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OTSR-581; No. of Pages 8
ARTICLE IN PRESS

Orthopaedics & Traumatology: Surgery & Research (2012) xxx, xxx—xxx

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Orthopaedics & Traumatology
Surgery & Research

ORIGINAL ARTICLE

Reliability of a new method for lower-extremity measurements based on stereoradiographic three-dimensional reconstruction

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Accepted: 12 March 2012

KEYWORDS
Radiographic image interpretation;
Computer-assisted orthopaedics;
Skeletal imaging;
Three-dimensional;
Radiation dosage;
Leg length measurements

Summary
Introduction: Several clinical and radiological techniques have been described to assess lower limb length and angle measurements. None of them has yet met the ideal criteria for a reliable, reproducible, safe, and inexpensive system. In this context, a new biplanar X-ray system (EOS™, EOS imaging, Paris, France) makes it possible to obtain a 3D reconstruction of the lower extremities from two 2D orthogonal radiographic images, with associated calculation of 3D measurements. The reliability of this technique has never been documented on adults.
Hypothesis: Lower limb measurements produced by the 3D EOS™ reconstruction system are reproducible regarding inter- and intraobserver assessment and more reliable with this 3D technique than when they are obtained from 2D measurements.
Materials and methods: This study included 25 patients awaiting total hip arthroplasty (50 lower limbs). Two independent observers made all measurements twice, both on the 2D frontal radiograph and using 3D reconstructions (femoral measurements of length, offset, neck shaft angle, neck length, and head diameter, as well as the tibia length, limb length, HKA and HKS). Reproducibility was estimated by intraclass correlation coefficients.
Results: Both the inter- and intraobserver reproducibility of the EOS™ measurements was excellent; more specifically inter- and intraobserver reproducibility was 0.997 and 0.997 for femoral length, 0.996 and 0.995 for tibial length, 0.999 and 0.999 for limb length, 0.894 and 0.891 for HKS, 0.993 and 0.994 for HKA, 0.870 and 0.845 for femoral offset, and 0.765 and 0.851 for neck shaft angle. For most of the variables, the interobserver correlations were statistically better with the EOS™ 3D reconstruction.

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1877-0568/$ - see front matter © 2012 Published by Elsevier Masson SAS.
doi:10.1016/j.otsr.2012.03.014

Please cite this article in press as: Guenoun B, et al. Reliability of a new method for lower-extremity measurements based on stereoradiographic three-dimensional reconstruction. Orthopaedics & Traumatology: Surgery & Research (2012), doi:10.1016/j.otsr.2012.03.014

Discussion: Our results show that the EOS™ systems allow reproducible lower limb measurements. Furthermore, 3D EOS™ reconstructions offer better reproducible measures for most of the parameters than radiographic 2D projection. Its use before deciding on surgery and during planning for lower limb arthroplasty appears essential to us.
Level of evidence: Level III: diagnostic prospective study on consecutive patients.

Introduction

Since the era of arthroplasty began, orthopedic surgeons have needed to take meticulous lower limb measurements to optimize preoperative planning. Currently, plain radiographs are used in clinical practice and research for most of these measurements. Even with digitization, however, these measurements remain limited to only two dimensions, and they may well be insufficiently accurate to allow diagnosis or preoperative planning [1,2]. The ability to measure the different relevant lengths and angles of the lower limb in 3D space is essential in the analysis of lower limb anatomy and biomechanics.

The choice of imaging technique requires consideration of accuracy, reliability, magnification, radiation dose, cost, need for special equipment, convenience, and the ability to image the entire limb. A technique's accuracy is defined as the variation of the measurement when using the imaging method compared with its variation with the reference technique or gold standard, whereas its reliability is the interobserver and intraobserver variation in measurements. Besides standard clinical techniques [3], the currently available methods for lower limb measurements are conventional and digital radiography [4], computed tomography (CT) [5], and magnetic resonance imaging (MRI) [6]. Most of these radiologic techniques, however, have specific limitations, and the specific protocols required do not appear to be routinely employed.

A new imaging method, the low-dose digital stereoradiography, was recently developed [7,8]. This technique is based on the multiwire proportion chamber for particle detectors, for which G. Charpak won a Nobel Prize in physics. A partnership between a team of biomedical engineers, orthopedic surgeons, and radiologists has transformed it into the low-dose system named EOS™ (EOS™ Imaging, Paris, France).

