 to 3.5	0.404	1.9°	1.1–2.6	**<0.001**	3.7°	2.3–5.1	**<0.001**	− 0.01	− 0.05 to 0.04	0.809	0.13	− 0.60 to 0.85	0.730
Sex																
Men	334	Reference			Reference			Reference			Reference			Reference		
Women	267	1.4°	− 0.3 to 3.08	0.097	0.7°	0.2–1.16	**0.005**	0.2°	− 0.7 to 1.14	0.668	− 0.03	− 0.05 to 0.00	**0.046**	0.40	− 0.09 to 0.88	0.108

n Sample size, *β* regression coefficient, *CI* confidence interval

sulcus angle range between 138° ± 6° [16] and 142° ± 8.0° [4], and indicates trochlear dysplasia if above 144° in the ‘Merchant view’ [26] or 143° in the ‘Brattström view’ [4]. These thresholds may be realistic for Western knees, but may not apply for other ethnicities, as over 50% of the Chinese knees would be considered dysplastic. Moreover, performing TKA in knees of different ethnicities can result in considerable mismatches in trochlear parameters.

Many surgical approaches for TKA orient the femoral component parallel to the surgical transepicondylar axis (sTEA) [10, 17, 21] to achieve a balanced flexion gap and externally rotate the posterior condylar axis [27]. This is also believed to favour patellar tracking [10, 17, 21]. Yet, patellofemoral complications after TKA remain common, mainly due to femoral component malpositioning [27]. Newman et al. [19] revealed high variability of trochlear rotation in 191 non-arthritic knees and concluded that the classification of trochlear rotation could yield tailored positioning of the femoral component. The larger trochlear rotation angles in Chinese and South African knees is therefore an important finding.

Previous reports revealed signs of trochlear dysplasia in TKA based on established thresholds [5, 23]. Furthermore, Li et al. [14] revealed that in all but one implant, the sulcus angle is greater than the third quartile of Caucasian knees, but within the second quartile of Asian knees. The present study also revealed mismatches between off-the-shelf TKA and native lateral trochlear inclination, trochlear depth index and trochlear asymmetry. In a TKA with PF complications, the usual diagnostic approach does not account for implant trochlear depth, width, sulcus angle, nor groove orientation [5], even though too high TKA trochlear height has been shown to increases the risk for secondary patellar resurfacing [29]. Custom TKA implants may therefore be beneficial to restore native anatomy in certain ethnicities, as they were shown to improve bone preservation [11], limb alignment [12, 24] and anatomical fit [2, 6, 24], while reproducing native knee kinematics [20, 28, 31].

The findings of the current study need to be interpreted in light of the following limitations. First, trochlear angles and ratios were derived from single CT angiogram slices. Farahmand et al. [8] revealed in a study on 12 participants that the sulcus angle would change by only ± 3.4° when the view angle was changed from 15° to 75° and that the groove geometry appeared constant along its length. Proximal femoral anatomy was also not accounted for, but in a study by Wright et al. [30] there was no correlation between the proximal femur parameters and sulcus angle nor lateral trochlear inclination. Second, the CT angiograms had been acquired to asses leg vasculature and were therefore only available for one limb per patient (no bilateral knees for intra-patient analysis) and lacked basic demographic data that would be relevant to plan TKA (aetiology, HKA angle, BMI, etc.).

