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3-dimensional computer tomography is more accurate than traditional long-leg radiographs in the planning and evaluation of coronal alignment in total knee arthroplasty: a prospective study on 121 knees

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Background and purpose — Accurate measuring tools are essential in preoperative planning and for the study of the association between postoperative alignment and clinical outcome in total knee arthroplasty (TKA). We aimed to describe a simple method to measure preoperative hip–knee–femoral shaft (HKFS) angle and postoperative coronal alignment in TKA with the use of standard 3D CT and to compare preoperative HKFS angles and postoperative coronal alignment measured with the 3D CT technique and with standing long-leg hip–knee–ankle (HKA) radiographs.

Patients and methods — HKA radiographs and 3D CT were taken preoperatively and 3 months after the operation in 121 knees. The interrater reliability for the 3D CT method was calculated with intra-class correlation coefficient (ICC). The preoperative HKFS angles and the postoperative deformity measured with the 2 methods were compared and illustrated on Bland–Altman plots, frequency tables, and by Cohen's kappa coefficients (κ).

Results — The 3D CT method was feasible in all knees and the ICC was excellent. Mean (SD, range) difference in HKFS angle measured on HKA radiographs and on 3D CT was –0.3° (0.9°, –4.1° to 2.4°). Mean (SD, range) difference in postoperative deformity was 0.1° (1.6°, –5° to 6°). The 95% limits of agreement were 1.4° and –2° for HKFS and ±3° for postoperative alignment. The agreement in outlier (≥ 3°) identification was moderate with a κ (95% confidence interval) of 0.48 (0.32–0.64).

Conclusion — 3-dimensional computer tomography was feasible and was shown to be more accurate than traditional long-leg radiographs

Correct alignment in the coronal (frontal) plane is considered an important factor for long-term survival and for good knee function after total knee arthroplasty (TKA) [1-3]. Consequently, accurate measuring tools are essential in preoperative planning of TKA and in clinical decision-making in painful TKAs. Alignment is also a critical endpoint in much orthopedic research, as in studies comparing different alignment goals [2,4] and studies aiming to establish limits for acceptable malalignment [3,5]. Likewise, in studies comparing conventional surgical techniques with computer-guided TKA and robotics [6,7], accurate and reliable measuring methods are essential.

Malalignment of TKAs may occur because of errors in the preoperative planning and/or intraoperatively because of inadequate surgery and/or inaccurate alignment tools. An apparent postoperative malalignment may be real or due to errors in measurements. Hence, both preoperative planning and postoperative evaluation depend on reliable imaging procedures and measuring methods.

The gold standard for both preoperative planning and postoperative evaluation of alignment is weight-bearing hip–knee–ankle (HKA) radiographs [8]. The reliability of this technique has proven to be excellent [9]. However, earlier studies have questioned the ability of the HKA radiographs to measure alignment in the true frontal plane [10-12]. A prerequisite for exact measurements of alignment is a clear definition of the plane in which the measurements are done. The surgical epicondylar axis [13] has been accepted as a gold standard for defining the rotational axis and the coronal plane of the knee [14]. However, this axis can only be seen on CT images. Therefore, during the traditional radiographic examination the technician must rely on a surrogate technique that consists of rotating the leg until the feet are facing directly forward and the patella is centered on the femoral condyles [15]. This is a difficult maneuver that depends on subjective judgement, which might induce an important source for systematic and

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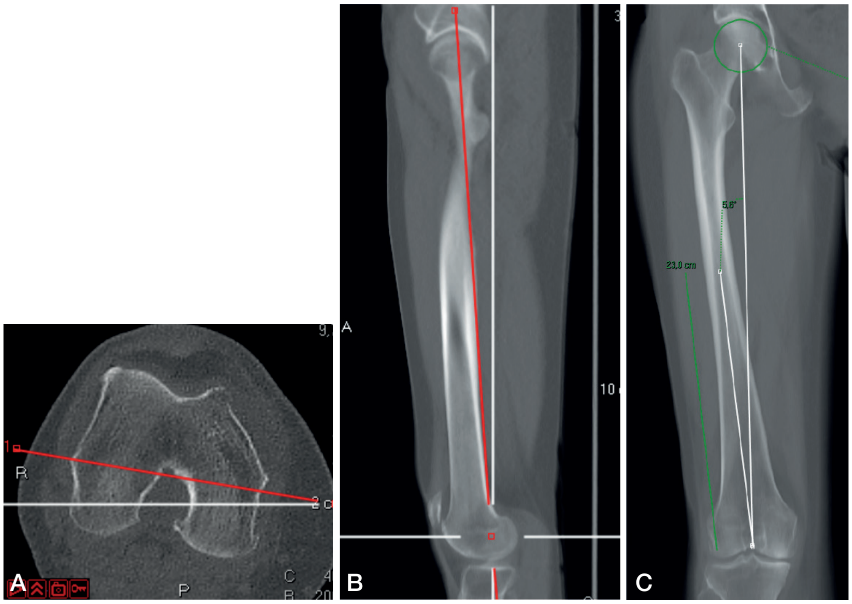