The system consists of a C-shaped vertically travelling arm supporting two image acquisition systems, placed orthogonally, each composed of an X-ray tube and a linear detector. The source and detector thus move together, with the beam always horizontal to the patient. The system produces full-length, weight-bearing images with minimal irradiation [7—9]. Specially designed software included in the workstation allows three-dimensional (3D) modelling of the bone envelope and automatic calculation of specific clinical variables (Fig. 1). Biplanar stereoradiography and personalized modelling of the skeleton have been extensively developed for various anatomic regions including the lumbar spine [10], cervical spine [11], ribs [12], pelvis [13]. In a recent study, the use of this technique on lower extremities was validated on children [14]. The goal of our study was to investigate intraobserver and interobserver reproducibility of these EOS™ 3D reconstruction measurements in vivo. As a secondary aim, we compared these results with 2D measurements.

Materials and methods

Patients

This study included 25 patients scheduled for total hip arthroplasty (50 lower limbs). Patients consented in writing to inclusion in the study after receiving comprehensive information about the study protocol and other details. Inclusion criteria for this study included need for a primary total hip replacement and provision of informed consent. This study received an institutional review board approval (Comité de Protection des Personnes Île-de-France X, Number: 2011-04-03).

Patients were excluded if they had previously had any kind of bone surgery (osteosynthesis or arthroplasty) for the lower limbs. Each patient underwent biplanar EOS™ long-leg radiography in a weight-bearing position. Dose received by the patient (entrance ''air kerma''), given by the acquisition system, was recorded for each patient.

2D measurement

For each patient, the EOS™ frontal 2D X-ray was used to perform 2D measurements with a dedicated software (SterEOS 2D, EOS™ Imaging, Paris).

Measurements were done as follows (Fig. 2):

- Femur length: between the center of the femoral head and the center of the femoral notch.
- Tibia length: between the center of the tibial plateau and the center of the tibial plafond.
- Total length: between the center of the femoral head and the center of the tibial plafond.
- HKA angle: between the femoral mechanical axis and the tibial mechanical axis. The femoral mechanical axis was defined as that connecting the center of the femoral head to the center of the femoral notch, and the tibial mechanical axis as the line from the center of the tibial plateau extending distally to the center of the tibial plafond.
- HKS angle: between the femoral mechanical axis and the femoral anatomical axis.
- Femoral head diameter: diameter of a circle fitting the femoral head.

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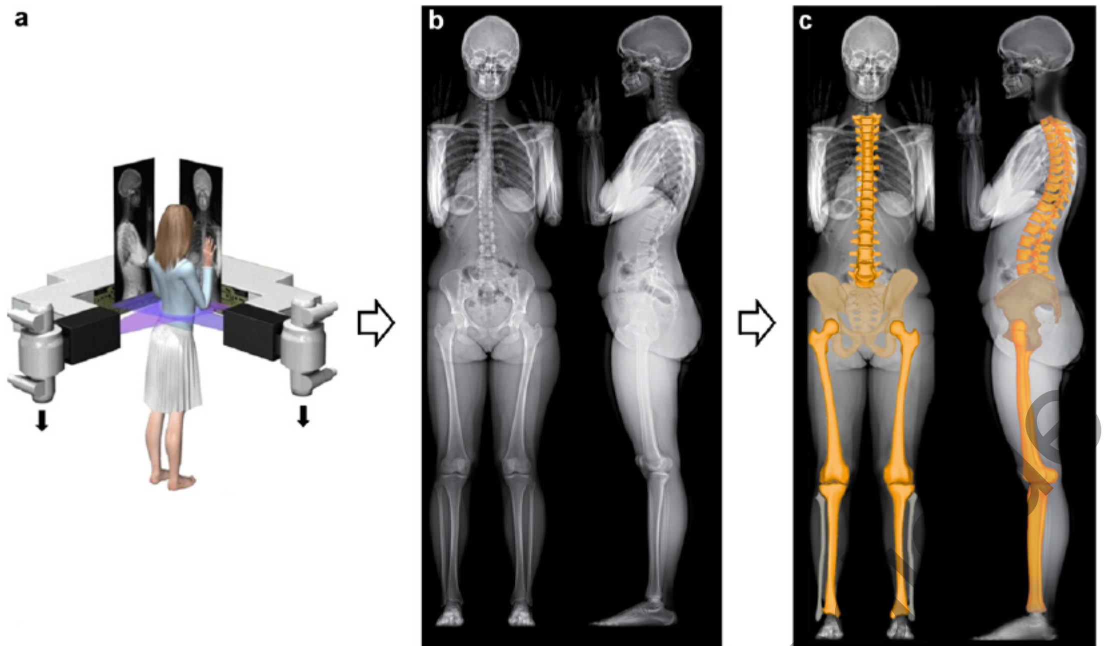

