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X-ray based morphological analysis of the knee – A review

Sonja Grothues[1] and Klaus Radermacher[1]

[1] Chair of Medical Engineering, Helmholtz Institute for Biomedical Engineering, RWTH Aachen University, Aachen, 52074, Germany

`grothues@hia.rwth-aachen.de`

Abstract

Mismatch between the patient's knee morphology and the implant geometry is linked to poorer clinical outcome after total knee arthroplasty (TKA). Hence, patients whose knee morphology differs strongly from the norm may have a higher risk to be dissatisfied after surgery. Consequently, a preoperative risk assessment regarding differences between individual knee morphology and implant geometry is favorable. For adequate availability and limited radiation dose, this should be based on standard imaging in TKA, being conventional radiographs.

We reviewed morphological measures of the knee to be evaluated on X-ray images. Only measures of the articulating areas, without connections to pathologies such as patellar instability or pain, were included. In addition, the accuracy of 2D-3D knee reconstruction was reviewed, in order to assess the potential use for 3D X-ray based analysis.

Various parameter definitions for the evaluation on anterior-posterior and lateral X-rays exist in the literature. If given, the inter- and intraobserver reliability can be interpreted as moderate to excellent. Several authors have reported on 2D-3D reconstruction accuracies with maximum absolute errors of ~5-6 mm for in vitro studies.

Mismatch between the bone morphology implant geometry can partly be assessed in 2D, using single X-rays. Methods for 2D-3D reconstruction demonstrated potential for enabling 3D X ray-based analyses. However, improvements regarding accuracy and larger in vivo validation studies are pending.

A basic preoperative risk assessment using X-rays is possible. Future steps could include the automation of the parameter derivation and an enhancement of 2D-3D reconstruction for enabling a more comprehensive assessment.

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1 Introduction

Total knee arthroplasty (TKA) is one of the most common procedures in orthopedic joint surgery, with a prospectively increasing relevance. Compared to total hip arthroplasty, improvements in patient satisfaction (pre-op vs. post-op) are significantly lower (OECD 2019). While there are many influence factors for patient satisfaction, implant design is one aspect to consider. Mismatch between the patient's knee morphology and implant geometry is linked to poorer clinical outcome (Bonnin et al. 2013; Mahoney and Kinsey 2010). Hence, patients whose knee morphology differs strongly from the norm may have a higher risk to be dissatisfied after TKA. Consequently, a preoperative risk assessment is favorable; in order to decide whether other measures such as more extensive analyses and planning or even a patient-specific knee implant is advisable. Standard imaging prior to TKA includes a weight-bearing anterior-posterior (AP), a lateral and a patellofemoral joint X-ray (Tanzer and Makhdom 2016). With accurate positioning and the use of scaling objects, a derivation of morphological parameters from those X-rays is possible. While measurement accuracy is expected to be sufficient (La Fuente Klein 2008), measurement reliability would have to be ensured.

Relevant parameters which cannot be evaluated in 2D are e.g., the TT-TG distance or overhang along the full bone contour. Therefore, methods for 2D-3D surface reconstruction are also of interest for a mismatch analysis. Based on a small number of (calibrated) X-ray images, the knee surface is reconstructed, potentially enabling analyses of the whole bone morphology. While parameter definitions for 3D bone assessment have already been studied by our group (Asseln et al. 2018), the applicability of surface models from 2D-3D reconstruction has not been investigated. For an adequate assessment, an accuracy of 1mm (Grothues and Radermacher 2021) to 3mm (Mahoney and Kinsey 2010) at minimum would be required.

Therefore, the aim of this study was to evaluate the applicability of conventional TKA imaging for preoperative risk assessment by reviewing morphologic parameters to be assessed on single X-rays and the accuracy of X-ray-based 2D-3D surface reconstruction of the knee.

