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RAPTOR: The Innovation for Making Long Leg Standing Radiography for Total Knee Arthroplasty from Conventional Radiography

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Purpose: To evaluate the reliability and validity of femoral anatomical-mechanical angle (fAMA), hip knee ankle angle (HKA), and overlap of long leg standing radiography (LLSR) obtained using a Rapid Orthoroentgenography Making Machine (RAPTOR) compared with a standard X-ray generator.

Methods: This observational study was conducted between July 2021 and August 2021, including patients diagnosed with primary knee osteoarthritis that underwent preoperative LLSR for total knee replacement. Three orthopedic surgeons blindly evaluated LLSR (fAMA, HKA, overlap of the femoral shaft) twice within one-month using the Visio program. Intra- and interobserver reliability and validity were analyzed.

Results: Three evaluators assessed 30 LLSRs. The intraobserver agreement levels were -0.951–1.062° for fAMA, -10.338–11.076° for HKA, and -0.418–0.418 mm for overlap of RAPTOR, while for the standard X-ray generator the agreement levels were -1.359–1.114° for fAMA, 11.844–12.467° for HKA, and 0 mm for overlap. The intraclass correlation was 0.55–0.99 for all RAPTOR measurements and 0.56–0.99 for standard X-ray generator. The interobserver's levels of agreement were -1.441–1.175° for fAMA, -7.453–7.475° for HKA, and -0.681–0.637 mm for overlap of RAPTOR, whereas those of the standard X-ray generator were -1.149–1.424° for fAMA, -4.789–6.171° for HKA, and 0 mm for overlap. The intraclass correlation was 0.69–0.97 for all RAPTOR measurements and 0.71–0.95 for the fAMA and HKA standard X-ray generator measurements. The mean and 95% limits of agreement of the comparison between RAPTOR and standard X-ray generator were -0.131° (-1.187, 0.925) for fAMA, -0.126° (-4.724, 4.471) for HKA, and 0.363 (-) mm for overlap. Only overlap was significantly different between the two methods (p=0.0243). Intraclass correlations between the two radiographic methods were 0.75 (0.63, 0.88) for fAMA and 0.93 (0.89, 0.97) for HKA.

Conclusions: Estimation of fAMA, HKA, and overlap had moderate to excellent reliability and inter- and intra-rater reliabilities in both RAPTOR and standard X-ray generator. Only overlap was different between the two methods.

Keywords: femoral anatomical mechanical angle, hip knee ankle angle, limb length discrepancy, orthoroentgenography, overlap

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Successful total knee arthroplasty (TKA) requires restoration of the mechanical axis, joint line, soft tissue balance, equalization of flexion and extension gap, and patella femoral joint alignment [(1)]. Infection, instability, osteolysis, periprosthetic fracture, mechanical loosening [(1-3)], and mechanical failures are common causes of revision TKA. These may result from unacceptable alignment of the mechanical axis within 180 ± 3° [(4-6)] of which prosthetic loosening is 24% compared with 3% in knees with mechanical axis alignment within 180 ± 3° [(17)]. Thorough preoperative planning is crucial for reducing mechanical failures resulting from surgical technique, and it should also consider the optimal implant position and soft tissue balance [(3,7)]. Long-leg standing radiography (LLSR) is a reliable standard for the preoperative planning of TKA [(10,12,13)], being superior to short films in measuring the hip knee ankle angle (HKA), femoral anatomical-mechanical angle (fAMA), coronal laxity, deformity, and hip and ankle pathology [(8,9)].

Preoperative planning for TKA on the femoral side and distal femoral cut is performed perpendicular to the mechanical axis to restore the axis of the limb using the measured fAMA. Determining the fAMA for the distal femoral cut using an LLSR is an inexpensive method that can be used to achieve an acceptable mechanical axis of femoral side during TKA [(6)].