Figure 1 EOS™ 3D modelling process. a: simultaneous radiographic acquisition; b: radiographic images; c: 3D modelling.

- Femoral neck length: length of the neck axis between the center of the femoral neck and the point joining the neck axis and the diaphysis axis.
- Neck-shaft angle: angle between the femoral neck axis and the axis of the diaphysis.
- Femoral offset: distance between the center of the femoral head and the axis of the diaphysis.

Two independent observers did each 2D measurement twice.

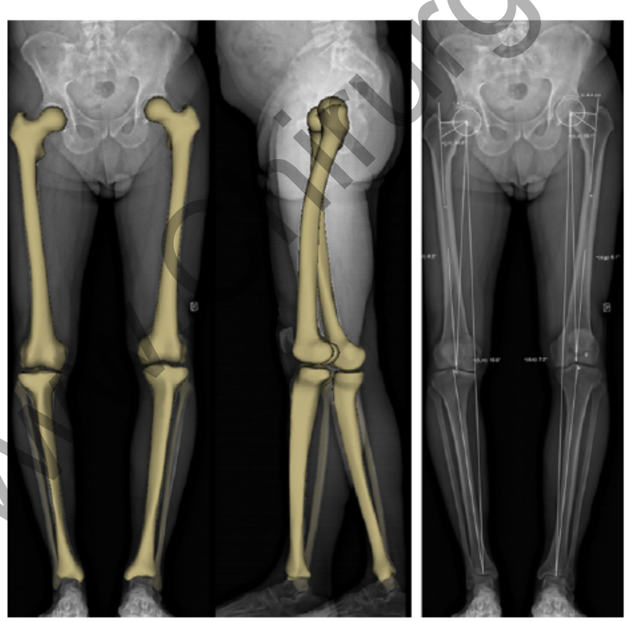

Figure 2 3D lower limb reconstruction and long-leg radiograph.

3D measurement

With the dedicated 3D software (SterEOS 3D, EOS™ Imaging, Paris), the same operators reconstructed each lower extremity in 3D. The reconstruction process begins by the selection of anatomical landmarks: center of the femoral head, femoral condyles, and tibial extremities (proximal and distal). The application creates the lower limb envelope; the operators then adjust the reconstruction manually to match the model better. Finally, the clinical measurements are automatically extracted from the final envelope. The available lower limb measurements were: femur length, tibial length, lower limb length, HKS angle, HKA angle, femoral offset, neck shaft angle, femoral head diameter, femoral neck length, femoral anteversion, femoro-tibial rotation, tibial torsion, and presence of flexion contracture or recurvatum (Fig. 2). Landmarks used to do the 2D measurements were equivalent to those used by the 3D software for the automated calculations. Two independent observers did each 3D measurement twice.

Statistical analysis

These data enabled us to calculate intraclass correlation coefficients [15] to determine the intra- and interobserver reliability for each technique. The means, SD, and 95% confidence intervals were calculated for the variables above (two observers by two times by 100 lower limbs). We investigated intra- and interobserver reproducibility of each variable with multivariate four-way analysis of variance. Means for the quantitative variables were compared with Student's *t*-test or the nonparametric Mann-Whitney test for comparing paired means. Significance was defined as a *P* value of 0.05. Completed data were analyzed with use of the Statistical

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Table 1 Results of lower limb measurements by 3D EOS™ and the 2D EOS™ radiograph.

