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ORIGINAL PAPER

Dual-position calibration markers for total hip arthroplasty: theoretical comparison to fixed calibration and single marker method

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Abstract

Purpose Digital templating is considered a standard for total hip arthroplasty. Different means for the necessary calibration of radiographs are known. While single marker calibration with radiopaque spheres is the most common, it is associated with possible significant deviations from the true magnification of the hip. Notably, fixed magnification factors showed better results. Therefore, a dual-position calibration marker method was simulated and compared to the established methods.

Methods First, an empirical fixed magnification factor was identified and applied to a series of radiographs. Second, three magnification factors were generated based on sagittal patient data of 398 CT scans. These methods were compared to the fixed factor.

Results The fixed factor was 122.6%. In the clinical application, the error of the fixed factor was 2.5% while the error of the single marker was 5.2%. In the CT cohort, the mean reference factor was 120.5% in females and 120.3% in males. The reference factor was compared to sex-specific means, sex-specific linear functions, and sex-specific cubic functions. The best results were found for the linear regression model with a mean difference of 0.8% from the reference value. No proportional bias was found ($p = 0.623$).

Conclusion The simulation of the dual-position marker method using the linear regression model showed promising results, superior to all other methods. In future studies, its clinical application should be tested.

Keywords Planning techniques · Arthroplasty · Calibration · Total hip replacement · Diagnostic imaging

Abbreviations

Abs	Absolute
APP	Anterior pelvic plane
CT	Computed tomography
ECM	External calibration marker
MF	Magnification factor
Min	Minimum
Max	Maximum
THA	Total hip arthroplasty
SD	Standard deviation

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Introduction

Digital templating is considered a standard in elective total hip arthroplasty (THA). [1] To achieve high precision in implant selection and positioning, correct calibration of the digital radiograph prior to templating is a prerequisite. [2–4] Calibration can be achieved by different means. [2, 5–7] Most common is the use of a single radiopaque sphere (i.e., metal) as an external calibration marker (ECM). This method has been challenged in recent reports as imprecise due to incorrect ECM placement resulting in inaccurate calibration and subsequent templating. [2, 4, 8, 9]

The use of the traditional fixed magnification factors (MF) as known from acetate templating based on empiric data has been proposed recently. A higher precision was found in comparison to single marker calibration for digital radiographs. [9]

Dual calibration markers were introduced as an alternative to single markers. [6, 7] Hereby, two markers are placed in front of and behind the patient. The theoretical advantage of this method is the identification of the sagittal patient diameter and the subsequent calculation of the supposed hip level above the detector. Thus, the precision might be less vulnerable to placement errors and provide more reliable MF. However, this method requires empiric data to calculate the right level in dependence of the sagittal diameter.

This study aimed to provide reliable empirical data for the dual marker approach. Therefore, a stepwise approach was followed. The study was divided into two major parts with two subsections, respectively.

In the first part, the problem of ECM error was reevaluated and the supposed superiority of a fixed MF was tested. Therefore, an empirical fixed MF was generated based on clinical radiographs of one post-operative cohort with unilateral THA. Subsequently, this fixed method was compared to the ECM method in a second collective with conventional radiographs after unilateral THA.

In the second part, the dual marker method was tested. Therefore, sagittal parameters were measured in a large CT cohort and a regression model for a dual marker method was calculated. To compare the fixed factor method with a dual marker method in a theoretical experiment, the fixed and the dual marker method were compared and different sex-specific approaches for the dual marker method were analyzed.

Material and methods

Part 1

Section I—generation of the fixed magnification factor

A cohort of 100 consecutive pelvic radiographs with a unilateral THA of known implant size was included from a previous study. [3] The diameter of the femoral head component was measured and repeated and blinded measurements by two independent observers of all 100 radiographs were performed. Intraclass correlation coefficients (ICC) for intra- and inter-observer reliabilities were 0.996 ($p < 0.001$) and 0.996 ($p < 0.001$). [3] The MF ($MF_{Reference}$) was calculated for each pelvis separately. The arithmetic mean of all 100 measurements was used as the fixed MF (MF_{Fix}). The accuracy of this MF_{Fix} was compared to the individual $MF_{Reference}$. The difference between the MF_{Fix} and the individual $MF_{Reference}$ was the calibration error. Differences and absolute differences were calculated.

Section II—reliability of the fixed magnification factor

For the reliability analysis, the MF_{Fix} of the primary cohort was applied to a second consecutive cohort of 111 consecutive pelvic radiographs with unilateral THA. Again, the femoral head component was used as the reference for the accuracy-analysis and compared to the ECM. Repeated measurements by two independent and blinded observers were performed in a random sample of 11 cases (10%).

