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Variation of the femoral J-Curve in the native knee

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Abstract

The J-Curve in the native knee as well as the femoral component's J-Curve after total knee arthroplasty are known to have a high influence on kinematics. Furthermore, the J-Curve's shape affects ligament strain and tension and consequently already slight changes may strongly alter knee forces and stability. To optimize current implants' J-Curve design with regard to the population's morphology, information about the main sources of contour variation is necessary.

In this study, a principal component analysis (PCA) was performed on the medial and lateral femoral J-Curves of 90 cadavers without history of osteoarthritis. The J-Curves' mean shapes were further investigated by geometric parameter analysis and effect sizes were calculated for the first three principal components (PCs). In addition, a combined PCA for both sides was performed and evaluated qualitatively. The results were compared with the variation in standard implants' J-Curve shape.

The isolated PCA of medial and lateral J-Curves resulted in PCs involving changes in contour orientation, arc length, scaling and circularity. The combined PCA of both sides resulted in PCs comprising combinations of the individual variations together with changes in relative position. In contrast, the qualitative evaluation of J-Curves from 2 different standard implant systems revealed no visible changes in shape but only changes in size.

Limitations of this study were the restriction to a 2-dimensional contour derivation and the sole consideration of the femoral contours. Nevertheless, the sagittal variability in the medial, lateral and combined femoral J-Curves should be considered in implant design.

1 Introduction

The sagittal contour of the femoral condyles, often referred to as J-Curve, is known to have a high influence on knee kinematics and is related to relevant motion phenomena such as femoral rollback, medial pivot and screw home mechanism [1, 2]. Similar, in total knee arthroplasty (TKA), the femoral implant component's J-Curve has a high influence on kinematics [3]. In addition, the J-Curve's shape or rather its alteration highly affects ligament strain and related forces. E.g. for a ligament stiffness of 80 N/mm for both compartments [4] 1 mm local condylar offset may result in 80 N additional knee forces, additional ligament strain or instability due to ligament relaxation. Therefore, efforts need to be taken to better replicate the J-Curve of the native knee in order to better restore patient-specific kinematics as well as ligament strain and tension. So far the J-Curve has been analyzed with regard to thereon fitted geometric primitives such as circles and ellipses [5–9]. However, variations in the contour itself have not been investigated in detail yet. Consequently, the aim of this study was to analyze the main patterns of variation of the femoral J-Curve in the native knee by means of principal component analysis (PCA) and geometric parameter analysis [10] and to compare the results to standard implants' J-Curve variation.

2 Materials and methods

Segmented femoral bone surface data of 90 cadavers of North American ethnicity, thereof 56 male, 32 female and 2 without gender information, without history of osteoarthritis and without visible osteophytes was available. The femora were aligned to a patient-specific bony coordinate system [10] and the individual J-Curves of the medial and lateral condyles were extracted, using a semi-automatic workflow which is described in a previous publication by our group [11]. Subsequently, the J-Curves were approximated by 300 equidistant points and a PCA was performed. This method reduces dimensionality and thereby enables the identification of dominant patterns within a multivariate dataset [12]. Therefore, the respective dataset of multiple variables, here point coordinates, is transformed to new linearly independent variable sets, called principal components (PCs) [12].

The calculation of the PCs and their analysis was performed according to Shlens [13]. The PCA was performed isolated for medial and lateral J-Curve as well as combined for both sides. For the isolated PCA, the derived mean shapes were analyzed with regard to height, width, and the radii describing the posterior and distal proportion of the condyles [11] as well as their center position. In addition, effect sizes for the first three PCs were calculated with regard to the respective mean shape. The combined PCAs results were evaluated qualitatively. The analysis was performed for all knees and for male and female knees separately, in order to evaluate differences between genders. To evaluate the analyzed variance with regard to the one in implant design, the J-Curve from 2 different standard implant systems of various sizes, including narrow versions, were extracted from the planning software mediCAD (mediCAD Hectec, Altdorf, Germany). Therefore, images were taken from the software and contours were extracted by thresholding. All contours were scaled to the corresponding first size, for qualitative evaluation of their variance.