2 Materials and Methods

A literature research on morphological parameters of the distal femur, the proximal tibia and the patella to be evaluated on single X-rays was performed. As search engine, Google Scholar and as search terms, knee, X-ray/ radiographs, parameter, and anatomy/ morphology were used. The reference lists of the papers considered were also searched for potential articles. Morphological parameter definitions requiring 3D bone models were not considered in this article, as they have been previously studied by our group (Asseln et al. 2018). Only parameters with relevance for an implant mismatch assessment were searched, being parameters describing the articulating areas of the knee. Parameter definitions where abnormal measures are linked to pathologies such as patellar instability or pain were excluded. In addition to the parameter search, articles on the general accuracy of 2D-3D reconstruction were reviewed, in order to evaluate their potential use for more comprehensive, 3D morphological analyses. As search terms, knee, X-ray, 2D-3D reconstruction, anatomy/ morphology and computed tomography were used. The requirement for consideration was the comparison against segmented bone models from CT images, being the gold standard for in vivo bone surface model derivation.

3 Results

Overall 32 definitions of different morphological parameters to be evaluated on single X-ray images were found in the literature, which are listed in **Table 1**. For some parameters, several references were found e.g., for the tibial slopes. In addition, for some measurements different parameter names were found (e.g., *coronal tibial slope* and *tibial plateau - tibial shaft angle*). Anteroposterior measurements were mostly described as "*depth*", proximodistal measurements as "*height*" and mediolateral measurements as "*width*". In case of deviations, the naming was adjusted. Most parameter definitions were found for the femur, second for the tibia and none for the patella. Relevant landmarks or reference points were identified manually, or no details on landmark identification was given. For several measurements, inter- and intraobserver reliabilities were evaluated. Seven studies evaluated intra class coefficients (ICC) for the respective parameter definitions, which ranged from 0.64 to 0.99 for interobserver- and from 0.77 to 0.98 for intraobserver reliability.

14 studies reported measures of accuracy for 2D-3D reconstruction of the knee, which are presented in **Table 2**. The methods for 2D-3D reconstruction include the use of e.g. statistical shape models (Baka et al. 2011; Cerveri et al. 2017; Wu and Mahfouz 2021; Zheng et al. 2018) and/or bone databases/atlases (ElHak et al. 2007; Messmer et al. 2001). The reconstruction was based on standard/calibrated X-rays, EOS/Fluoroscopy images or DRRs. We classified studies using DRRs as in vivo & in silico or in vitro & in silico, according to the data source (subjects/cadavers). Different error metrics were reported in the literature, including the mean absolute error (MAE), the root mean square error (RMSE) and the Hausdorff distance. Furthermore, different calculation methods were applied e.g., point-to-point (P2P) and point-to-surface (P2S) distances. In addition one group quantified normal/projected error vectors (Shetty et al. 2021). The errors were either calculated unidirectional, or no information regarding directionality was given.

Table 1: Morphological parameter definitions for the evaluation on single X-ray images. KF = Knee Flexion. AP = Anteroposterior. PA = Posteroanterior. * = more specific description to be found in the respective article.

