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Biomechanical Evaluation of the Accuracy in Radiographic Assessment of Femoral Component Migration Measurement after Total Hip Arthroplasty

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ABSTRACT

Introduction. Implant subsidence is one criteria utilized to monitor for prosthesis loosening after total hip arthroplasty (THA) with initial implant subsidence assessment often done utilizing plain radiographs. The specific aim of this study was to identify the most reliable references when using plain radiographs to establish an image magnification with the goals being easy to use, inexpensive, reliable, and accurate.

Methods. Two femoral stem implants (stem lengths: 127 mm, 207 mm) were utilized to simulate hemiarthroplasty of the hip with composite femurs. Different combinations of femoral stem distances from the radiographic film (ODD), source-detector differences (SDD), hip rotation, and hip flexion were elected. Standardized anterior-posterior pelvis for each parameter combination setup were taken. Radiographic measurements (head diameter, stem length, stem seating length) were undertaken five times by three examiners. Radiographic image magnification factors were generated from two references (head diameter and stem length). Radiograph measurement reproducibility and stem seating length errors using these magnification factors were evaluated.

Results. High level of repeated measurements reliability was found for head diameter (99 ± 0%) and stem length (90 ± 7%) measurements, whereas seating length measurements were less reliable (76 ± 6%). Stem length error using the femoral head magnification factor yielded 11% accuracy. Stem seating length error using both magnification factors were not reliable (< 7% accuracy). All parameters, except SDD, showed significant effect on calibrated measurement error.

Conclusion. Current methods of assessing the implant subsidence after THA are inaccurate and unreliable. Clinicians should recognize these limitations and be cautious when diagnosing implant stability using plain radiographs alone. ***Kans J Med 2020;13:65-70***

INTRODUCTION

The stability of the prosthetic components after total hip arthroplasty (THA) is critical for long-term implant performance. Early migration of prosthetic stems and cups greater than 3 mm resulted in later aseptic failure of the prosthesis.[1-15] The prognostic value of early recognition of prosthetic component migration for long-term implant performance also has been demonstrated.[7,11,16] With small distances of implant migration being critical, the accuracy of measurement methods to evaluate component migration after THA is essential.

Femoral stem subsidence is one criteria utilized to monitor for prosthesis loosening after THA with initial implant subsidence assessment often utilizing plain radiographs. Several studies investigated the validity and reliability for measuring displacement on plain radiographs for different parts of the body.[17-20] Their results indicated that caution should be taken when interpreting clinical results using plain radiographs to measure displacement. However, these studies did not suggest improving accuracy and reliability when using radiographs to calculate the radiographic image magnification factor and implant migration. Walker et al.[12] pointed out that using landmarks close together on the femur and the stem of the implant were optimal for determining femoral stem migration. To our knowledge, there have been few studies to evaluate the effect of selecting different references for the radiographic image magnification factor that could lead to better accuracy or precision when determining femoral stem migration. The specific aim of this study was to identify the most reliable references when using plain radiographs to establish an image magnification with the goals being easy to use, inexpensive, reliable, and accurate.

METHODS

Two femoral stem implants were utilized, one with a stem length of 127 mm (SL-1) and the other with a stem length of 207 mm (SL-2; Figure 1). The stem length of these implants were measured from the tip of the proximal end to the distal tip of the stem. Both implants had a femoral head size of 32 mm. Two composite large femurs (Model 3406, Sawbones USA, Vashon Island, WA) were used to simulate hemiarthroplasty of the hip utilizing the two selected femoral stems (Figure 1). The femur was placed into a custom-designed holding jig to replicate patient positioning in a supine position while obtaining a radiographic image.