Variable	3D		2D		Difference	*P*
	Mean (Min; Max)	SD	Mean (Min; Max)	SD		
Femur length (cm)	41.66 (48.16; 36.75)	2.42	41.15 (36.40; 47.70)	0.47	0.51	< 0.05
Tibia length (cm)	36.29 (41.48; 30.54)	2.59	35.54 (29.40; 40.60)	0.55	0.75	< 0.05
Lower limb length (cm)	78.15 (88.47; 67.87)	4.80	77.29 (66.70; 88.60)	0.84	0.86	< 0.05
HKS angle (°)	6.02 (9.23; 2.07)	1.48	5.59 (1.30; 9.00)	0.36	0.43	< 0.05
HKA angle (°)	1.10 (−20.83; 14.32)	5.36	0.71 (−23.10; 16.70)	0.71	0.38	< 0.05
Femoral offset (cm)	4.27 (5.84; 3.11)	0.54	3.60 (2.30; 6.00)	0.68	0.67	< 0.05
Neck shaft angle (°)	122.69 (139.56; 108.87)	5.96	130.73 (110.30; 146.20)	0.96	−8.04	< 0.05
Femoral head diameter (cm)	4.47 (5.16; 3.70)	0.29	4.55 (3.50; 5.80)	0.47	−0.08	< 0.05
Femoro-tibial rotation (°)	7.16 (27.61; 0.23)	5.52				
Tibial torsion (°)	28.91 (43.93; 9.76)	7.13				
Femoral neck length (cm)	5.01 (6.51; 4.04)	0.50	4.78 (3.50; 6.90)	0.68	0.25	< 0.05
Flessum/Recurvatum (°)	6.67 (18.24; −14.72)	6.11				
Femoral anteversion (°)	10.27 (35.03; −6.28)	8.65				

Package for the Social Sciences, version 17.0 (SPSS, Chicago, Illinois).

Results

Values of each lower limb variable extracted from the 2D measurement and 3D EOS™ reconstruction are reported in Table 1 and did not differ from the value of the literature [4,16–18]. We found a statistical difference for all the lower limb variables between the 2D and the 3D techniques ($P < 0.05$).

The intraobserver correlations of the 3D technique were excellent as they were for the 2D technique. This was the case confirmed for all the variables. On the other hand, correlations were somewhat lower for some of the variables for the 2D technique: neck shaft angle, and femoral head diameter. The intraobserver correlations were statistically better with the 3D technique than the 2D technique for most of the variables (Table 2).

The interobserver correlations of the 3D EOS™ technique were also excellent, as for the 2D technique. Again, this result was confirmed for all variables in the 3D reconstructions, while for the 2D technique, some variables were less well correlated (HKS angle, neck shaft angle, femoral head diameter, and femoral neck length). For most of the variables, the interobserver correlations were statistically better with the 3D reconstruction (Table 2).

The mean difference between the two observers is shown in Table 3. For all lower limb measurements, 3D technique SD was systematically slightly inferior to 2D measurement ($P \leq 0.005$).

The average dose delivered for the stereoradiographic examination (AP + LAT) was 0.54 mGy (SD = 0.05 mGy).

Discussion

The ideal method for measuring lower limb variables should be readily available, accurate, reliable, inexpensive, allow visualization of the entire limb, minimize radiation exposure, and have no magnification error. Review of the literature shows that, until now, no single imaging method could be considered ideal. Until now, the EOS™ system has been available only in a few medical centers in France and a few major cities in Europe and North America. The literature about this technique is thus sparse. In this study, we aimed to evaluate the interest of a new 3D modelling technique for the assessment of lower limb lengths and angles in terms of measurement reliability. Overall, we found the 3D technique to have similar or better intra- and inter-operator reliability than 2D radiography. We compared these to the results reported for various other tools for assessing lower limb variables so that we could discuss its potential advantages and pitfalls.

The main limitation of our study is the use of lower limbs from a hospital-based population of patients requiring total hip arthroplasty. This inclusion criterion meant that most of the proximal limbs viewed had major coxarthrosis. Coxarthrosis causes significant anatomical changes in the proximal extremities of the femur and may cause difficulty at the time of reconstruction when the anatomical model is used. Similarly, it may distort measurements on 2D radiography; we found 2D reproducibility slightly worse than rates reported in the literature for equivalent measurements [20,21]. It would probably have been better to use healthy bones to test the reproducibility of the EOS™ system, but it would have been difficult from an ethical point of view to expose subjects to radiation without any clinical purpose. Besides, the differences in shape of repeated lower limb reconstructions, the high intraobserver and interobserver reproducibility in the 3D reconstruction showed the stability of the reconstructions. The promising results of the current in vivo study demonstrate that it should be possible to use EOS™ stereoradiography for lower limb measurements in clinics, despite the pitfalls related to the superposition of multiple soft tissue and bony structures. In addition, the absence of significant differences between subjects showed that the method was both feasible and reproducible for most subjects. Secondly, we did not compare measurement of the 3D reconstruction with conventional full-length radiographs or the CT-scan, principally in order to avoid an additional exposure for the patients. Even if these techniques are the