No.	**Bone**	**Parameter name**	**Xray side**	**Xray requirements**	**Weight bearing**	**in vivo/ in vitro** (number of subjects/ knees)	**Method for reliability measurement**	**Inter-observer reliability**	**Intra-observer reliability**	**source**
1	Femur	Sagittal depth of the condyles	Lateral	Standard	No	in vivo (100/100)	Correlation coefficients	0.98	0.89	(Fridén et al. 1993)
2	Femur	Medial femoral condyle depth	Lateral	True lateral, with apparatus*	Yes	in vivo (n.a./53)	n.a.	n.a.	n.a.	(Mensch and Amstutz 1975)
3	Femur	Lateral femoral condyle depth	Lateral	True lateral, with apparatus*	Yes	in vivo (n.a./53)	n.a.	n.a.	n.a.	(Mensch and Amstutz 1975)
	Femur	Lateral femoral condyle depth	Lateral	30° KF, overlapping condyles	n.a.	In vivo (36/n.a.)	n.a.	n.a.	n.a.	(Fernandes et al. 2017)
4	Femur	Height of the condyles	Lateral	Standard	No	in vivo (100/100)	Correlation coefficients	0.96	0.95	(Fridén et al. 1993)
5	Femur	Height to depth ratio	Lateral	Standard	No	in vivo (100/100)	n.a.	n.a.	n.a.	(Fridén et al. 1993)
6	Femur	Flattened portion of the condyle	Lateral	30° KF, overlapping condyles	n.a.	In vivo (36/n.a.)	n.a.	n.a.	n.a.	(Fernandes et al. 2017)
7	Femur	Anterior Femoral Offset	Lateral	Standard	n.a.	in vivo (970/n.a.)	n.a.	n.a.	n.a.	(Matz et al. 2017)
8	Femur	Posterior Condylar Offset	Lateral	True lateral	n.a.	in vivo (150/n.a.)	n.a.	n.a.	n.a.	(Bellemans et al. 2002)
	Femur	Posterior Condylar Offset	Lateral	True lateral, overlapping condyles*	n.a.	in vivo (n.a./105)	ICC	0.84 (95% CI 0.1 - 0.95)	0.94 (95% CI 0.74-0.98	(Clement et al. 2014)
9	Femur	Posterior Condylar Offset Ratio (divided by cortical depth)	Lateral	True lateral, overlapping condyles*	n.a.	in vivo (n.a./105)	ICC	0.93 (95% CI 0.86-0.97)	0.9 (95% CI 0.63-0.96)	(Clement et al. 2014)
10	Femur	Posterior Condylar Offset Ratio (divided by condylar depth)	Lateral	True lateral, overlapping condyles*	n.a.	in vivo (100/100)	ICC	0.882	0.899	(Johal et al. 2012)
11	Femur	Lateral femoral condyle ratio	Lateral	Condylar overlap < 6mm	n.a.	in vivo (200/n.a.)	ICC	0.80	0.77	(Pfeiffer et al. 2018)
12	Femur	Width of the femur	PA	Modified tunnel view*	No	in vivo (n.a./53)	n.a.	n.a.	n.a.	(Mensch and Amstutz 1975)
13	Femur	Medial femoral condyle width	PA	Modified tunnel view*	No	in vivo (n.a./53)	n.a.	n.a.	n.a.	(Mensch and Amstutz 1975)
14	Femur	Lateral femoral condyle width	PA	Modified tunnel view*	No	in vivo (n.a./53)	n.a.	n.a.	n.a.	(Mensch and Amstutz 1975)
15	Femur	Intercondylar notch width	PA	Modified tunnel view*	No	in vivo (n.a./53)	n.a.	n.a.	n.a.	(Mensch and Amstutz 1975)
16	Femur	Medial condyle height ratio	PA	Rosenberg, 45° KF	n.a.	in vivo (66/n.a.)	ICC	0.64	n.a.	(Minami et al. 2018)
17	Femur	Lateral condyle height ratio	PA	Rosenberg, 45° KF	n.a.	in vivo (66/n.a.)	ICC	0.72	n.a.	(Minami et al. 2018)
18	Femur	Distal condylar angle	AP	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	(Luo 2004)
19	Femur	Joint line angle (method 1)	AP	Standard	n.a.	in vitro (n.a./5)	ICR (Eliasziw et al. 1994)	0.796 (95% CI 0.675–1.0)	0.973 / 0.85	(Weber et al. 2013)
20	Femur	Joint line angle (method 2) ≙ Anatomical lateral distal femur angle	AP	Standard	n.a.	in vitro (n.a./5)	ICR (Eliasziw et al. 1994)	0.836 (95% CI 0.742–1.0)	0.958 / 0.832	(Weber et al. 2013)
	Femur	Anatomical lateral distal femur angle	AP	Standard	Yes	in vivo (n.a./20)	ICC	0.992 (95% CI 0.979 - 0.997)	0.984 (95% CI 0.959 - 0.994)	(Springer et al. 2020)