Testing all combinations of different femoral stem distances from radiographic film (ODD), source-detector differences (SDD), hip rotation, and hip flexion systematically created a large number of possible combinations prohibitively large (Figure 2). This study elected to test combinations of parameters that were clinically relevant and included ODD: 82 mm, 177 mm, 277 mm; SDD: 102 cm, 122 cm; hip rotation angle: -15° (internally rotated), 0°, 15° (externally rotated); and hip flexion angle: 0°, 5°, 10°. The ODD of 82 mm was selected presumptuous the radiographic film cassette was on the radiographic table top and right under a patient's buttocks. When the radiographic film cassette was put under the radiographic table the ODD increased to 177 mm, as the distance between the radiographic table top to the radiographic film cassette; drawing for the cassette under the radiographic table was 95 mm. The ODD of 277 mm was assumed; the femoral stem was 100 mm above the radiographic table top.

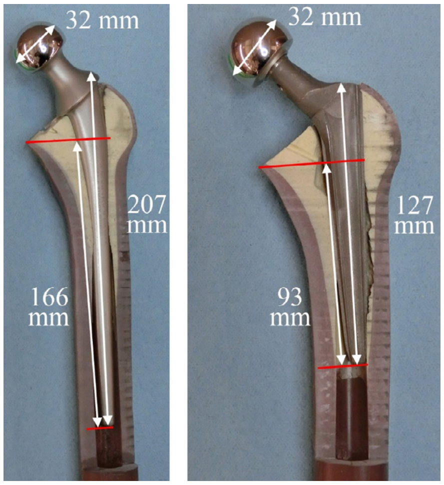

Figure 1. Cutout view of the simulated hemiarthroplasty of the hip using sawbone models with measured femoral stem seating length.

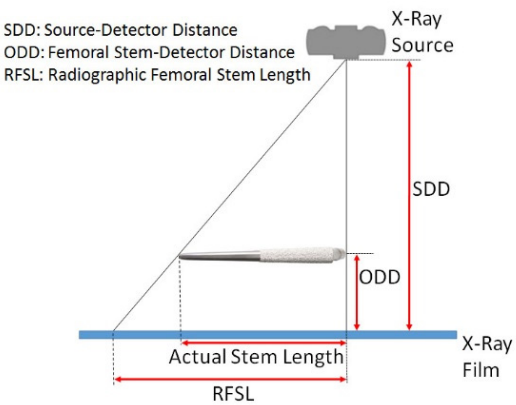

Figure 2. Radiographic image testing setup.

Radiographic images were simulated as standardized anterior-posterior (AP) pelvis radiographs in a supine position for each parameter combination setup (Figures 3a and 3b). Three examiners evaluated the radiographic measurements for each image, which were provided in a randomized order. These radiographic measurements included measurement of femoral head diameter (FHD), femoral stem length (FSL), and femoral stem seating length (FSSL). The femoral stem seating length was measured between the most medial and inferior point of the resected portion of the femur and the distal tip of the stem (Figure 3c). Standardized magnification (zoom in) was utilized to “landmark” the most superior and most inferior aspects of the femoral stem, similar for the femoral seating length and the femoral head diameter. After all the measurements were recorded, the measurements on the radiographs were cleared and the images zoomed out to normal view. This process was repeated five times by each examiner with at least one day between repeated measurements. All radiographs were evaluated using the Sectra IDS7 PAC system (Sectra AB, Linköping, SWEDEN) with a measurement resolution of 0.1 mm.

Two references for the radiographic image magnification were selected: femoral head diameter (FHD) and femoral stem length (FSL). The magnification factor (Mag_FHD, Mag_FSL) was generated by comparing either the FHD to the known implant diameter or the FSL to the known implant stem length, respectively.