In our hospital, we do not have an X-ray generator to obtain LLSRs, and we cannot preoperatively plan TKAs using patients' fAMA, distal femoral cuts, and proximal tibial cuts. An X-ray machine, such as iQuia GC85A FDR Visionary Suite or SAMSUNG FUJIFILM Visionary Suite, and an X-ray generator, such as Optimus 80 PHILIPS, can be used to obtain LLSRs. These machines are 2-3 times more expensive than the X-ray generators used in most public hospitals. A novel low-radiation-dose EOS™ imaging system, which enables three-dimensional full-length weight-bearing images in one session, is a new reliable radiographic method for assessing knee osteoarthritis using the fAMA and limb lengths and is comparable to LLSR [(16)]. This model has been widely used in medical schools. In our setting, many public hospitals in rural areas have limited access to expensive and specialized X-ray equipment. Instead, they must use short films for preoperative planning.

To create an LLSR, the Suphan Model 4.0 was developed in 2016[(19)]. This new method consists in manual movement of a Suphan Model 4.0 detector holder, at the level of the hip, knee, and ankle center. The radiograph is taken while the radiological technician moves the detector to each of the radiation locations positioned at levels of the hip, knee, and ankle center. In this study, some length loss of radiography, lack of validation of the fAMA and HKA, and overlap of the femur image with standard LLSR were observed [(19)].

In the present study, a device called the Rapid Orthoroentgenography Making Machine (RAPTOR) was devised to create an orthoroentgenography/LLSR. This device can be installed at public hospitals in every province to enable common X-ray machines to create an LLSR at an affordable cost. The RAPTOR is used in conjunction with digital radiography and a stitching program.
We hypothesized that the LLSRs created by our newly-developed RAPTOR would be equivalent to the standard LLSR from the standard X-ray generator and could be used for preoperative planning of TKA. The aim of this study was to assess the reliability and accuracy of the fAMA, HKA, and overlap of the femur image of an LLSR created by RAPTOR compared to the standard X-ray generator.

METHODS

This observational study was conducted at our hospital from July 2021 to August 2021. The study included 30 patients who were diagnosed with primary knee osteoarthritis and knee pain. Weight-bearing knee radiographs showed a joint space narrowing < 3 mm, subchondral sclerosis, marginal osteophytes, subchondral cysts, deformity of the femoral condyles, and tibial plateau. Radiographic severity was determined using the Kellgren and Lawrence (KL) score [(18)] and LLSR was performed for preoperative TKA planning. The inclusion criteria were age > 55 years, varus angulation < 30°, flexion contracture < 20°, and being able to stably stand up. The exclusion criteria were hip osteoarthritis; avascular necrosis of the femoral head; previous hip, femur, knee, or ankle surgery; secondary osteoarthritis, such as posttraumatic osteoarthritis or rheumatoid arthritis, and recurvatum of the knee; or having received a repeated X-ray more than twice due to unavailable true knee anteroposterior (AP) view in which the femoral and tibial condyles should be symmetrical; the head of the fibula was superimposed at one-third or one-fourth of the lateral tibial condyle, and the patella position was at the center of the distal femur; knee joint pain during LLSR which shows a Numeric Rating Scale score higher than 4. LLSR was obtained for all 30 patients using a standard X-ray generator (Optimus 80 PHILIPS, Hamburg, Germany) and RAPTOR on the same day at two different hospitals. This study was approved by the relevant Institutional Review Board.

The evaluators of this study were two orthopedic surgeons with more than ten years of professional experience and one orthopedic surgeon who had five years of experience; they were blinded for evaluation of the radiographs. The patients' baseline characteristics included age, sex, weight, height, and body mass index (BMI). The desired outcomes included fAMA (°, degrees), HKA (°, degrees), and overlap (mm). All LLSRs were processed using the Microsoft Visio 2010 Model 64-bit Service Pack 2 for Education software (Microsoft Corporation, Redmond, WA, USA) [20.21].

LLSRs from RAPTOR were originally taken with 10–20° of internal rotation of the foot, and a 30-cm gap between the two feet; the patient's position was adjusted until the tibial tuberosity and patella faced forward to the head tilt unit (Fig. 1).