21	Femur	mechanical lateral distal femur angle	AP	Standard	Yes	in vivo (n.a./20)	ICC	0.989 (95% CI 0.971-0.996)	0.978 (95% CI 0.944-0.991)	(Springer et al. 2020)
22	Tibia	Anteroposterior depth	Lateral	n.a.	No	in vivo (157/157)	ICC	~0.82	~0.89	(Zhang et al. 2018)
	Tibia	Anteroposterior depth	Lateral	30° KF, overlapping condyles	n.a.	in vivo (36)	n.a.	n.a.	n.a.	(Fernandes et al. 2017)
23	Tibia	Medial plateau depth	Lateral	True lateral, with apparatus*	Yes	in vivo (n.a./53)	n.a.	n.a.	n.a.	(Mensch and Amstutz 1975)
24	Tibia	Medial posterior slope	Lateral	n.a.	n.a.	n.a. (286)	n.a.	n.a.	n.a.	(Luo 2004)
25	Tibia	Lateral posterior slope	Lateral	n.a.	n.a.	n.a. (286)	n.a.	n.a.	n.a.	(Luo 2004)
26	Tibia	Posterior slope	Lateral	n.a.	No	in vivo (157/157)	ICC	~0.77	~0.9	(Zhang et al. 2018)
	Tibia	Posterior tibial slope	Lateral	Standard	No	in vitro (20/40)	n.a.	n.a.	n.a.	(Dargel et al. 2009)
	Tibia	Tibial slope	Lateral	30° KF, overlapping condyles	n.a.	In vivo (36/n.a.)	n.a.	n.a.	n.a.	(Fernandes et al. 2017)
	Tibia	Tibial slope	Lateral	n.a.	No	in vitro (n.a./10)	n.a.	n.a.	n.a.	(Giffin et al. 2004)
	Tibia	Tibial slope	Lateral	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	(Massin and Gournay 2006)
27	Tibia	Mediolateral width	AP	n.a.	No	in vivo (157/157)	ICC	~0.85	~0.85	(Zhang et al. 2018)
	Tibia	Mediolateral width	PA	Modified tunnel view*	No	in vivo (n.a./53)	n.a.	n.a.	n.a.	(Mensch and Amstutz 1975)
28	Tibia	Medial tibial plateau width	PA	Modified tunnel view*	No	in vivo (n.a./53)	n.a.	n.a.	n.a.	(Mensch and Amstutz 1975)
29	Tibia	Lateral tibial plateau width	PA	Modified tunnel view*	No	in vivo (n.a./53)	n.a.	n.a.	n.a.	(Mensch and Amstutz 1975)
30	Tibia	Interspinous distance	PA	Modified tunnel view*	No	in vivo (n.a./53)	n.a.	n.a.	n.a.	(Mensch and Amstutz 1975)
31	Tibia	Coronal tibial slope (reference = anatomical axis)	AP	n.a.	No	in vivo (157/157)	ICC	~0.79	~0.89	(Zhang et al. 2018)
	Tibia	Plateau angle (reference = anatomical axis)	AP	n.a.	Yes	in vivo (390/n.a.)	ICC	0.93	0.89	(Higano et al. 2016)
	Tibia	Tibial plateau - tibial shaft angle (reference = anatomical axis)	AP	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	(Luo 2004)
32	Tibia	Medial proximal tibial angle (reference = mechanical axis)	AP	Standard	Yes	in vivo (n.a./20)	ICC	0.979 (95% CI 0.948 – 0.992)	0.980 (95% CI 0.950 – 0.992)	(Springer et al. 2020)

Table 2: Accuracy of 2D-3D reconstruction from a small number of X-ray images compared to 3D models from CT. Various different error metrics were used and often no specification regarding directionality and type of measurement (P2P/P2S) is given, which complicates the assessment and comparison of the studies' results. (DRR = digitally reconstructed radiographs, CI = confidence interval, P2P = Point to Point, P2S = Point to Surface. * Evaluated at specific landmarks ** Evaluated normal to plane.)