Figure 1. A. Frontal plane defined by surgical transepicondylar axis (sTEA). B. Center of femoral head. C. Thick slice of this frontal plane used for measurement of the angle between the mechanical axis of the femur and the femoral shaft (HKFS), see text for details.

random errors due to the parallax effect [12]. This problem is exaggerated in cases with flexion contracture of the knee, a common situation in osteoarthritis.

We have developed a simple technique for measurements of the hip–knee–femoral shaft (HKFS) angle and coronal alignment of the prosthetic components based on a low radiation dose, 3-dimensional computed tomography (3D CT).

We aimed to describe a method to measure the preoperative HKFS angle and postoperative coronal alignment in TKA with the use of standard 3D CT and to compare preoperative HKFS angles and postoperative coronal alignment measured with 3D CT and with traditional HKA radiographs.

Patients and methods

In this prospective study 130 consecutively operated knees in 128 patients were assessed for eligibility. The inclusion criterion was patients scheduled for primary TKA. Exclusion criteria were revision arthroplasties and knees with severe deformity of bone and/or ligaments that made them unsuitable for a standard cruciate-retaining prosthesis. All patients were operated on at the surgical department at Sykehuset Innlandet Hospital Trust, Lillehammer, between February 2020 and August 2021. In 4 bilaterally operated patients the lastly operated knee was excluded. Excluded also was 1 patient operated on with a constrained LCCK prosthesis and 1 patient who suffered a tibial fracture 6 weeks after the operation. 3 patients declined to participate in the study.

Standing long-leg HKA radiographs and 3D CT of the lower limb were taken preoperatively and 3 months after the operation.

Radiographic techniques

Standing long-leg HKA radiographs were acquired with GE Discovery XR 656 (2010) (GE HealthCare, Chicago, IL, USA) with stitching technique. The leg was rotated until the feet were facing directly forward and the patella was centered on the femoral condyles [15].

Preoperatively, the preferred varus/valgus position of the femoral component was estimated as follows. On the HKA radiograph the expected position of a 23 cm long and 7 mm diameter intramedullary rod introduced from the center of the femoral condyles into the femoral shaft was marked with a line. The angle between this line and the mechanical axis of the femur (HKFS angle) was then measured. The preoperative coronal plane deformity of the knee was measured on the HKA radiographs in degrees as the deviation from neutral mechanical axis. Varus was denoted as positive values and valgus negative values.

At 3 months' follow-up the mechanical lateral distal femoral angle (mLDFA), the mechanical medial proximal tibial angle (mMPTA), and the joint line congruence angle (JLCA) were measured [16]. The JLCA was denoted as positive when open laterally and as negative when open medially. The deformity (deviation from neutral mechanical axis) was then calculated with the following formula: Deformity = mLDFA – mMPTA + JLCA.

3D CT technique

2 different CT scanners were used: Philips Ingenuity (2011) (Philips Healthcare, Amsterdam, the Netherlands) and General Electrics Revolution ES (2018) (GE HealthCare, Chicago, IL, USA). A volume scan from hip to ankle of both limbs was acquired with a low-dose protocol (kV = 120 and mAs = 10 as scan parameters for the Philips and kV = 120 and smart mA 20–50 dose modulation for the GE). For CT measurements the images were loaded into the standard multiplanar reconstruction (MPR) application of our PACS system, Carestream Vue PACS (https://www.carestream.com).

Preoperatively, the preferred varus/valgus position of the femoral component was estimated as follows. First, the frontal plane of the femur was defined as a plane through the surgical epicondylar axis and the center of the femoral head (Figures 1A and B). Using the MPR tool, thick slices (4–5 cm) were reconstructed to visualize the femur in this plane. The expected position of a 23 cm long and 7 mm diameter intramedullary rod introduced from the center of the femoral condyles into the femoral shaft was marked with a line. The angle between this line and the mechanical axis of the femur (HKFS angle) was then measured (Figure 1C).