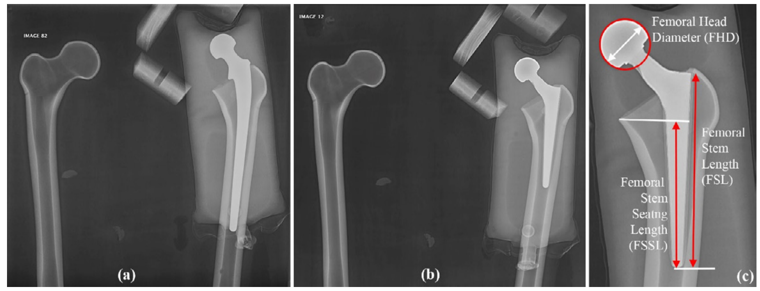

Figure 3. Radiographic images: (a) Simulated standardized AP pelvis radiograph with 207 mm stem length implant, (b) Simulated standardized AP pelvis radiograph with 127 mm stem length implant, (c) Radiographic measurements.

$$Mag\_FHD = (FHD/\text{actual head diameter})$$

$$Mag\_FSL = (FSL/\text{actual stem length})$$

With femoral head diameter as the magnification factor, the “calibrated femoral stem lengths” then were calculated using the generated Mag_FHD.

$$\text{calibrated femoral stem length} = (FSL/Mag\_FHD)$$

Stem length error was defined as the difference between the calibrated femoral stem length and the actual known stem length.

$$\text{stem length error} = \text{calibrated femoral stem length} - \text{actual stem length}$$

The femoral stem seating length measured on the radiographs was modified using both generated magnification factors (Mag_FHD, Mag_FSL) to arrive at a calibrated seating length for both.

$$\text{calibrated stem seating length\_FHD} = (FSSL/Mag\_FHD)$$

$$\text{calibrated stem seating length\_FSL} = (FSSL/Mag\_FSL)$$

The stem seating length error was defined as the difference between the calibrated FSSLs and the actual stem seating length. The actual stem seating length for the two selected implant stem lengths of 127 mm and 207 mm were physically measured and were 93 mm and 166 mm, respectively (Figure 1).

$$\text{stem seating length error}_{FHD} = \text{calibrated } FSSL_{FHD} - \text{actual stem seating length}$$

$$\text{stem seating length error}_{FSL} = \text{calibrated } FSSL_{FSL} - \text{actual stem seating length}$$

Statistical Analysis. Data retrieved from the radiographic measurements were analyzed using a histogram to evaluate the frequency distribution of the absolute differences between the five repeated measured values for each radiograph, and for each examiner, to represent the majority of the measurement error. This study also calculated the percent of absolute differences that were less than 0.5 mm between radiographic measurements to provide an estimate of intra-reliability. An absolute difference of less than 0.5 mm was defined as an “excellent” reliability. Descriptive statistics of the mean, standard deviation, 95% confidence interval, and range were determined for all radiographic measurement variables. Frequency distribution analyses were utilized to represent the distribution of the stem length errors and seating length errors using the two reference magnification factors

(Mag_FHD, Mag_FSL). One-way analysis of variance (ANOVA) with the Least Significant Difference (LSD) multiple comparisons post hoc test method in SPSS software (Version 19.0; SPSS Inc, Chicago, IL) was utilized to determine significant effect among different parameters (ODD, SDD, hip rotation angle, and hip flexion angle) on stem length error and seating length error, with $p < 0.05$ denoted as significant.

RESULTS

A total of 92 radiographic images of simulated THAs were included and reviewed. On the same radiographs, all examiners displayed a high level of repeated measurements reliability for FHD and FSL measurements with 99 ± 0.2% and 90 ± 7.1% within 0.5 mm error difference in measurements, respectively. The mean absolute differences for these two measurements were 0.16 ± 0.13 mm (range: 0.0 - 1.0 mm, 95% CI: 0.01 mm) and 0.24 ± 0.23 mm (range: 0.0 - 2.2 mm, 95% CI: 0.02 mm), respectively (Table 1). The reliability for FSSL measurements was less consistent than the other two measurements above (reliability: 76.3 ± 5.5 % within 0.5 mm error; mean absolute difference: 0.39 ± 0.35 mm; range: 0.0 - 4.6 mm; 95% CI: 0.02 mm; Table 1). A frequency of measurement errors is shown in Figure 4.