A 240-cm distance was set between the head tilt unit and detector. A 120-cm metal ruler was placed upright at the lateral malleolus, facing 90° to the head tilt unit. The hip, knee, and ankle heights were identified, and the positions of the hip, knee, and ankle center were set at equal distances from the RAPTOR detector holder. Subsequently, a radiograph was taken while the radiographer moved to each radiation position. A

(a) (b)

Fig. 1 Patient's position for LLSR capturing using (**a**) RAPTOR and **(b)** standard X-ray generator. LLSR, long leg standing radiography; RAPTOR, Rapid Orthoroentgenography Making Machine.

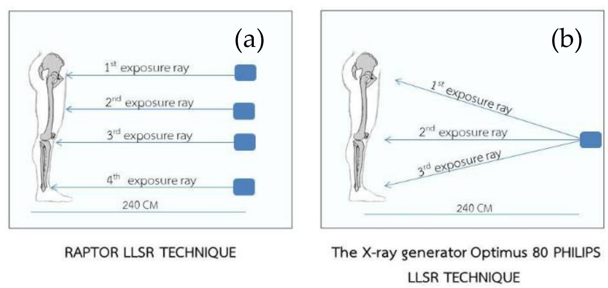
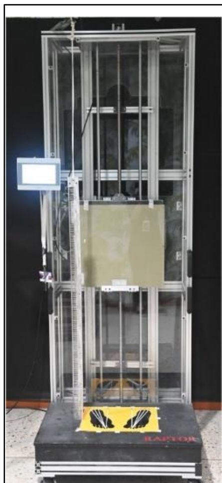


Fig. 2 LLSR imaging techniques of the **(a)** RAPTOR and **(b)** standard X-ray generator. LLSR, long leg standing radiography; RAPTOR, Rapid Orthoroentgenography Making Machine.

10-m radiofrequency remote control directed the RAPTOR detector holder to be in relation to and in continuity with the hip, knee, and ankle preset height (Fig. 2). RAPTOR is a semiautomatic machine that has manual and semiautomatic operative modes, which have two functions for determining the detector position, a teaching function that can preset the detector position by users, and an overlap detector position between 0–20 cm. The RAPTOR determines the movement of the detector by a servomotor at 0.06 m/s, and a working distance of 240 cm. Safety switches and torque protection were used for emergency stops in the case of unexpected events. The RAPTOR was controlled by a Programmable Logic Controller and incorporated into a user interface with a touchscreen display. Images in five defined positioning heights were captured manually and automatically (Fig. 3).

The radiographs were then digitally stitched, the new image was checked for whether it met the standards for a true AP knee radiography, and finally recorded in a picture archiving and communication system (PACS). For the standard X-ray generator, LLSR was performed using the same positioning technique as in RAPTOR, and the standard radiographic technique of the standard X-ray generator was used. Before a radiograph was obtained, the head tilt unit of the standard X-ray generator was set to face the knee joint position and then face toward the hip joint. The process was then repeated on the knee and ankle joints (Fig. 3). The radiograph was then stitched using an automatic stitching program and checked to determine whether it met the standards for a true AP knee radiography, and finally recorded in a PACS. The distance resolution was set as 0.0001 mm. The angle resolution was 0.001°, measured using a tool for engineering measurements [20,21].



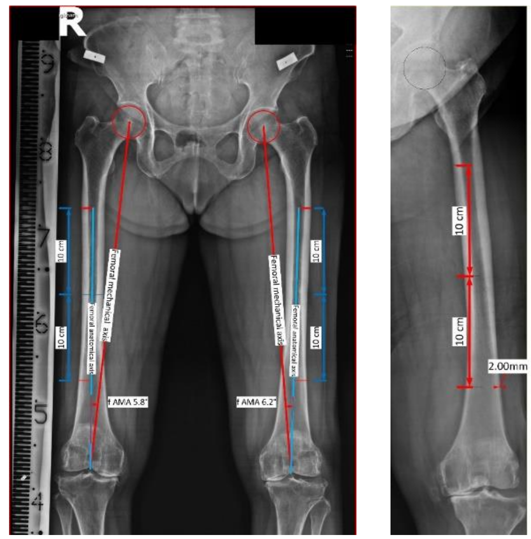
(a)

(b)

Fig. 3 (a) RAPTOR and **(b)** touch screen display. RAPTOR, Rapid Orthoroentgenography Making Machine.