Figure 2. Measurement of postoperative mLFDA.

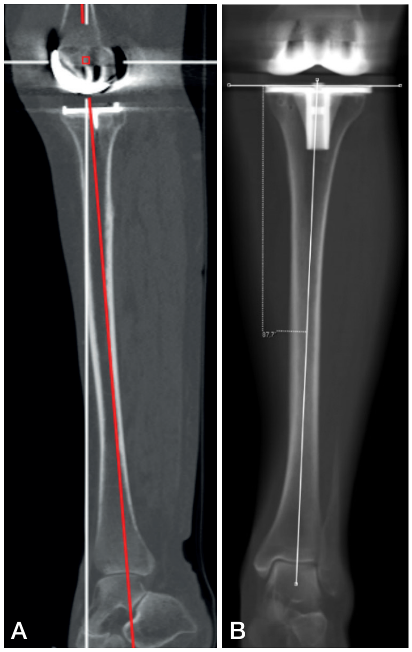

Figure 3. Measurement of postoperative mMPTA.

At 3 months' follow-up the position of the femoral and tibial components was evaluated. The femur was visualized in the frontal plane as explained above and the coronal alignment of the femoral component was measured as the mLDFA (Figure 2). The position of the tibial component was assessed with the tibia oriented in a plane defined by the surgical epicondylar axis and a point at the center of the distal tibial articular surface (Figures 1A and 3A). The coronal alignment of the tibial component was then measured as the mMPTA (Figure 3B). Lastly, the joint line congruence angle (JLCA) was measured. The deformity of the knee was calculated in the same way as for the radiographs.

To estimate the interobserver reliability of the 3D CT technique, the preoperative HKFS angle and the postoperative mLDFA and mMPTA were measured by 3 independent observers (EAl, JER, and SGS), 1 experienced specialist, 1 less experienced specialist, and 1 trainee, blinded to each other's measurement results. According to the recommendations of Koo et al., 50 knees were randomly selected, and intra-class correlation coefficients (ICC) were calculated. With the intention of making our results generalizable to a wide range of raters, the 2-way random effects model was chosen [17].

The differences in the preoperative HKFS angle and postoperative deformity measured by the 2 methods are presented on Bland–Altman plots and on frequency tables. Cohen's κ coefficient was used to assess the agreement between the methods on outlier identification.

The effective radiation dose was calculated using software with a mathematical phantom and Monte-Carlo simulations and the IRCP103 report for tissue weighting.

Surgical technique

All knees were operated on with a posterior cruciate retaining prosthesis (NexGen, Zimmer, Warsaw, IN, USA). A 23 cm long and 7 mm wide intramedullary rod was introduced into the femur and the distal cutting block was seated at the preoperatively planned HKFS angle measured on the 3D CT. Rotational alignment of the femoral component was determined with the clinical rotational axis (CRA) method [18]. Soft-tissue balancing was performed with the intention of obtaining rectangular or slightly trapezoidal (anatomic) gaps with 1–3 mm laxity [19]. The tibial component was set at 90° to the mechanical axis in the coronal plane and 7° posterior slope in the sagittal plane with an extra-medullary guide. Tibial component rotation was set according to the Akagis line [20]. We aimed for mechanical neutral alignment, which means the postoperative mechanical tibia–femoral angle (mTFA) should ideally be 180°, that is zero degrees deformity.

The "Guidelines for Reporting Reliability and Agreement Studies" (GRRAS) were followed [21].

Statistics

Categorical variables are presented as numbers and percentages. Assessments of normality were done on histograms and QQ plots. The mean and standard deviations (SD) or median and range are given as appropriate. The inter-observer reliability of the 3D CT technique was estimated with intra-class correlation coefficient (ICC), 2-way random effects model, single rater, and absolute agreement. ICC was interpreted as follows: values less than 0.5 are indicative of poor reliability, values between 0.5 and 0.75 indicate moderate reliability, values between 0.75 and 0.9 indicate good reliability, and values greater than 0.90 indicate excellent reliability (17).

Mean differences in HKFS angles and postoperative deformity between 3D CT and HKA radiographs were analyzed with paired samples t-tests. The agreement between the 2 methods is demonstrated on Bland–Altman plots with 95% limits of agreement (LoA). Proportional bias was estimated with linear regression analysis. Frequency tables are also presented to show how frequently different levels of divergence between the methods occur. Cohen's κ coefficient was used to assess the agreement of outlier identification between the 2 methods. Outliers were defined as deformity ≥ 3°. Cohen's κ coefficient was interpreted as follows: 0–0.40, poor; 0.41–0.60, moderate; 0.61–0.80, good; 0.81–1.00, excellent agreement [22]. A significance level of 5% was used. Statistical analyses were performed using the IBM SPSS statistics version 27.0 (IBM SPSS Inc; IBM Corp, Armonk, NY, USA).