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Table 2 Interobserver and intraobserver correlations (95% CI) of the clinical variables according to the 2D and the 3D techniques.

	Interobserver			Intraobserver		
	2D (95% CI)	3D (95% CI)	Z	2D (95% CI)	3D (95% CI)	Z
Femur length	0.993 (0.990–0.995)	0.997 (0.995–0.998)*	2.96	0.994 (0.991–0.996)	0.997 (0.995–0.998)*	2.42
Tibia length	0.993 (0.990–0.995)	0.995 (0.995–0.998)	1.95	0.995 (0.993–0.997)	0.995 (0.985–0.998)	0
Lower limb length	0.998 (0.997–0.999)	0.999 (0.999–1.000)*	2.42	0.998 (0.996–0.998)	0.999 (0.998–1.000)*	2.42
HKS angle	0.593 (0.347–0.743)	0.894 (0.847–0.928)*	5.29	0.876 (0.821–0.915)	0.891 (0.843–0.926)	0.48
HKA angle	0.992 (0.988–0.995)	0.993 (0.989–0.995)	0.47	0.994 (0.991–0.996)	0.994 (0.991–0.996)	0
Femoral offset	0.831 (0.756–0.884)	0.870 (0.812–0.911)	0.99	0.845 (0.777–0.893)	0.915 (0.876–0.942)*	2.22
Neck shaft angle	0.587 (0.023–0.811)	0.765 (0.673–0.835)*	2.33	0.794 (0.709–0.857)	0.851 (0.786–0.897)	1.24
Femoral head diameter	0.565 (0.029–0.793)	0.721 (0.443–0.846)	1.88	0.793 (0.706–0.855)	0.886 (0.834–0.922)*	2.27
Femoro-tibial rotation		0.652 (0.523–0.751)			0.719 (0.609–0.802)	
Tibia torsion		0.730 (0.621–0.811)			0.826 (0.751–0.880)	
Femoral neck length	0.618 (0.133–0.814)	0.870 (0.785–0.919)*	4.26	0.828 (0.754–0.881)	0.921 (0.885–0.946)*	2.88
Flessum/Recurvatum		0.991 (0.987–0.994)			0.996 (0.994–0.997)	
Femoral anteversion		0.821 (0.728–0.882)			0.912 (0.872–0.940)	

To compare the coefficient correlations, we use the Fisher transformation [19] to create the Z variable then we compare it to the normal distribution ($Z = 1.96$ for an alpha error risk of 0.05 and a bilateral hypothesis).
Significant differences are labeled by *.

Table 3 Mean interobserver differences in clinical variables with the EOS™ 2D and 3D techniques.

	2D	3D
Femur length (cm)	0.206	0.132*
Tibia length (cm)	0.218	0.159*
Lower limb length (cm)	0.224	0.127*
HKS angle (°)	0.868	0.519*
HKA angle (°)	0.519	0.497*
Femoral offset (cm)	0.312	0.269*
Neck shaft angle (°)	4.685	2.937*
Femoral head diameter (cm)	0.359	0.252*
Femoral neck length (cm)	0.466	0.265*

Significant differences are labeled by *.

clinical routine practice or the most reproducible techniques used to measure lower limb variables. However, a recent study [22] suggests that orthopedic measurements done on EOS™ 2D images are comparable with those performed on conventional 2D X-rays. We chose instead to compare it with EOS™ 2D frontal X-rays, to optimize the usefulness of our study for the everyday practice of orthopedic surgeons.

The third major limitation of this study is that all the measurements were performed by two experienced operators. For this study alone, each operator did 100 EOS™ reconstructions and the same number of measurements of EOS™ 2D frontal X-rays. Obviously, in everyday practice, these reconstructions must be performed by an experienced operator. The data processing requires specific staff training and the image takes about 5 minutes for each reconstruction for a training user. Unlike other studies, we did not assess here the impact of operator experience on the reproducibility of measurements.