When investigating the stem length error using the generated magnification factor from the femoral head diameter, there were only 11% accurately measured with an error of 0 mm between the calibrated stem length and the actual stem length (Figure 5). There was 45% accuracy to within 1 mm between the calibrated stem length to the actual stem length. The accuracy of radiographic calibrated stem length was higher with the shorter stem length (127 mm) when compared to the longer stem length (207 mm; Figure 5).

When comparing the calibrated stem seating length measurement with the two reference magnification factors (Mag_FHD, Mag_FSL) it was found that the overall accuracy measurement with both reference magnification factors were not reliable with only 6% and 3% within 0 mm error, respectively (Figure 6). There was less than 50% (Mag_FHD: 47%, and Mag_FSL: 39%) accuracy to within 2 mm error when compared to the actual stem seating length. It was also noticed that the accuracy of calibrated stem seating length was higher with the longer stem length (207 mm) when compared to the shorter stem length (127 mm; Figure 6).

The results of this study observed significant differences in calibrated measurement error with combinations of different femoral stem distances from radiographic film (ODD), hip rotation angle, and hip flexion angle. However, there was no significant difference detected in calibrated measurement error with the effect of the SDD (Table 2, $p > 0.05$).

Table 1. Summary results of mean absolute difference between three examiners.

		Examiner #1	Examiner #2	Examiner #3	Overall
Femoral Head Diameter (FHD)	SL-1	0.2 ± 0.1 (0.0 – 0.9)	0.2 ± 0.1 (0.0 – 1.0)	0.2 ± 0.1 (0.0 – 0.7)	0.2 ± 0.1 (0.0 – 1.0)
	SL-2	0.2 ± 0.2 (0.0 – 0.6)	0.2 ± 0.1 (0.0 – 0.6)	0.2 ± 0.1 (0.0 – 0.5)	0.2 ± 0.1 (0.0 – 0.6)
	Overall	0.2 ± 0.1 (0.0 – 0.9)	0.2 ± 0.1 (0.0 – 1.0)	0.2 ± 0.1 (0.0 – 0.7)	**0.2 ± 0.1 (0.0 – 1.0)**
Femoral Stem Length (FSL)	SL-1	0.1 ± 0.1 (0.0 – 0.9)	0.2 ± 0.2 (0.0 – 1.0)	0.3 ± 0.3 (0.0 – 1.7)	0.2 ± 0.2 (0.0 – 1.7)
	SL-2	0.2 ± 0.2 (0.0 – 1.2)	0.3 ± 0.3 (0.0 – 1.0)	0.3 ± 0.4 (0.0 – 2.2)	0.3 ± 0.3 (0.0 – 2.2)
	Overall	0.2 ± 0.2 (0.0 – 1.2)	0.2 ± 0.2 (0.0 – 1.0)	0.3 ± 0.3 (0.0 – 2.2)	**0.2 ± 0.2 (0.0 – 2.2)**
Femoral Stem Seating Length (FSSL)	SL-1	0.4 ± 0.4 (0.0 – 3.2)	0.6 ± 0.4 (0.0 – 1.9)	0.5 ± 0.5 (0.0 – 4.6)	0.5 ± 0.4 (0.0 – 4.6)
	SL-2	0.3 ± 0.2 (0.0 – 1.2)	0.3 ± 0.2 (0.0 – 1.4)	0.3 ± 0.3 (0.0 – 1.5)	0.3 ± 0.2 (0.0 – 1.5)
	Overall	0.3 ± 0.3 (0.0 – 3.2)	0.4 ± 0.4 (0.0 – 1.9)	0.4 ± 0.4 (0.0 – 4.6)	**0.4 ± 0.4 (0.0 – 4.6)**

*Values represent in mean ± SD (mm) (range).