Ethics, funding, and disclosures

The protocol was approved by the Regional Committee of Research Ethics at the University of Oslo (ID number 154324). All the patients signed an informed consent form. Funding was received from Sykehuset Innlandet Hospital Trust. The authors have no conflicts of interest. Completed disclosure

Table 1. Patient characteristics (N = 121)

Factor	n (%)	Mean (SD) range
Age		68.6 (9.1) 49–90
BMI		29.3 (4.0) 20–43
Female/male sex	76 (63)/45 (37)	
Right/left knee	64 (53)/57 (47)	
Preoperative coronal alignment		
Varus	85 (70)	7.5° (4.0°) 0.9°–17°
Valgus	29 (24)	7.0° (4.4°) 0.4°–18°
Neutral	7 (6)	

Table 2. Interrater reliability expressed as intraclass correlation coefficient (ICC) 2-way random effects model. Single measures are given for absolute agreement

Factor	ICC (CI)
Preoperative HKFS	0.95 (0.92–0.97)
Postoperative mLDFA	0.91 (0.86–0.94)
Postoperative mMPTA	0.92 (0.88–0.95)

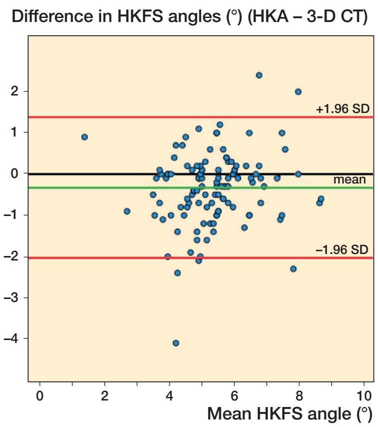

Figure 4. Bland–Altman plot illustrating the differences in HKFS angles between the 2 measuring methods for each knee on the vertical axis, against the mean of the 2 measurements on the horizontal axis. Green line indicates the mean difference and the red lines represent the mean ±1.96 SD of the mean, that is the upper (1.4°) and lower (–2.0°) 95% LoA.

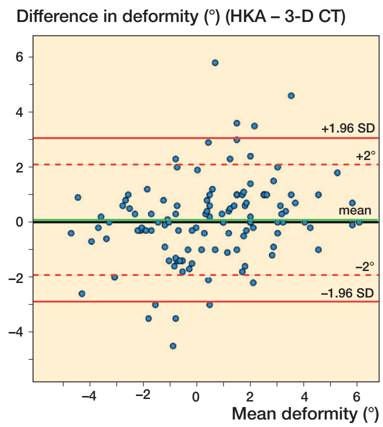

Figure 5. Bland–Altman plot illustrating the differences in postoperative deformity between the 2 measuring methods. For details see Figure 4. Red lines represent the mean ±1.96 SD of the mean, that is the upper (3.1° varus) and lower (2.9° valgus) 95% LoA. Stippled red lines represent the mean ± 2°.

Table 3. Frequency table showing the difference in HKFS angle measured on standing HKA radiographs and on 3D CT (N = 121)

Difference HKA–3D CT	Number of knees	Distribution % (CI)
< 1°	57	47 (38–56)
≥ 1°	64	53 (44–62)
≥ 2°	11	9.1 (5.2–16)
≥ 3°	1	0.8 (0.1–4.5)
≥ 4°	1	0.8 (0.1–4.5)

Table 4. Frequency table showing the difference in postoperative deformity measured on standing HKA radiographs and on 3D CT (N = 121)

Difference HKA–3D CT	Number of knees	Distribution % (CI)
< 1°	45	37 (29–46)
≥ 1°	76	63 (54–71)
≥ 2°	29	24 (17–32)
≥ 3°	12	9.9 (5.8–17)
≥ 4°	7	5.8 (2.8–12)
≥ 5°	3	2.5 (0.9–7.0)
≥ 6°	1	0.8 (0.1–4.5)

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Results

121 knees were investigated (Table 1). The 3D CT method was feasible in all knees. The interrater reliability was excellent for the measurements of preoperative HKFS and the postoperative mLDFA and mMPTA (Table 2).