Radiographic quality assessment by orthopedists

The center of the hip joint was determined using a digital Mose's circle. Then, the hip center was determined by choosing the circumference that touches the 11, 3, and 5 o'clock positions of the hip joint radiograph. The center of the knee was defined as the top of the distal femoral intercomdylar notch. The center of the ankle was specified as the center of the talus.

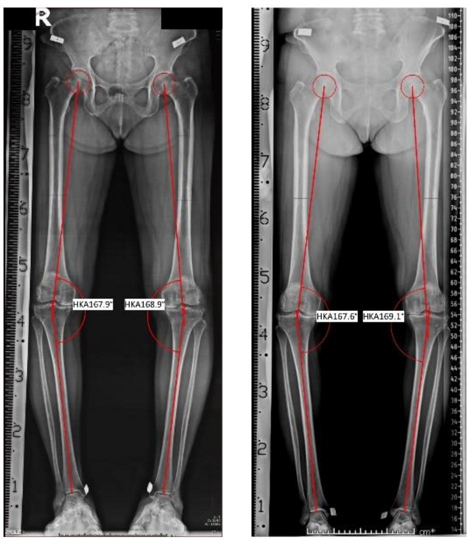


(a) (b)

Fig. 4 (a) The femoral anatomical (in blue) and mechanical (in red) axes and fAMA. **(b)** The 2-mm overlap of the femoral shaft at 10 cm below midshaft of the femur. fAMA, femoral anatomical mechanical angle.

Regarding the anatomic femoral axis, a line was drawn along the femoral diaphyseal axis by connecting the two points in the middle of the medullary canal. The first point was 10 cm above the midshaft of the femur and the second point was 10 cm below the midshaft of the femur. The femoral mechanical axis was drawn from the center of the hip to the knee center (Fig. 4a). Overlap was measured using an area 10 cm above and below the midshaft of the femur (Fig. 4b). The fAMA was evaluated using the angle from the intersection of the femoral anatomic and mechanical axes (Fig. 4a). The HKA was quantified using the angle from the intersection between the mechanical axis of the femur and the line drawn from the center of the ankle to the mid-point of the interspinous tibia (Figs. 5a and b). The methods of measurement and display of orthoroentgenography/LLSR from RAPTOR and those from the standard X-ray generator are shown in Figs. 5a and b.

All evaluators received a one-hour measurement training from the author, who was trained for measurements by an engineer with approximately 30 LLSR films. The training session consisted of a 5-minute overview, 30 minutes of workshop, and 25 minutes of discussion, questions, and answers. LLSRs were measured twice by the three evaluators with a 30-day interval between measurements. The LLSR details were blinded and randomized. During the 30-day interval, all measurements were monitored and audited by all evaluators to ensure the same standard.



(a) (b)

Fig. 5 Orthoroentgenography/LLSR created by **(a)** RAPTOR and **(b)** standard X-ray generator. LLSR, long leg standing radiography; RAPTOR, Rapid Orthoroentgenography Making Machine.

Baseline continuous variables are presented as mean and standard deviation, and categorical data are presented as frequencies and percentages. Intra and interobserver's reliabilities for measurement of fAMA, HKA, and overlap were analyzed using mean difference and 95% limits of agreement by Bland and Altman, and intraclass correlations with 95% confidence intervals (CI). The fAMA, HKA, and overlap from three observers were averaged and the 95% limits of agreement between the RAPTOR and the standard X-ray generator were obtained. All statistical analyses were performed using STATA 16.1, StataCorp, College Station, Texas, USA). The significance level was set at $p < 0.05$.

Intraclass correlation coefficient (ICC) values lower than 0.5 indicate poor reliability; values between 0.5 and 0.75, moderate reliability; values between 0.75 and 0.9, good reliability; and values greater than 0.90 indicate excellent reliability.