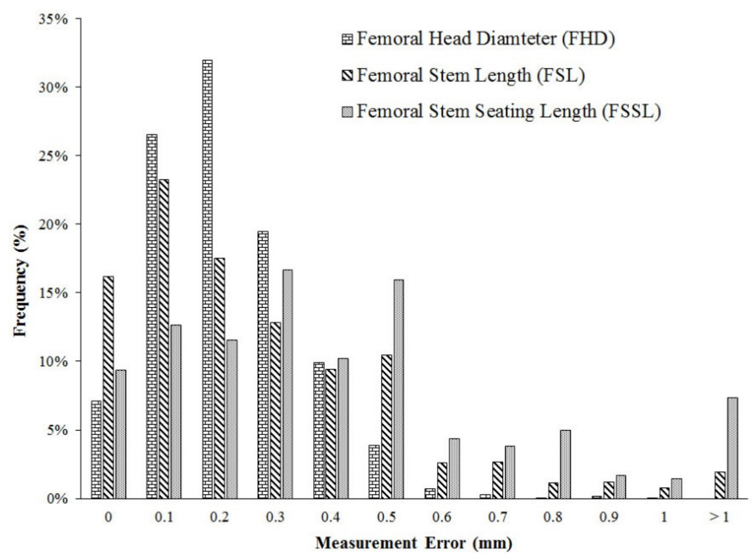

Figure 4. Histogram analysis of radiographic measurement error between each repeated measurements for all three examiners of femoral head diameter, femoral stem length, and femoral stem seating length.

DISCUSSION

Several radiological measurement techniques using conventional plain radiographs have been developed and utilized for the detection of implant migration. Some studies utilized different reference lines or points on the implants and the bone, and/or used markers on the bone for these measurements.[21-24] Some recognized that the accuracy and precision of each measuring method varies. Malchau et al.[20] have shown that measurements of stem migration on conventional radiographs varied from 4 mm to 12 mm when compared to the results with radiostereometry (RSA), depending on the choice of landmarks. Several other studies[17-20] also evaluated the validity and reliability for measuring displacement on plain radiographs of different parts of the body, and their results indicated that caution should be taken when interpreting clinical results using plain radiographs to measure displacement.

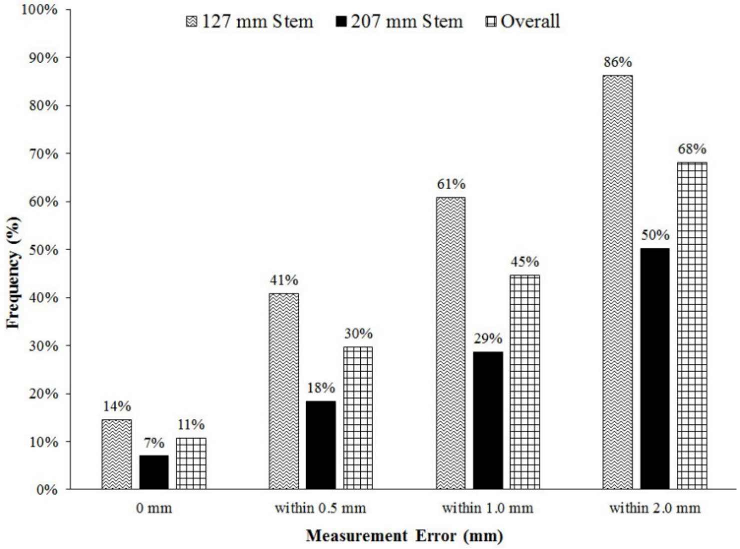

Figure 5. Frequency distribution analysis of calibrated femoral stem length errors using magnification factor based on the femoral head diameter (mag_fhd).