3 Results

The separate analysis of female and male J-Curves revealed highly similar results. Consequently, only the results of the analysis of all knees are presented in **Figure 1** and **Table 1**. The mean width and mean distal radius were greater in the lateral condyle than in the medial while the mean height and mean posterior radius were similar. The results of the isolated PCA of the medial and lateral side showed similar J-Curve variations (**Figure 1-A1:A2**). The analysis revealed a dominant first PC, accounting for 62.2% (73.1%) of variance in the medial (lateral) condyle (**Table 1**). It comprised changes in the orientation and arc length of the J-Curves. Thereby also the radii's center positions were affected. In addition, the overall size of the lateral side and the width of the medial side was changed by the first PC. The second PC of the medial and lateral J-Curve accounted for 33.1% and 22.5% of variance, respectively. They both mainly contained changes of the contour's overall size and height. The third PC accounted for 3.5% and 3.0% of variance of the medial and lateral J-Curve, respectively. It mainly inherited changes in the contours' circularity, whereby the radii's size and center positions were affected. The combined PCA of medial and lateral side involved the beforehand described individual side variations in combination with changes in relative position (**Figure 1-A3**). The PCs were less distinguishable and the accounted variance was more distributed (PC1 48.4%, PC2 24.4%, PC3 15.8%). The extracted standard implant J-Curves showed no changes in shape but predominantly changes in size (**Figure 1-B1:B4**).