In our study, radiation doses delivered by the biplane system were slightly higher than what was reported on spine examination on adolescents with the same system [23], but far from the doses classically reported for a single AP pelvis conventional X-ray or CT-scan [24] and from European diagnostic reference levels [25].

Despite rapidly advancing technology, it is important to bear in mind that the accuracy and ease of obtaining measurements with any imaging modality is not a substitute for a thorough clinical assessment. Clinical evaluation of patients with long-standing limb shortening, especially with associated muscle weakness, can use blocks under the short limb to estimate the amount of correction that feels optimal; a goniometer can also be used to measure angular deformities. It is nonetheless generally agreed now that radiographs are more accurate and reliable than a clinical exam for analyzing the lower limb variables [26,27].

Accuracy has increased with digitization of radiography: digital total-leg radiography is a reliable method that produces no significant angle differences compared to conventional radiography systems and requires significantly less evaluation time [4], its simplicity of implementation and interpretation distinguishes it from all other techniques. Although standard long-leg radiography remains the reference technique for the evaluation of the clinical variables of the lower limb, numerous studies have demonstrated its limitations in terms of accuracy and

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Table 4 Interobserver and intraobserver correlation for clinical lower limb discrepancy with a variety of imaging techniques.

	Interobserver	Intraobserver
Clinical		
Jonson and Gross [3]	0.970	0.650
Standing AP radiograph		
Sabharwal et al. [32]	0.968	0.978
Leitzes et al. [6]	0.980	0.990
Slit scanograms		
Terry et al. [27]	NA	0.990
CT scanograms		
Aitken et al. [20]	0.995	NA
Sabharwal et al. [32]	NA	0.979
MRI		
Leitzes et al. [6]	0.990	0.990
3D EOS™	0.999	0.999

NA: non applicable.

reproducibility. These studies have reported measurements of these variables, and most specifically lower limb discrepancies, with a variety of other imaging techniques, including orthoroentgenograms [28,29], CR-based teleoroentgenograms [30], Slit scanograms [31], CT scanograms [20,21,32], or MRI [6].

Many factors can modify the interpretation of measurements calculated from standard radiographs, despite the standardization of theoretical angles: source position and motion, the direction of the incident rays, the extent of their penetration, and the patient's position (position and rotation of the hip, knee and ankle). The technical characteristics of the EOS™ system control for most of these factors. Only a one-way scan is needed to record both the frontal and lateral views, unlike most other techniques. The full process time is around a 20-second scanning process. This shorter acquisition time reduces the number of movements during the process, compared, for example, with techniques such as orthoroentgenograms or scanograms, which are prone to errors due to patients moving between exposures. EOS™, unlike CT scanograms and MRI, has the advantage of displaying the entire length of the lower limb, without any magnification error: the source of irradiation moves during the procedure, with the structure to be measured always centered in the gantry [33].

Our study provided excellent inter- and intraobserver reproducibility for the 2D measurements and the 3D modelling values. Comparison of our data with the literature shows that the reproducibility of the assessment of lower limb lengths using EOS™ 3D modelling [3] is better than clinical assessment [3] and better than or at least equivalent to methods using plain X-rays [19,28,34–36], computed radiography teleoroentgenograms [30], CT scanograms [20], or MRI [6] (Table 4). All the techniques had satisfactory inter- and intraobserver correlation coefficients (high to excellent). However, there are disadvantages to most of these techniques as well, including the need for special radiographic equipment such as grids, filters, and processors along with the need for long radiographic cassettes, which may not be readily available given the recent advances in digital imaging and which can be difficult to store. The CT-scan was presented as a solution that both improves reproducibility and reduces 2D projection error phenomena. It has, however, several important limitations: the dose required to perform the examination is higher than that needed for conventional radiography, patients cannot be examined in a weight-bearing position, and the measurements, which depend too highly on the decision markers, lack reproducibility.