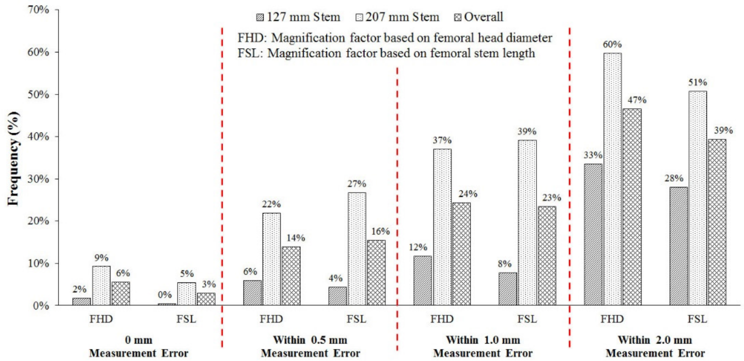

Figure 6. Frequency distribution analysis of calibrated stem seating length errors using different reference magnification factors, mag_fhd and mag_fsl.

This study utilized two references for the radiographic image magnification with the hypothesis that using femoral stem length to generate the radiographic image magnification factor shall provide a more reliable and accurate reference for determining femoral stem migration after THA. The results agreed with previous studies that measuring displacement on plain radiographs is not reliable regardless of selecting different references for the radiographic image magnification. This may be because plain radiographs provide a two-dimensional projected representation of a three-dimensional object.

The selected reference for the correction of magnification and the choice of the reference lines on conventional radiographs have significant effect on the accuracy and precision of the implant migration measurement. Even with standardized radiographic positioning and procedures guidelines, the radiographic images of the same patient at different points in time produce difficulties with accuracy and reliably to measure implant migration. The present study showed that minor changes in hip rotation, hip flexion, and ODD of the patient resulted in significant changes in calibrated radiographic measurement error. A change in hip rotation of 15°, hip flexion of 5°, and ODD of 100 mm resulted in a maximum absolute change of 1.9 mm, 2.2 mm, and 0.6 mm in calibrated stem seating length error of chosen reference for the radiographic image magnification, respectively (Table 2).

Table 2. Significance of parameter variability on radiographic measurement error.

Parameter			Average ± SD	Min-Max
Rotation	Stem Length Error	-15°	-0.8 ± 2.1	(-7.7 – 3.6)
		0°	-1.8 ± 1.9	(-9.0 – 2.3)
		15°	-2.5 ± 1.9	(-9.2 – 8.9)
	Stem Seating Length Error_FHD	-15°	-0.7 ± 2.5	(-5.4 – 6.3)
		0°	-1.8 ± 2.6	(-7.1 – 6.9)
		15°	-3.0 ± 2.8	(-9.6 – 5.1)
	Stem Seating Length Error_FSL	-15°	-1.4 ± 1.2	(-4.2 – 1.0)
		0°	-3.2 ± 1.5	(-6.6 – 0.0)
		15°	-5.0 ± 2.0	(-9.9 – 1.7)
Flexion	Stem Length Error	0°	-2.1 ± 2.0	(-9.2 – 1.3)
		5°	-0.6 ± 1.9	(-6.2 – 8.9)
		10°	-1.4 ± 2.0	(-8.4 – 3.2)
	Stem Seating Length Error_FHD	0°	-0.6 ± 2.6	(-6.2 – 6.9)
		5°	-2.8 ± 2.1	(-7.4 – 4.0)
		10°	-3.4 ± 2.2	(-9.6 – 2.3)
	Stem Seating Length Error_FSL	0°	-2.3 ± 1.6	(-6.1 – 0.8)
		5°	-3.4 ± 1.8	(-7.3 – 1.7)
		10°	-4.6 ± 2.4	(-9.9 – 0.6)
ODD	Stem Length Error	177 mm	-1.5 ± 2.0	(-9.0 – 8.9)
		277 mm	-1.3 ± 2.1	(-9.2 – 3.6)
	Stem Seating Length Error_FHD	177 mm	-2.0 ± 2.5	(-7.3 – 6.9)
		277 mm	-2.6 ± 2.7	(-9.6 – 6.2)
	Stem Seating Length Error_FSL	177 mm	-3.3 ± 2.1	(-8.6 – 1.7)
		277 mm	-3.6 ± 2.3	(-9.9 – 0.8)
SDD	Stem Length Error	102 cm	-1.6 ± 2.3	(-9.2 – 8.8)
		122 cm	-1.6 ± 1.6	(-8.4 – 2.6)
	Stem Seating Length Error_FHD	102 cm	-1.8 ± 3.0	(-9.6 – 6.9)
		122 cm	-1.8 ± 2.7	(-8.6 – 4.7)
	Stem Seating Length Error_FSL	102 cm	-3.2 ± 2.2	(-9.9 – 1.7)
		122 cm	-3.1 ± 2.1	(-9.3 – 0.7)
Stem Length	Stem Length Error	SL-1	-0.8 ± 1.5	(-8.4 – 8.9)
		SL-2	-2.4 ± 2.1	(-9.2 – 3.6)
	Stem Seating Length Error_FHD	SL-1	-3.4 ± 2.0	(-8.6 – 1.2)
		SL-2	-0.2 ± 2.7	(-8.2 – 6.9)
	Stem Seating Length Error_FSL	SL-1	-4.0 ± 1.8	(-9.9 – 1.7)
		SL-2	-2.2 ± 2.1	(-8.0 – 1.0)