From a pilot study, the sample size was determined based on alpha 0.05 and beta 0.2. The acceptable difference between the RAPTOR and standard X-ray generator was set at 1° for either fAMA or HKA, or 1 mm of overlap, standard deviation 1.95°. The calculated sample group comprised 30 patients.

RESULTS

A total 30 patients (45 knees) underwent TKA. The average age of the patients was 66.7 ± 8.0 years, there were 24 (53.3%) right-side knees, and 25 of the patients (83.3%) were female. The average body weight and height were 64.2 ± 11.2 kg and 157.6 ± 7.0 cm, respectively, resulting in an average BMI of 26.4 ± 4.3 kg/m^2. Five patients were classified as KL grade 3 and 25 as KL grade 4.

The intraobserver reliabilities for the RAPTOR and the standard X-ray generator of each observer are shown in Table 1. Mean differences with 95% limits of agreement were -0.951–1.062° for fAMA; -10.338–11.076° for HKA; and -0.418–0.418 mm for overlap using the RAPTOR; and -1.359–1.114° for fAMA; 11.844–12.467° for HKA; and 0 mm for overlap using the standard X-ray generator. The ICC was 0.55–0.99 for all measurements of the RAPTOR and 0.56–0.99 for the fAMA and HKA measurements of the standard X-ray generator.

The interobserver reliability is shown in Table 2. The mean differences with 95% limits of agreement between three observers were -1.441–1.175° for fAMA, -7.453–7.475° for HKA, and -0.681–0.637 mm for overlap using the RAPTOR; and -1.149–1.424° for fAMA, -4.789–6.171° for HKA, and 0 mm for overlap using the standard X-ray generator. The ICC was 0.69–0.97 for all measurements of the RAPTOR, and 0.71–0.95 for the fAMA and HKA measurements of the standard X-ray generator.

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Table 1 Intraobserver reliability.

Variable	*Mean (SD)*, Mean difference (95% limits of agreement)								
	Observer 1			Observer 2			Observer 3		
	Time 1	Time 2	Difference	Time 1	Time 2	Difference	Time 1	Time 2	Difference
RAPTOR									
f AMA, °	*5.470 (0.860)*	*5.540 (0.903)*	-0.069 (-0.762, 0.624)	*5.570 (0.890)*	*5.600 (0.930)*	-0.027 (-0.850, 0.797)	*5.710 (0.840)*	*5.660 (0.880)*	0.056 (-0.951, 1.062)
HKA, °	*168.410 (7.240)*	*169.000 (6.920)*	-0.596 (-4.651, 3.460)	*168.930 (6.650)*	*168.600 (6.040)*	0.336 (-6.443, 7.114)	*168.400 (5.820)*	*168.030 (5.66)*	0.369 (-10.338, 11.076)
Overlap, mm	*0.360 (1.040)*	*0.360 (1.040)*	0.000 (-0.418, 0.418)	*0.380 (1.090)*	*0.360 (1.030)*	0.022 (-0.270, 0.314)	*0.360 (1.020)*	*0.380 (1.090)*	-0.022 (-0.314, 0.270)
Standard X-ray generator									
f AMA, °	*5.660 (0.780)*	*5.710 (0.830)*	-0.051 (-0.811, 0.709)	*5.790 (0.910)*	*5.810 (0.740)*	-0.020 (-1.084, 1.044)	*5.630 (0.802)*	*5.760 (0.900)*	-0.122 (-1.359, 1.114)
HKA, °	*169.160 (7.160)*	*168.850 (7.020)*	0.309 (-2.026, 2.644)	*168.440 (6.660)*	*168.750 (6.820)*	-0.309 (-6.449, 5.831)	*168.620 (6.820)*	*168.300 (6.400)*	0.312 (-11.844, 12.467)
Overlap, mm	*0.000 (0)*	*0.000 (0)*	*0.000 (0)*	*0.000 (0)*	*0.000 (0)*	*0.000 (0)*	*0.000 (0)*	*0.000 (0)*	*0.000 (0)*

SD, standard deviation; fAMA, femoral anatomical mechanical angle; HKA, hip knee ankle angle.

Table 2 Interobserver reliability.