Part 2

Section III—sagittal parameters of 400 CT scans

A previously described cohort of 400 patients with computed tomography scans was analyzed. [10, 11] Four groups of 100 patients each were included: male > 18 and < 65 years, male ≥ 65 years, female > 18 and < 65 years, and female ≥ 65 years. The sagittal CT-profile was measured according to King et al. [7] Whole-body CT scans were used and a multiplanar reconstruction was performed using PACS client IMPAX EE (AGFA HealthCare GmbH, Bonn, Germany). The method was performed following Boese et al. [10] Starting from the anterior pelvic plane, the sagittal plane was centered to the pubic symphysis. The coronal plane cut both femoral head centres at the level of the maximum femoral head circumference. The axial plane was tilted until the pubic symphysis and the coccygeal bone were visible. Measurements were performed in the axial view. Thus, positional effects of the patient were eliminated and all planes were comparable. The anterior soft tissue (A), the anterior bone (B), the posterior bone (C), and the posterior soft tissue (D) were identified and the distances measured. The cutting point of the sagittal line through A–D with a line connecting the hip centres was defined as the hip plane (E) (Fig. 1).

Sex-specific measurements were performed. The hip plane from posterior up (distance DE) was more consistent than the anterior down (distance AE) measurement. Therefore, the relation of the patient diameter (AD) to the hip plane from

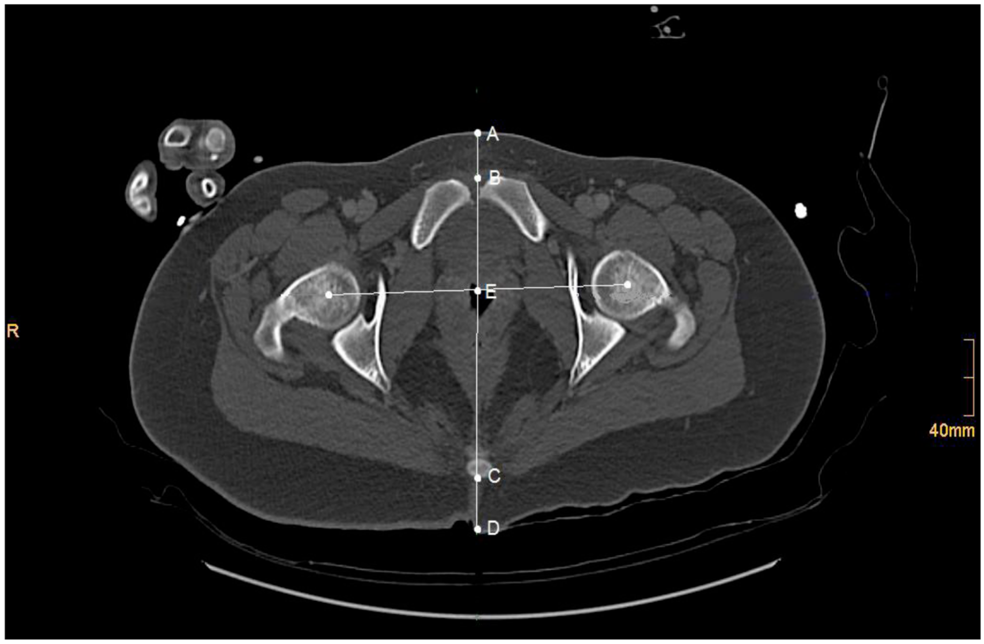

Fig. 1 Measurement of sagittal parameters in the axial slice after multiplanar CT reconstruction in the anterior pelvic plane

posterior up (DE) was used to describe the position of the hip in relation to the sagittal diameter.

Based on the intercept theorem, the theoretic magnification of each hip plane was calculated and defined as the reference MF for the CT (MF_{CT}) cohort. Thus, this MF_{CT} was a value specific for every pelvis in the CT cohort similar to the radiographic $MF_{Reference}$. To calculate the theoretical magnification of hips in the CT cohort, the individual height of the hip centre was combined with the table height (65 mm) in the local setting. The tube-to-film distance was 1100 mm as for conventional radiographs and x being the distance of the hip centres to the posterior soft tissue. Thus, the magnification in percent (MF_{CT}) was calculated by Equation 1:

$$MF_{CT} = \left(100^{*}1100\right)/(1100-x) \quad (1)$$

For this study, parameters were measured sagittal to the reconstructed anterior pelvic plane (APP). The sagittal distances were measured at the height of the pubic symphysis. The anterior soft tissue, the anterior margin of the pubic symphysis, the cutting point of the femoral head centres (joint plane) and the midline, the posterior bone (coccygeal bone), and the posterior soft tissue were identified and the sagittal distances measured. The height of the joint plane over the table was summed up.