Most studies dealing with radiographic measurements consider even small differences in length as significant.[1-15] This raises the question if radiographic parameters, as suggested in literature, truly provide reliable information on outcomes after THA in clinical routine. If displacement measurements from plain radiographs are inaccurate and reliable, then it is impossible to understand the effect of implant subsidence on outcome, and clinicians cannot communicate effectively about the stability of prosthetic components after THA based on radiographic evaluation. The stability of the prosthetic components after THA, therefore, shall not be diagnosed exclusively with a sequence of radiographic images, it shall be diagnosed with a combination with clinical situation and symptoms.

Roentgen stereophotogrammetric analysis (RSA) generally is accepted as the gold standard of implant migration measurement tools, especially regarding accuracy and three-dimensional (3-D) migration measurement. RSA use has been reported with an accuracy within 0.2 mm for implant subsidence.[12, 25-30] RSA has added a great deal to the assessment of implant subsidence in THA, and these 3-D reconstructions aid significantly in evaluating post-operative implant migration and the rate of migration. However, this is not being used for routine post-operative follow-up due to concerns of cost, feasibility only for prospective study designs as small radio-opaque markers are introduced into the bone and the prosthesis to serve as well-defined artificial landmarks, and impracticality for long-term studies with large patient populations.[25-31]

This study has certain limitations. First, this biomechanical investigation was performed using radiographs of Sawbones models without soft tissues which potentially could differ from the radiographic quality of images than are obtained in the clinical setting. Second, this study contained only two selected implants (SL-1 and SL-2) that could limit the generalization to different types, sizes, or shapes of implants. Third, femoral stem seating length was measured from the most medial and inferior point of the resected portion of the femur, which is not a typical clinical assessment. The authors understood that the most common landmark on the femur used to measure the stem seating length is with the lesser trochanter, as the resected portion of the femur will change over time. It was performed this way for the present study due to the fact the lesser trochanter was sometimes difficult to visualize in radiographic images depending on the orientation of the femur, whereas the resected potion of the femur could be observed easily in all the evaluated radiographic images. The main goal was to determine the accuracy of displacement measurement between calibrated radiographic measurement to the actual implant measurement. Despite these limitations, the outcomes of this study were valuable because this study shed light on the limitations of utilizing serial digitized plain radiographs to perform radiological displacement measurements. Further evaluation is required to support our findings.

CONCLUSIONS

Current methods of assessing the implant subsidence after THA are inaccurate and unreliable. Literature citing acceptable implant migration displacement based on plain-film radiographic parameters should be interpreted with caution. Our results indicated that measurement errors are most likely to be expected. Clinicians should recognize these limitations and be cautious when diagnosing implant stability using plain radiographs alone.

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