Source	**Image type, number**	**In vivo, in vitro, in silico** (number of subjects/ bones)	**Bone(s)**	**Accuracy (mm)**					**Error metric specifics**	
				MAE ± SD (CI 95%)	**Max. Absolute Error**	**RMSE ± SD**	**Max. RMSE**	**Hausdorff distance**	**Uni-/ bi-directional**	**P2P / P2S**
(Chaibi et al. 2012)	EOS, 4	in vitro (n.a./11)	Tibia& Femur	1.0 (CI 95%: 2.4)	6.6	/	/	/	uni	P2S
(Mahfouz et al. 2006)	DRRs, 2	in vivo/ in silico (1/1)	Femur	n.a.	0.46	/	/	/	/	P2S
(Zheng et al. 2018)	EOS (+ fixation device), 2	in vivo (23/n.a.)	Femur	1.4 ± 0.3	/	/	/	6.6 ± 1.6 (One-Sided)	uni	P2S
			Tibia	1.2 ± 0.3	/	/	/	5.6 ± 1.7 (One-Sided)	uni	P2S
(ElHak et al. 2007)	X-rays biplanar 2	n.a.	Femur	1.9	/	/	/	/	/	P2P
			Tibia	1.82	/	/	/	/	/	P2P
(Gamage et al. 2009)	X-rays, 2	in vitro (3/6)	Femur	0.86	/	/	/	/	/	P2P
(Quijano et al. 2013)	DRRs, 2	in vitro/ in silico (n.a./9)	Femur	1.3 (CI 95%: 3.5)	8.2	/	/	/	/	P2S
			Tibia	1.3 (CI 95%: 3.2)	8.1	/	/	/	/	P2S
			Distal Femur	1.2 (CI 95%: 3.1)	6.5	/	/	/	/	P2S
			Proximal Tibia	1.3 (CI 95%: 3.2)	8.1	/	/	/	/	P2S
(Schmutz et al. 2008)	X-rays Calibrated, 2	in vitro (7/7)	Distal Femur	1.21	5.81	/	/	/	/	P2P
(Laporte et al. 2003)	X-rays Calibrated, 2	in vitro (n.a./8)	Distal Femur	1.0	/	1.4	/	/	uni	P2S
(Baka et al. 2011)	X-rays Calibrated, 5	in vivo (30/30)	Distal Femur	/	/	1.68 ± 0.35 *	/	/	uni	P2S
(Cerveri et al. 2017)	DRRs, 3	in vivo/ in silico (20/n.a.)	Distal Femur	/	/	0.75	/	1.5	/	/
(Tchinde Fotsin et al. 2019)	DRRs (orthogonal), 2	in vivo/ in silico (n.a./109)	Distal Femur	/	/	0.72	1.38	/	/	/
			Proximal Tibia	/	/	0.99	1.81	/	/	/
(Messmer et al. 2001)	X-rays (+ fixation device) 2	in vitro (1/1)	Tibia (condyles)	2.4 ± 0.82	4.5	/	/	/	/	/
(Shetty et al. 2021)	Xrays Calibrated, 2	in vivo (25/45)	Distal Femur	1.0 ± 0.9	1.7	/	/	/	uni	P2S**
			Proximal Tibia	1.1 ± 1.0	1.7	/	/	/	uni	P2S**
(Wu and Mahfouz 2021)	Fluoroscopy, 1	in vivo (5/5)	Distal Femur	/	/	1.19 ± 0.36	/	/	/	/
			Proximal Tibia	/	/	1.15 ± 0.17	/	/	/	/
	Fluoroscopy and standard Xray, 2	in vivo (5/5)	Distal Femur	/	/	1.04 ± 0.33	/	/	/	/
			Proximal Tibia	/	/	1.03 ± 0.19	/	/	/	/

4 Discussion

Various parameter definitions to describe knee morphology using AP and Lateral X-rays are present in the literature, of which some correspond to the few established implant measures (7207-1:2007(E), 2007). In order to achieve adequate measurements, requirements are listed, such as true lateral images or a scaling object. However, these are similar to requirements for digital implant planning software. If given, the reported interrater- and intraobserver reliability can be interpreted as good to excellent (Cicchetti 1994) or moderate to excellent (Koo and Li 2016).