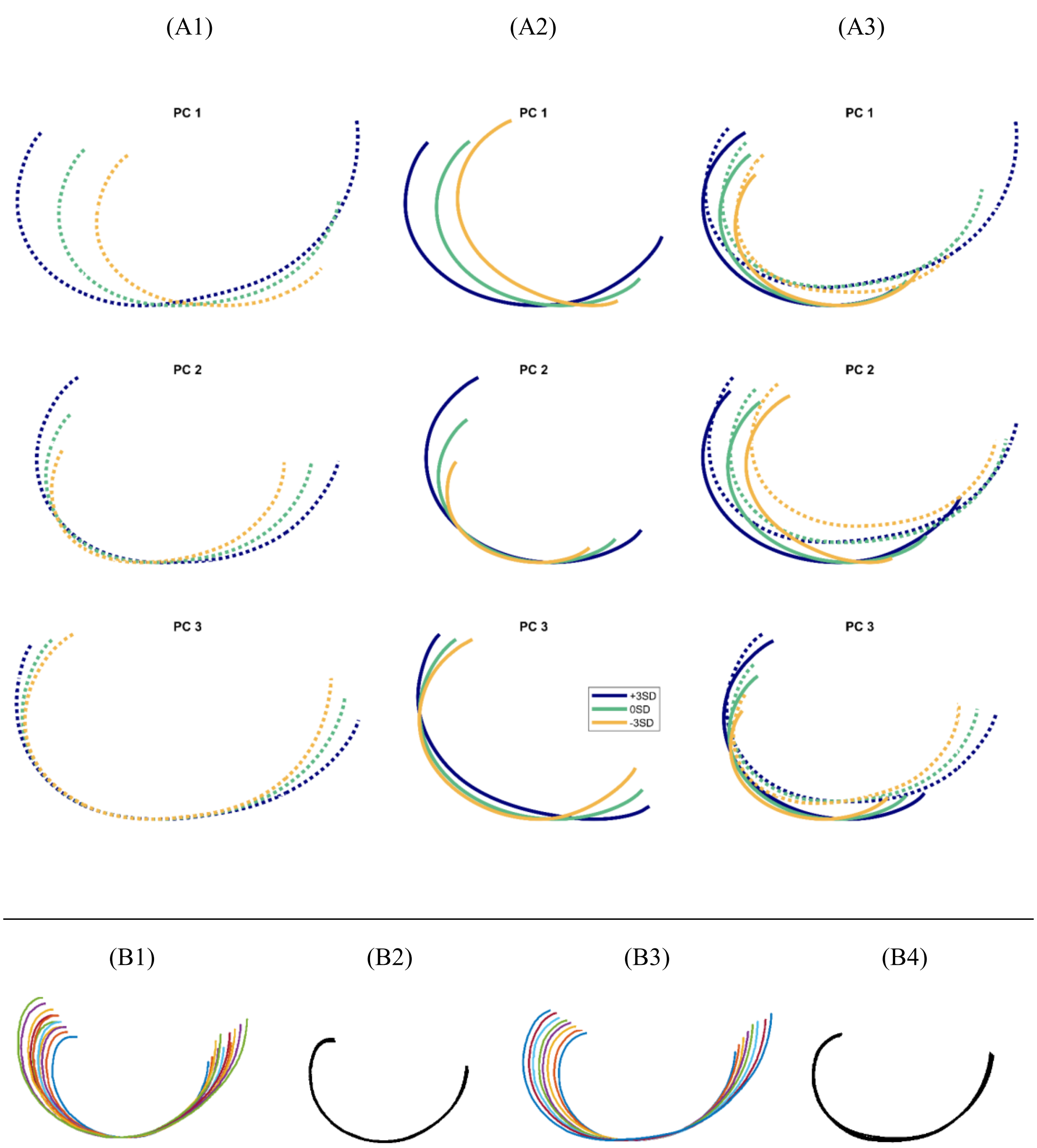

Figure 1: The first three PCs of (A1) the lateral, (A2) the medial and (A3) the combined femoral cadaveric J-Curves. For the combined PCA the point coordinates of both lateral and medial side were included. (Solid line: medial, dashed line: lateral. 3SD = 3 standard deviations). In comparison, Implant J-Curves (B1) of sizes 1-8 from the ATTUNE knee system (DePuy Orthopaedics, Warsaw, IN) and (B3) of sizes 1-6 from the Triathlon total knee system (Stryker, Kalamazoo, MI), which were scaled to their corresponding size 1 ((B2): Attune, (B4): Triathlon). All contours were oriented to their most distal point in proximodistal direction, for better comparison of the respective variance.

Mean shape	Side	Absolute measures [mm]					
		Height	Width	Radius Distal	Radius Posterior	Radius Center Distal (AP)	Radius Center Posterior (PD)
	Medial	37.1	45.9	32.0	18.9	11.9	10.9
	Lateral	35.5	63.8	36.8	19.8	2.0	10.5

PC	Side	Accounted variance [%]	Effect size (with regard to the mean shape)					
			Height	Width	Radius Distal	Radius Posterior	Radius Center Distal (AP) [mm]	Radius Center Posterior (PD) [mm]
1	Medial	62.2	-0.6 % (-0.2 mm)	+26.2 % (+12.0 mm)	+7.8 % (+2.5 mm)	+7.9 % (+1.5 mm)	-5.3	+2.0
	Lateral	73.1	+18.7 % (+6.6 mm)	+21.6 % (+13.8 mm)	+18.2 % (+6.7 mm)	+14.7 % (+2.9 mm)	-5.0	-0.6
2	Medial	33.1	+29.5 % (+10.9 mm)	+21.6 % (+9.9 mm)	+16.9 % (+5.4 mm)	+22.7 % (+4.3 mm)	+2.0	+0.6
	Lateral	22.5	+25.3 % (+9.0 mm)	+13.7 % (+8.7 mm)	+22.9 % (+8.4 mm)	+20.7 % (+4.1 mm)	+2.0	+1.4
3	Medial	3.5	+2.8 % (+1.0 mm)	+3.9 % (+1.8 mm)	+19.7 % (+6.3 mm)	+11.4 % (+2.2 mm)	+4.9	+3.1
	Lateral	3.0	-3.1 % (-1.1 mm)	+6.1 % (+3.9 mm)	-0.2 % (-0.1 mm)	+13.3 % (+2.6 mm)	+1.2	+3.4

Table 1: Results of the geometric parameter analysis, including measures of the mean shapes as well as effect sizes for the individual PCs (for adding 3 standard deviations to the mean shape). AP = anteroposterior direction, PD = proximodistal direction. Color code for changes:
Center positions: ≥ ± 2.5 mm : ☐ | ≥ ± 5.0 mm : ■ Other measures: ≥ ± 10 % : ☐ | ≥ ± 20 % : ■

4 Discussion

The mean shapes of the lateral and medial cadavers' J-Curves showed relevant differences, which are in agreement with other morphological studies of the native knee [6, 11]. The isolated PCA of medial and lateral J-Curves resulted in PCs involving changes in contour orientation, arc length, scaling and circularity. The combined PCA of both sides resulted in PCs comprising combinations of the individual variations together with changes in relative position. Thereby, further variation due to combination of the 2 contours were evidenced. The J-Curve variation e.g. due to changes in circularity amounted to several millimeters, being highly relevant for ligament tension and elongation. Scaling was a relevant aspect of the first 3 PCs of the combined analysis, accounting for 88.6% of the contours' variance. Fitzpatrick et al. [14] analyzed the contours of the femoral resection cuts of 36 patients scheduled for TKA by PCA. They found that 59.7% of variation was due to changes in overall size [14]. A direct comparison of the percentages however is not feasible, as the PCs of our study involved relevant changes in shape. In contrast, the standard implants' J-Curve variance consisted almost exclusively of changes in size.

A limitation of our study was the restriction to a 2-dimensional contour derivation. In addition, so far only the femoral J-Curve has been analyzed, while the tibial sagittal contours were not considered. Nevertheless, the sagittal variability in the medial, lateral and combined femoral J-Curves should be considered in implant design to best accommodate for the population's knee morphology, kinematics and load situation.

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Disclosures

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