The mean (SD, range) difference in HKFS angle measured on HKA radiographs and on 3D CT was –0.3° (0.9°, –4.1° to 2.4°). Agreement between the 2 methods is illustrated in the Bland–Altman plot in Figure 4. The upper and lower 95% LoA were 1.4° and –2.0°. Regression analysis showed no statistically significant proportional bias.

In 57 knees (47%) there was no difference between the measurements. In 11 knees (9%) the difference was 2° or more (Table 3).

Mean (SD, range) difference in postoperative deformity measured on HKA radiographs and 3D CT was 0.1° (1.6°, –5° to 6°). Agreement between the 2 methods is illustrated in the Bland–Altman plot in Figure 5. The upper and lower 95% LoA were 3.1° varus and 2.9° valgus. Regression analysis showed a statistically significant proportional bias, β (95% confidence interval [CI]) was 0.17 (0.05–0.29). In 12 knees (9.9%) the difference between the measuring methods was ≥ 3°. The maximum disagreement between the measuring methods was 6° (Table 4). The agreement between the 2 measuring methods in outlier (≥ 3°) identification was moderate, and Cohen's kappa coefficient (CI) was 0.48 (0.32–0.64). The JLCA on the postoperative HKA and 3D CT was 0° in all but 3 (HKA) and 2 (3D CT) (max 1°, min –1°).

The calculated effective radiation dose received per CT scan was 0.3 mSv for the Philips Ingenuity scanner and 0.4 mSv for the General Electrics Revolution scanner. For the HKA radiographs the dose was 0.15 mSv.

Discussion

We aimed to describe a simple method to measure preoperative HKFS angle and postoperative coronal alignment in TKA with the use of standard 3D CT and to compare with measurements on standing long-leg hip–knee–ankle (HKA) radiographs.

We found that measurements on HKA radiographs are disposed to important random errors compared with 3D CT. The weak agreement between traditional HKA radiographs and the 3D CT techniques in outlier identification of postoperative deformity indicates that outliers identified on HKA radiographs are not always the same as those identified on 3D CT.

Effect of parallax

The reason for the discrepancy between the 2 methods is probably that they measure alignment in different planes. The definition of the frontal plane on weight-bearing HKA radiographs depends solely on subjective judgement of the technician, whereas in the 3D CT technique the frontal plane is defined by more objective parameters. The reason why measurements on the same object in different planes lead to different results is the effect of parallax, that is a difference in the apparent position of an object viewed along 2 different lines of sight [12].

Our results are supported by earlier studies. Lonner et al. [12] studied the effect of rotation and knee flexion on radiographic alignment measurements in TKA using a model made of synthetic bones (Sawbones). They found that limb rotation and knee flexion of l0°, either alone or in combination, had a highly statistically significant effect on measured values of the anatomic alignment. Average radiographic anatomic alignment ranged from 2.3° valgus in 20° external rotation and 10° flexion, to 6.7° valgus in 25° internal rotation and 10° flexion. Kawakami et al. [11] investigated the effects of rotation on 2D measurement of lower limb alignment for knee osteotomy using a CT-based 3D bone model of the lower limb. They found that the mean (SD) rotation angle of the whole-leg radiographs, relative to the epicondylar axis, was 7.4° (3.9°) of internal rotation, ranging from 8° of external rotation to 14° of internal rotation. Consequently, the mean changes in FTA (femoro-tibial angle) and HKA angle were 3.5° (SD 2.2°, range 0.4–8.6) and 1.6° (SD 1.3°, range 0.2–4.9), respectively. They concluded that 3D methods are preferable for surgical planning.

HKFS

The mean difference in HKFS angle measured on HKA radiographs and on 3D CT was small and most likely without clinical importance. On an individual basis the difference was ≥ 2° in 9% of the knees. In isolation this is probably an unimportant difference. However, malalignment in TKA is often due to many factors with additive effects. For example, if in addition the femoral and tibial components are malaligned 2°in the same direction, the total deformity can reach 6°, which may compromise functional outcome and the longevity of the prosthesis. Therefore, to obtain correct alignment all known variables should be minimized.

Postoperative deformity

The mean difference between the measuring methods in postoperative deformity was negligible, hence no systematic bias was observed (Figure 5). However, our findings indicate that measurements on HKA radiographs are disposed to important random errors. Furthermore, we showed a statistically significant proportional bias, indicating that the difference between the 2 measuring methods increases with increasing deformity. This is a logical consequence of the effect of parallax on HKA radiographs: the greater the varus or valgus deformity, the greater the effect of poor projections.