The functional relevance of the morphological parameters identified differs. In previous morpho-functional analyses, parameters with highest functional relevance are reported to be the femoral sagittal radii, the tibial slopes and the lateral trochlear elevation (Asseln et al. 2021; Fitzpatrick et al. 2012). Other studies have reported the significance of individual parameters for postoperative outcome, such as of the PCO for postoperative flexion range of motion (Bellemans et al. 2002). Parameters with high relevance for function or other outcome measures should be focused on in a mismatch analysis. However, an accurate assessment of e.g. implant overhang, which is associated with decreased flexion ROM and worse pain scores (Bonnin et al. 2013), is only possible with 3D surface data.

Several authors reported on methods for 2D-3D reconstruction and the accuracy achieved. However, differences in error measurements or missing specifications complicate the assessment and comparison of the reported accuracies. The characteristics of the different error metrics (MAE/ RMSE /Hausdorff) and calculation methods used (P2P/P2S, uni/bidirectional) have to be considered when comparing the reported accuracies, thus they are discussed in the following.

Unidirectional errors measure distances either from the reconstructed mesh to the ground truth or vice versa. Hence the focus of the former is to quantify offsets and of the latter to evaluate for missing surface areas. Bidirectional errors are the combined unidirectional errors, both from and to the reconstructed mesh. A unidirectional P2P error is defined as the distance between a mesh point and its nearest neighbor in the respective other mesh (reconstruction/ ground truth). In contrast, a unidirectional P2S error is defined as the minimal distance between a mesh point to the surface of the respective other mesh (Dumic et al. 2018). Hence, a P2S is lower compared to a P2P error for the same reconstruction. Furthermore, one has to differentiate normal absolute errors or projected errors. Those quantify the length of a projection of the error along the normal direction, hence resulting again in lower errors. The Hausdorff distance measures the overall highest distance between two point sets bidirectional, and is therefore equivalent to the maximum bidirectional absolute error. Consequently, the One-Sided Hausdorff distance is equivalent to the maximum unidirectional absolute error.

Few methods for 2D-3D reconstruction showed MAE or RMSE in the submillimeter range and maximum absolute errors below two millimeters. However, those were solely in silico analyses as they were based on DRRs. One in vivo study reported a normal maximum absolute error of 1.7 mm (Shetty et al. 2021). The projection of the error vectors may be the reason for the comparably low maximum absolute error. Other in vitro studies showed maximum absolute (P2S/ P2P) errors of ~5-6 mm, and hence do not reach the required accuracy, defined in the introduction. In addition, most studies required image calibration or EOS images, limiting their availability. The small study populations constitute a further limitation. Therefore, the accuracy for in vivo reconstruction of knees e.g. of different morphotypes, ethnities etc. may be significantly lower than reported in literature.

5 Conclusions

A basic preoperative risk assessment from radiographs is possible. The associated identification of landmarks is potentially time consuming. 2D-3D reconstruction is a promising option for enabling more comprehensive analyses, solely based on X-ray images. However, maximum errors reported are still too high for a risk assessment in TKA. Hence, future steps should include the automation of the parameter derivation and an enhancement of 2D-3D reconstruction for enabling a more comprehensive assessment.

Overall, comprehensive and automated evaluation of adequate radiographs could assist in identifying cases at risk for poor patient satisfaction without requiring additional resources. Else 3D imaging based on CT, MRI or 3D Ultrasound would be recommended

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