A MF was calculated for all hips, comparable to pelvic radiographs, as a reference value for the prediction-models. Three models were generated to predict the hip plane based on the anteroposterior diameter of the patient at the height of the pubic symphysis sagittal to the APP. First, a sex-specific mean was calculated. Second, a linear regression model and finally, a cubic regression model were calculated.

Section IV—comparison of four calibration methods

These three prediction-models and the fixed MF were compared to the reference value (MF_{CT}) for each subject in the CT cohort. Differences and absolute differences were calculated.

Statistical analysis

Absolute mean values, standard deviations (SD), and ranges of the measured variables are reported. The level of significance was set at $p < 0.05$ and confidence intervals were 95%. Pearson correlation coefficients (r) were calculated. Bland-Altman-Plots were generated and linear regression analysis (ANOVA) was performed to test for proportional bias. The Bland-Altman-plot comprised two limits of agreement: (1) lines for one standard deviation (SD) and (2) lines for 1.96 standard deviations presenting the 95% confidence interval. Analysis to identify proportional bias was performed employing an analysis of variance (ANOVA).

IBM SPSS Statistics 22 (IBM Corporation, Armonk, NY, USA) and Microsoft Excel 2008 for Mac version 12.3.6 (Microsoft Corporation, Redmond, WA, USA) were used.

Results

Part 1

Section I—generation of the fixed magnification factor

The MF_{Fix} for 100 pelvic radiographs with unilateral THA as reference was 122.6% (range 115–129%; SD 2.5%). The mean error of the MF_{Fix} was 0.0% (range − 6.7–7.3%; SD 12.5%) and for absolute values 1.9% (range 0.1–7.3%; SD 1.7%). The error of the ECM in this cohort was 2.8% (range − 11.4-26.9%; SD 6.9%) and for absolute values 5.4% (range 0.0–26.9%; SD 5.1%).

Section II—reliability of the fixed magnification factor

The ICCs for intra- and inter-observer of repeated measurements of the femoral head were 0.990 ($p < 0.001$) and 0.987 ($p < 0.001$), respectively.

The application of the MF_{Fix} to an independent series of 111 pelvic radiographs showed mean errors of 0.0% (range − 13.2–16.1%; SD 3.9%) and for absolute values 2.5% (range 0.0–16.1%; SD 2.9%). The error of the ECM in this cohort was − 1.9% (range − 23.3–16.8%; SD 6.8%) and for absolute values 5.2% (range 0.0–23.3%; SD 4.8%). The mean $MF_{Reference}$ of this cohort was 122.6% (range 107–136%; SD 3.9%).

Part 2

Section III—sagittal parameters of 400 CT scans

Of the 400 CT scans, 398 depicted all relevant anatomical parts. Two cases (one female) were excluded due to incomplete depiction of the soft tissue. The sex-specific means of the hip height from posterior were 55.02% in males and 57.41% in females.

Linear regression models as well as cubic regression models were calculated for sex-dependent calculation of hip center positions relative to the sagittal patient diameter.

The mean MF_{CT} was 120.5% in females and 120.3% in males (Table 1).

Section IV—comparison of four calibration methods.

First, the non-sex-specific MF_{Fix} was compared to the individual MF_{CT}. Results for the MF_{CT} and the mean differences are shown in Table 2.

The combined results of three methods based on sagittal parameters are shown in Table 3. The MF_{CT} was compared to sex-specific means, sex-specific linear functions, and sex-specific cubic functions. The descriptive data of combined male and female MF of the methods are given. The relative difference and absolute difference of these MF and individual MF_{CT} are described.

The linear regression model was interpreted as the best fitting model due to the minimal absolute differences in comparison to the other models. Therefore, a Bland-Altman-Plot (Fig. 2) was generated. The linear regression analysis (ANOVA) did not reveal proportional bias ($p = 0.623$).

Table 1 Sex-dependent reference magnification factor. Based on CT-measurements. Mean, range and standard deviation (SD) are shown

	Female (%)	Male (%)
Mean	120.5	120.3
Min	116.3	116.3
Max	126.6	124.7
SD	1.8	1.5

Discussion

The importance of precise preoperative templating in total joint replacement is well accepted and various studies focused on its optimization. [2–4, 6] In digital templating of THA, the identification of anatomic landmarks and the correct placement of calibration markers is an unresolved issue. [2] Various factors affect the placement and the resulting calibration factor (i.e., MF). Initially, King et al. described the idea of a dual calibration marker and the calculation of the hip center based on CT data. [7] However, the published data is based on a small series of CT scans and the practical application of the large dual calibration marker has relevant disadvantages. On one hand, the bulky marker is difficult to handle and on the other hand, only radiographs in the supine position are possible.