Variable	Observer	Mean difference (95% limits of agreement)	
		2	3
RAPTOR			
fAMA, °	1	-0.104 (-1.008, 0.799)	-0.238 (-1.102, 0.626)
	2		-0.133 (-1.441, 1.175)
HKA, °	1	-0.522 (-5.358, 4.313)	0.011 (-7.453, 7.475)
	2		0.533 (-6.377, 7.444)
Overlap, mm	1	-0.022 (-0.681, 0.637)	0.000 (-0.418, 0.418)
	2		0.022 (-0.488, 0.532)
Standard X-ray generator			
fAMA, °	1	-0.129 (-1.124, 0.866)	0.024 (-1.149, 1.198)
	2		0.153 (-1.117, 1.424)
HKA, °	1	0.722 (-4.727, 6.171)	0.546 (-4.789, 5.882)
	2		-0.176 (-4.273, 3.921)
Overlap, mm	1	0.000 (0)	0.000 (0)
	2		0.000 (0)

SD, standard deviation; fAMA, femoral anatomical mechanical angle; HKA, hip knee ankle angle.

Table 3 Limits of agreement between RAPTOR and standard X-ray generator.

Variables, degree Mean (SD)	RAPTOR (N = 30)	Standard X-ray generator (N = 30)	Mean difference (95% limits of agreement)
fAMA	5.590 (0.830)	5.720 (0.740)	-0.131 (-1.187, 0.925)
HKA	168.560 (5.880)	168.690 (6.350)	-0.126 (-4.724, 4.471)
Overlap	0.360 (1.040)	0	0.363 (-)

The data presented is the average of the values measured by 3 observers at 2 different measurement moments. SD, standard deviation; fAMA, femoral anatomical mechanical angle; HKA, hip knee ankle angle.

The average values of the two assessments by the three observers are summarized in Table 3. The mean and 95% limits of agreement compared between the RAPTOR and standard X-ray generator were -0.131 (-1.187, 0.925)° for fAMA, -0.126 (-4.724, 4.471)° for HKA, and 0.363 (-) mm for overlap (Table 3). Only the overlap measurement differed significantly between the two methods ($p = 0.0243$). ICC between the two radiographic methods was 0.75 (0.63, 0.88) for fAMA and 0.93 (0.89, 0.97) for HKA. The average operating times of RAPTOR and the standard X-ray generator were 37.6 ± 5.5 and 20.2 ± 2.5 seconds, respectively. The difference between two methods was 17.4 ± 5.1 seconds, with a significant $p < 0.0001$.

DISCUSSION

LLSR is a standard and reliable method for assessing the mechanical alignment and preoperative planning in patients undergoing TKA [10,12,33]. Many general hospitals cannot obtain LLSR owing to technological and budgetary limitations. RAPTOR is an innovative method that enables the creation of LLSRs using conventional X-ray machines in hospitals. However, the accuracy and precision of LLSRs from RAPTOR and those from standard X-ray generator need to be further explored by orthopedic surgeons. This study aimed to validate the overlap of LLSR images on the coronal axis, fAMA, and HKA obtained from a digital X-ray machine.

The fAMAs obtained using the RAPTOR and standard X-ray generator had moderate to excellent intra- and inter observer reliabilities. The lowest reliability was registered in Observer 3 with an intraobserver ICC of 0.72 (-0.122; 95%CI -1.359, 1.114) for the standard X-ray generator, and an interobserver ICC of 0.690 (-0.133; 95%CI -1.441, 1.175) for RAPTOR. We found that the years of experience of the evaluators may have affected the reliability of the radiographic assessments. Observers 1 and 2 had more than 10 years of work experience compared to Observer 3, who had only five years of experience. The results of our study are compatible with those of Anto et al., who found moderate to excellent inter-observer reliability for fAMA measurement [23]. There, a single measure intraclass correlation of 0.733 and an average measure intraclass correlation of 0.943 were reported.