Reproducibility of this 3D technique had been previously evaluated on a pediatric population [14]. The reliability of the assessment of femur length, tibia length, HKA angle, and neck shaft angle was evaluated on children with the same conclusion of excellent interobserver correlation for femoral and tibial length and HKA angle. Interobserver ICC for the neck-shaft angle was found to be 0.66 on children and 0.76 in our study, suggesting that this parameter is probably less reliable than the others. The mean values of each lower limb variable extracted from the 3D reconstruction did not differ from the values reported in the literature [4,16–18,37]. In addition to the significant difference for all lower limbs parameters between the 2D and 3D measurements, we saw remarkable differences for certain variables: total length, HKA angle, femoral offset, and neck-shaft angle. Various studies have demonstrated the negative impact of some deflections [20,29] or positions [38] of the lower limb on the accuracy of radiology measurements. A recent study on dry bones confirmed that the bias between 2D and 3D measurement is due to projection errors in 2D, by validating the accuracy of EOS™ 3D parameters against CT-scan on dry bones [14]. In the presence of axial rotation of the lower limb during acquisition, the measurement of frontal knee alignments may be biased [39], just as femoral neck anteversion can distort the assessment of 2D parameters of the hip [18]. Indeed, it is for the hip variables, especially the femoral offset and neck-shaft angle, that we see the largest differences between 2D and 3D measurements. Sariali et al. [18] measured femoral offset in a series of 223 hips in both 2D frontal projection and 3D acquisition by a CT-scan and found a mean offset of 38.7 mm in 2D and 42.2 mm in 3D. Similarly, Pasquier et al. [37] found in a series of 61 patients that the 2D femoral offset was undervalued by 3.3 mm. Our study found an offset of 36.0 mm in 2D and of 43.0 mm in 3D, for a difference of 7 mm. We also found a difference of 8° between 2D and 3D for the neck-shaft angle in our population, consistent with the findings by Kay et al. [40], which highlighted the effect of femoral rotation on the neck-shaft angle measurement.

The low dose system provides spectacular dose reduction, consistent with international recommendations on radiation protection [7] and ranging from six to 18 [23,25] times lower than for a standard long-leg X-ray [8]: 5 mrads. The irradiation dose is an important factor for consideration, not only in their young patients, but also in ours, often old, with multiple comorbid conditions and both requiring a thorough assessment for arthroplasty and likely to require many more imaging procedures with ionizing radiation.

Our study could overcome most of the limitations in the available articles about different findings in the assessment of lower limb measurements as retrospective case series

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with multiple confounding variables not clearly stated by the investigators, such as image size, presence of angular deformities and contractures of the lower limbs. The precision and accuracy of our measurements is quite remarkable, and especially useful for orthopedic surgery research. We can wonder, in any case, whether daily orthopedics practice requires measurements as precise and as accurate as EOS™ provides. Certainly, the standard surgery that will result from these measurements does not.

The final problem is not yet completely resolved: the difficulty of developing reconstruction models that take the prosthetic implant into account. Schlatterer et al. [41] were the first to test positioning 3D models of total knee arthroplasties for non-prosthetic reconstruction and found some difficulties, specifically related to the definition of the landmarks. We plan to follow this initial phase of evaluation with further development of this imaging tool, to create a protocol for complete preoperative planning, using this 3D reconstruction.

Conclusion

In our study, the EOS™ 3D modelling technique showed excellent inter- and intraobserver reproducibility, better than for 2D measurements. This technique appears to be a reliable tool for lower limb measurements, providing greatly reduced irradiation and satisfactory inter- and intraobserver reproducibility, high accuracy, and a low exam cost. This imaging system is a useful tool for preoperative assessment of the lower limbs (arthroplasty, tumor) and should be the second-line technique for the evaluation of lower limbs (in cases of massive long-leg discrepancy or frontal deformation) for planning surgery, to supplement standard radiography. For now, the major flaw of the EOS™ system is its lack of availability for everyday practice. All the radiologic methods, found in the literature, were reported to have similar and very high reliability for lower limb measurements. The standing AP radiograph of the lower limbs, including extremities, should be the method of choice for the first evaluation. Our department will continue to study the lower limb measurements obtained with the EOS™ system after total hip arthroplasty to evaluate the value of its use in orthopedics practice.

Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.

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Please cite this article in press as: Guenoun B, et al. Reliability of a new method for lower-extremity measurements based on stereoradiographic three-dimensional reconstruction. Orthopaedics & Traumatology: Surgery & Research (2012), doi:10.1016/j.otsr.2012.03.014

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