The goal of the present study was to generate robust CT-based data on sagittal parameters of human hips for the application of a modified dual marker calibration method. Therefore, the first part of the study described the problem of the established spherical calibration marker and in the second part the conventional method of fixed magnification factors was compared to the mono marker method. The third part described the acquisition of sagittal parameters and presented different calculations for the hip centre location. Finally, the fourth part compared all methods.

The extent of the magnification error based on external calibration markers has been documented in multiple publications. The high reliability of measurements for calculation of magnification factors was shown by high ICCs in both cohorts with radiographs. Comparable to Sinclair et al. (error of 6.8%, range 0–26%), [9], we found errors of 5.4% (range 0.0–26.9%) in this study. Additionally, Bayne and colleagues reported a magnification error of 8.86%. [12] A comparison of different approaches by Franken et al. showed a superiority of a fixed MF over marker-based factors. This has been confirmed in a recent study by Sinclair and colleagues. [9] The clinical significance of the magnification error on templating and subsequent surgery can be calculated. A magnification error of 2% can already result in deviations from the optimal component size in templating.

Table 2 Differences between fixed magnification and CT-based reference magnification

	Mean (%)	Minimum (%)	Maximum (%)	Standard deviation
$MF_{Reference}$ CT ($n = 398$)	120.4	116.3	126.6	1.7
Δ $MF_{Reference} - MF_{Fix}$	−2.2	−6.4	4.0	1.7
Abs Δ $MF_{Reference} - MF_{Fix}$	2.4	0.0	6.4	1.3

The present study identified a MF_{Fix} of 122.6%, and the comparison of the ECM-based MF to the reference MF verified the previous assumption of its superiority in two independent cohorts. This finding underlines the need to reevaluate the current clinical standards in calibration for digital templating. While the use of MF_{Fix} is a possible approach to minimize the magnification error, this method is imprecise and does not account for inter-individual anatomical variations. In particular, this method simplifies the calibration to one fixed sagittal plane and ignores the plane of the hip in relation to sagittal parameters.

King et al. proposed a dual marker method. [7] They suggested marking of the anterior and posterior boundaries of the patients in anteroposterior radiographs and mathematical identification of the hip plane based on CT data of sagittal parameters. While this new approach showed good results in two publications, no further studies were published. [6, 7] Additionally, the study had some important weaknesses. First, the cohort used for the generation of CT data was small and not described in detail. Second, the underlying mathematical methods and results were not completely revealed. There were differences in the presented factors of the two studies. Thus, the exact method and reasoning remain unclear.

For the present study, a thoroughly characterized cohort of 400 patients with whole-body CT scans was chosen for the detailed analysis of sagittal parameters of the pelvis. The well-defined measurement algorithm allowed for reliable identification of landmarks and measurement of distances. The distance from the hip plane to the posterior soft tissue showed less variance compared to the anterior soft tissue. Therefore, the relation of the hip plane to the posterior soft tissue was used to calculate the position of the hip based on the sagittal patient diameter. Three sex-dependent methods were used to anticipate the magnification of the hip plane based on sagittal parameters: the means of the position, linear regression, and cubic regression analysis. These methods and the fixed MF method were applied to the cohort and compared to the true hip plane. It was shown that the linear regression method achieved the best results. While the MF_{Fix} resulted in a mean error of 2.4% and a maximum deviation of 6.4%, the MF_{Linear} resulted in a mean error of 0.8% and a maximum of 4.7%. The Bland-Altmann Plot showed that most values were within 2% from the calculated difference and the standard deviation was 0.6%. A clinical significance of this error-reduction can be assumed regarding the theoretical effect of magnification errors on component templating.

The major limitation of this study is the comparability of CT scans with standing anteroposterior radiographs of the hip. While CT scans allow for a precise and reproducible measurement of pelvic parameters, the soft tissue distribution might change between standing and supine positions and therefore alter the sagittal patient diameter. Additionally, reconstructions in the defined plane cannot take individual patient pelvic orientation during conventional radiographs into account. However, the CT-based approach allowed us to test the method with reliable and robust data. For future studies on dual

Table 3 Comparison of three calculation methods with the reference magnification factors in 398 CT-based simulations