The HKA values obtained using the RAPTOR and standard X-ray generator had moderate to excellent intra- and interobserver reliabilities. The lowest ICC was registered in Observer 3 with an intraobserver ICC of 0.550 (0.369; 95%CI -10.338, 11.076) and an interobserver ICC of 0.83 (0.011; 95%CI -7.453, 7.475) for the RAPTOR. Our study was compatible with the study by Vaishya et al., who found that the results of HKA measurement had a better agreement between the observers as the experience of the surgeons increased, with an ICC of 0.7 (95%CI -2.2, 3.1) [24]. Nonetheless, our results for all observers' levels of agreement in HKA had a wider range, especially in Observer 3 (95%CI 10.380, 11.0760).

However, as the level of agreement was not significantly different between the observers, we found that the measurement technique may have affected reliability and validity. The individual variations in finding the center of the hip, knee, and ankle center can be attributed to inter-observer variability.

The data demonstrated less intra-interobserver reliability in HKA. The lack of clarity of the femoral head border, especially in obese patients, affects the accuracy of the hip center position when using a digital Mose's circle. Radiographic techniques must be performed to improve clarity. Furthermore, the radiological technician's skills and right stitching techniques can reduce anatomic femoral overlap.

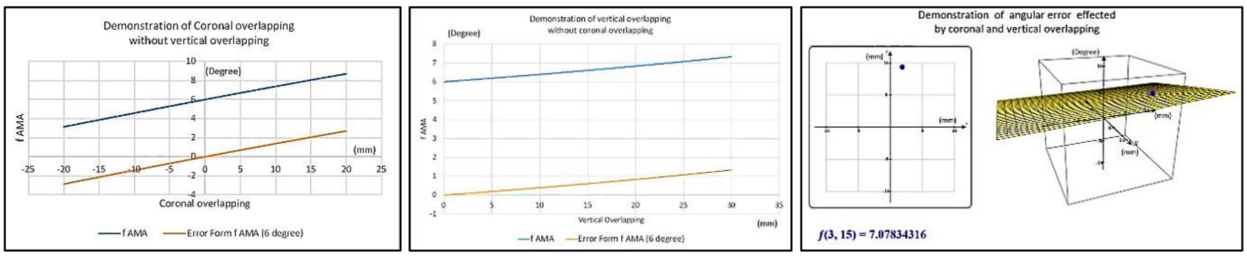
It was found that the clarity of the intertibial spine and midpoint of the ankle landmarks affected the measurement. In severe deformities of the knee, the intertibial spine is not clear enough in radiographs to allow determination of the exact point. In some cases, the ankle had osteoarthritis, which affected landmark determination. All these unclear landmarks affected the precision when determining HKAs between the two lines, and the apex of the angle affected the measurement's accuracy, especially in Observer 3.

After one week of observer evaluation of LLSRs, we found that observer 3 had errors in the determination of the landmarks of the three points of the hip center and angle measurement. After re-training the measurement methods, Observer 3 tended to measure the hip center more centrally.

Overlaps can be caused by simultaneous coronal, vertical, both coronal and vertical overlapping. From our mathematical calculations, it was found that coronal overlapping alone had an effect on fAMA of 1° when coronal overlapping was 7 mm to the lateral side of the femur and 8 mm when it was on the medial side (Fig. 6a). This coronal overlap may have been caused by patient movement [13] and prolonged radiographic time. We found that RAPTOR required longer periods to obtain LLSRs than the standard X-ray generator, with a mean difference of 17.4 ± 5.1 seconds. This prolonged time might also cause coronal overlapping.

We found that vertical overlapping could occur with LLSR length loss or incorrect stitching technique. Vertical overlapping can be identified by the simultaneous overlapping of both sides of the femoral cortex with a loss of length of 120 -cm ruler in the same area. From our mathematical calculations, it was found that vertical overlapping alone had a 1° effect on fAMA when vertical overlapping was 23 mm (Fig. 6b). In our practice, vertical overlapping can be minimized by using a 120-cm ruler as a landmark for the stitching technique, while keeping the standing distance between the patient and the head tilt unit at 240 cm for diminished length loss.

From the pilot study, we found that the coronal overlap of all LLSRs from RAPTOR was < 3 mm; therefore, we used mathematical calculations of both coronal and vertical overlapping by fixed coronal overlapping at 3 mm and variable vertical overlapping. We found that a 1° change in fAMA resulted from coronal overlapping medially for 3 mm with vertical overlapping at 15 mm (Fig. 6c).