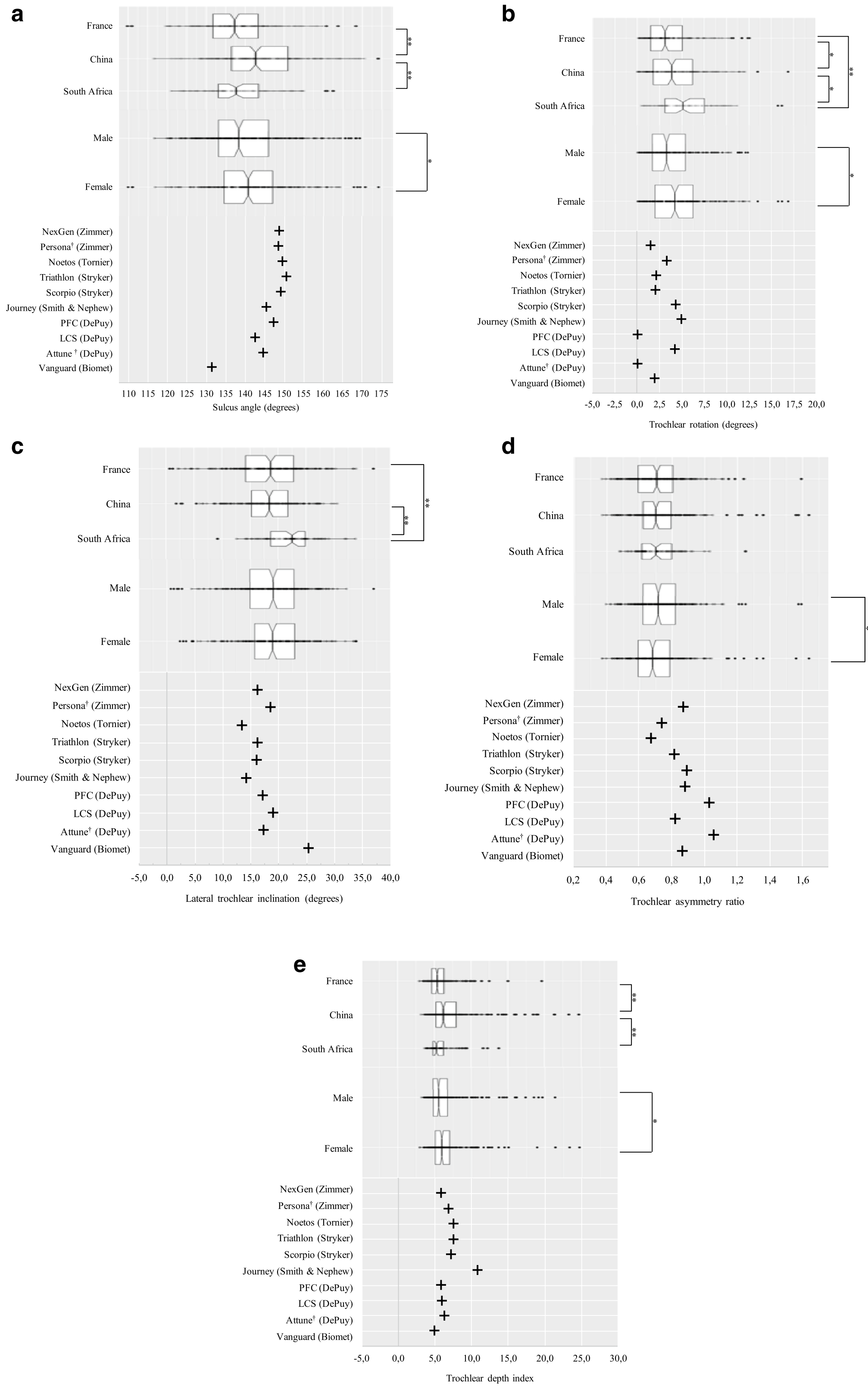

Fig. 3 Comparison of native trochlea to TKA trochlea (*$p<0.05$; **$p<0.001$). **a** Sulcus angle; **b** trochlear rotation; **c** lateral trochlear inclination; **d** trochlear asymmetry ratio; **e** trochlear depth index

Third, although no arthritis or lesions were observed, the authors did not specifically inspect for arthritic deformities or lesions as criteria for exclusion from the study. Fourth, landmarks on the TKA femoral components were quantified on a transverse plane that was parallel to the distal resection plane and coincident on the posterior condylar axis. This approach therefore does not account for surgical techniques which may change the posterior resection plane orientation. Lastly, the South African cohort was significantly smaller in comparison to the French and Chinese cohorts, and therefore the findings based on the South African cohort may be underpowered, which would require larger cohort studies to confirm the trends observed.

Conclusion

Sulcus angle, trochlear rotation, lateral trochlear inclination and trochlear depth index depended significantly on ethnicity, whereas trochlear rotation and asymmetry depended significantly on sex. The wide spectrum of morphotypes observed suggests that thresholds used in the diagnosis of patellofemoral instability may not be valid for all ethnicities.

Author contributions JHM: data analysis and interpretation, tables preparation, literature review and manuscript writing. KL: study design, data collection and analysis, manuscript editing. NR: data collection and analysis, manuscript editing. NT: study design, data collection and analysis, manuscript editing. MS: study design, data collection and analysis and manuscript writing. EC: study conception and design, data collection and analysis, literature review and manuscript writing.

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Compliance with ethical standards

Conflict of interest JHM and MS receive consulting fees from ReSurg SA. All other authors declare that they have no competing interests.

Ethical approval All patients had provided informed consent for the use of their data and images for study and publication purposes and institutional review board (IRB) approvals were obtained from all three healthcare facilities for the use of the existing data and images (Nos. 01-0415, 01-0416 and 01-417).

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