	Mean (%)	Minimum (%)	Maximum (%)	Standard deviation
Calculation of MF using sex-specific factors based on means of sex-specific joint height				
Combined female and male MF	120.5	116.6	129	1.9
Δ $MF_{Reference} - MF$	0.1	−4.5	4.0	1.1
Abs Δ $MF_{Reference} - MF$	0.9	0.0	4.5	0.7
Calculation of MF using sex-specific linear functions				
Combined female and male MF_{Linear}	120.4	117.5	126.8	1.4
Δ $MF_{Reference} - MF_{Linear}$	0.0	−4.7	3.2	1.0
Abs Δ $MF_{Reference} - MF_{Linear}$	0.8	0.0	4.7	0.6
Calculation of MF using sex-specific cubic functions				
Combined female and male MF_{Cubic}	120.5	117.6	127.2	1.3
Δ $MF_{Reference} - MF_{Cubic}$	0.1	−5.1	3.7	1.0
Abs Δ $MF_{Reference} - MF_{Cubic}$	0.8	0.0	5.1	0.6

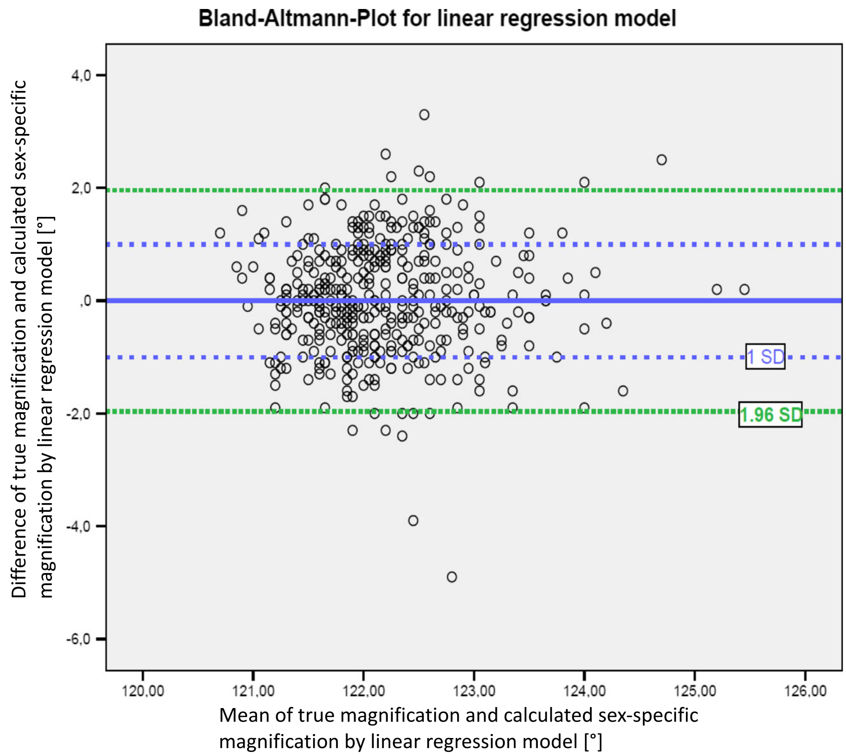

Fig. 2 Bland-Altmann-Plot for the linear regression model. Lines represent one standard deviation (dotted line, blue) and lines for 1.96 standard deviation (dotted lines, green). The latter represents the 95% confidence interval

calibration marker methods, prospective designs using dual markers and internal calibration markers (THA) as references need to be performed and should be used to generate large data samples. Secondly, the theoretical approach of this study simulates optimal dual marker placement and compares it to a real-life application of single markers. However, the dual marker method is far less susceptible to mal-placement of the marker due to its design. Finally, the exact position of the patients in the single marker collectives in regard to the film and source might vary. While patients are asked to stand against the screen to minimize the distance, some may have a larger distance from the screen and therefore the resulting distance of the internal and external markers from the film is increased. For this study, however, this effect is negligible because both markers underlie the same effect.

The strengths of this study are the systematic approach towards the problem and the applied methods of comparison. Additionally, the large cohort of 398 available CT scans for analysis is a major advantage over previous publications. Thirdly, the mathematical analysis of different CT-based factors identified the most promising type of calculation.

In conclusion, a relevant discrepancy between calculated magnification factors following the applications of single markers in comparison to reference values was identified. By using CT data, robust reference values for sagittal pelvic parameters were generated. They can be used to calculate a magnification factor by means of a dual calibration marker. This method has been shown to be superior to other methods in a theoretical setting. In the future, prospective clinical studies should be performed to compare dual and single calibration markers. Thus, precision of preoperative templating could be enhanced and patient safety could be improved.

Compliance with ethical standards

Conflict of interest CKB is an employee of Smith & Nephew GmbH, Germany. CKB may receive royalties from Medicad Hectec GmbH, Germany.

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