(a) (b) (c)

Fig. 6 (a) Demonstration of angular error affected by coronal overlapping without vertical overlapping. **(b)** Demonstration of angular error affected by vertical overlapping without coronal overlapping. **(c)** Demonstration of angular error affected by a fixed 3 mm coronal overlapping with variable vertical overlapping

The ICC between RAPTOR and standard X-ray generator was 0.75 (-0.131; 95%CI -1.187, 0.925) for fAMA and 0.93 (-0.126; 95%CI-4.724, 4.471) for HKA. They exhibit moderate to excellent reliability. This information confirms the excellent reliability and validity within 1° of fAMA in practical measurements. The average limits of agreement for HKA between RAPTOR and standard X-ray generator had a wide range of 5° (-0.126; 95%CI -4.724, 4.471). This wide HKA range may have been affected by coronal laxity and flexion contracture, combined with some rotation of the foot position between the two radiographs. Therefore, we recommend enforcing the same standard patient standing position every time LLSR is performed.

In this study, the interobserver reliability depended on the number of years of practice and training. The levels of agreement between Observers 1 and 2, who had more surgical experience, were closer to each other than to Observer 3.

The strength of our study was the adequate sample size. In the pilot study, the number of enrolled patients was eight; here, we included 30 patients; blinded observers' evaluation; assessment of both intra- and interobserver reliabilities, and ICCs of fAMA, HKA, and overlap; and validation with orthopedic surgeons. The Visio program allowed experienced users to determine the point of the hip center in the same way as when using Mose's circle. This is different from the PACS, which determines the point using an oval and adjusts it to the circumference of the hip joint. Although radiography, different timings, places, and radiological techniques affected the positioning of the patients, using the same specified protocol produced similar LLSRs in both RAPTOR and the standard X-ray generator. This demonstrates the reproducibility and accuracy of the two machines.

The limitations of this study are as follows: 1) the accuracy of radiographic measurement.

Variations in the rotation of the lower extremity and orientation of the X-ray beam may alter true projections. External rotation increases the varus angle of the knee, whereas internal rotation decreases it [14]. Malrotation between 20° external rotation and 20° internal rotation has demonstrated a 2.5° modification of angulation [15]. This would have impacted our results more significantly if the patient had flexion contracture [16]. The most common error is placement of the foot with less internal rotation. In severe cases of knee osteoarthritis, knee alignment involves extreme external rotation. To obtain a true knee AP radiograph, the feet should be placed with more internal rotation, and sometimes higher than 20°. 2) The clarity of radiograph affected landmark determination of the femoral head, interspinous tibia, and ankle, causing inaccuracy in fAMA and HKA measurements. 3) Severe varus angulation radiograph might have affected the observers' measurement bias due to the recognition of radiography at the first measurement. 4) Measurement techniques were performed using the Visio program, which is unfamiliar to orthopedic surgeons. This might have affected the determination of landmarks and resulted in a lack of expertise and understanding of the tool use, thereby causing measurement errors. After one week of the repeated training, it was found that measurement techniques and the determination of points were more precise. 5) LLSR is a new technique in our hospital, but the training of radiological technicians and the stitching technique using a 120-cm ruler were indicators of radiograph precision. After more than 10 radiological technicians training sessions, no overlap was found. 6) As the radiographs were obtained on the same day, patients may have experienced fatigue when taking a second radiograph.

CONCLUSIONS

Many public hospitals in rural areas have limited access to LLSRs for preoperative TKA planning and evaluation of fAMA and HKA. We invented the RAPTOR device to allow the use of LLSRs in public hospitals. The RAPTOR's orthoroentgenographic technique combined X-ray generator with radiographic image stitching using the Visio program can create LLSRs.

In this study, LLSRs from the RAPTOR and standard X-ray generator had moderate to excellent intra-interobserver reliability and were comparable in terms of fAMA and HKA. Only the overlap was different between the two methods.

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