In our study, the upper and lower 95% limits of agreement (LoA) were 3.1° varus and 2.9° valgus. There is no consensus on how large a difference between these measures would be clinically acceptable. However, in clinical decision-making as well as in orthopedic research ±3° would certainly be of interest. We suggest an acceptable limit of < 2° (red hatched line in the Bland–Altman plot in Figure 5). Consequently, angular measurements on HKA radiographs on individual patients may not be reliable and clinical decision-making may be prone to mistakes. In orthopedic research, measurements of alignment in the frontal plane are often an important dependent or independent variable and erroneous measurements may lead to flawed results.

Our results are supported by Ueyama et al. [23], who compared 2D and 3D measurements in the identification of prosthetic alignment and outliers after TKA. They found that the mean prosthetic alignment and rate of outliers were not significantly different between 2D and 3D measurements, but the agreement in outlier identification was poor. Yoshino et al. found that 3D-CT measurements of component positions after TKA showed good intra- and interobserver reliability for the femoral and tibial components in coronal plane [24].

However, comparisons between different studies are complicated by the fact that the definition of the frontal plane in which alignment measurements were performed varies [23-25]. In the AURORA protocol [25] the tibial antero-posterior axis was defined by the tibial tubercle and the PCL insertion. Yoshino et al. [24] defined the coronal plane as a vertical to the “Akagi line.” However, other studies have demonstrated that these landmarks are hard to define and have low interobserver reliability [26,27].

In our study CT measurement were done by radiologists. Once the technique is learned it takes about 5 minutes for preoperative HKFS measurement and 15–20 minutes for postoperative coronal alignment measurements. It does require access to and familiarity with software that can reconstruct CT in 3 planes. In practice this is probably most easily done by radiologists. An important advantage with the 3D CT method is that measurements on rotational alignment and sagittal plane alignment are easily done in the same session.

Limitations and strengths

In the native knee the rotational plane of the knee changes from flexion to extension due to the "screw home" mechanism and comparable biomechanics have also been observed in some prosthetic knee joints. Consequently, the true frontal plane may change during motion. However, we investigated alignment in extension, and currently the surgical epicondylar axis is probably the best axis for definition of the true frontal plane. The intramedullary rod used in this study was 7 mm in diameter. In patients with wide intramedullary canals the position of the rod in the canal may not be exactly replicated from the preoperative planning. Definition of the surgical epicondylar axis on the CT scans may be difficult in some knees because of artifacts from metal implants. Nevertheless, we were able to define the surgical epicondylar axis in all knees and the excellent ICC values indicate very limited interobserver variation in the definition of the surgical epicondylar axis.

There is no consensus on what degree of alignment leads to inferior clinical outcome [2,3,5,28-30]. Therefore, the definition of outliers or unacceptable alignment is somewhat arbitrary. However, in order to satisfy the current demands of knee function and 10 years' prosthetic survival of more than 98% [31], it seems reasonable to assume that even relatively small inaccuracies may be of importance.

3D CT cannot fully substitute long-leg standing HKA radiographs because the latter also give important information regarding the status of the collateral ligaments. The tibial cuts were done at 7° posterior slope. Our results on the mMPTA should be interpreted with caution in cases where the tibial cut is done at 0°.

The strengths of the study are the prospective design and relatively high number of patients, as well as the definition of the frontal plane through the surgical transepicondylar line. Another strength of this study is the definition of the preoperative HKFS angle. The HKFS angle is often defined as the angle between the anatomical and mechanical axes of the femur. However, when inserting the intramedullary rod into a deformed distal femur the rod may not line up with the anatomical axis. To avoid this problem, we defined the HKFS angle as the angle between the expected position of the rod and the mechanical axis.

Conclusion

We found that measurements of preoperative HKFS angles and postoperative coronal alignment measured on standing HKA radiographs are disposed to important random errors compared with measurements on 3D CT. We also found less than perfect agreement in outlier identification between the methods. In perspective, it seems reasonable to assume that the 3D CT measurements are closer to the true values than the measurements on HKA radiographs. Consequently, we suggest that 3D CT should be included in preoperative planning and postoperative evaluation of TKA.

EAu and EAl developed the 3D CT method. EAu designed the study protocol. All authors performed radiographic measurements. Statistical analyses were performed by EAu with support from Oslo Centre for Biostatistics and Epidemiology. EAu drafted the manuscript, which was critically revised by all authors.

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