Received: 2 August 2019 | Revised: 9 January 2020 | Accepted: 11 February 2020

DOI: 10.1002/jor.24627

SPECIAL ISSUE RESEARCH ARTICLE

Journal of Orthopaedic Research®

Uncemented femoral stem orientation and position in total hip arthroplasty: A CT study

Martin A. Belzunce[1] | Johann Henckel[1] | Anna Di Laura[1] | Alister Hart[1,2]

[1]Institute of Orthopaedics, Royal National Orthopaedic Hospital, Stanmore, UK

[2]Institute of Orthopaedics and Musculoskeletal Science, University College London, Stanmore, UK

Correspondence
Martin A. Belzunce, Royal National Orthopaedic Hospital, Brockley Hill, Stanmore HA7 4LP, UK.
Email: martin.belzunce@nhs.net

Funding information
RNOH Charity; The Maurice Hatter Foundation; Rosetrees Trust; Stoneygate Trust; The National Institute for Health Research University College London Hospitals Biomedical Research Centre

Abstract

In total hip arthroplasty (THA), accurate positioning of components is important for the functionality and long life of the implant. Femoral component version has been underinvestigated when compared with the acetabular cup. Accurate prediction of the femoral version on the preoperative plan is particularly important because a well-fitting uncemented stem will, by definition, press-fit into a version that is dictated by the anatomy of the proximal femur. A better understanding of this has recently become an unmet need because of the increased use of uncemented stems and of preoperative image-based planning. We present the first, three-dimensional (3D) comparison between the planned and achieved orientation and position of the femoral components in THA. We propose a comparison method that uses the 3D models of a, computed tomography-generated (CT-generated), preoperative plan and a postoperative CT to obtain the discrepancy in the six possible degrees of freedom. We ran a prospective study (level 2 evidence) of 30 patients undergoing uncemented THA to quantify the discrepancy between planned and achieved femoral stem orientation and position. The discrepancy was low for femoral stem vertical position and leg length, and varus-valgus and anterior-posterior orientation. The discrepancy was higher for femoral version with a mean (±SD) of −1.5 ± 7.8 deg. Surgeons should be aware of the variability of the eventual position of uncemented stems in THA and acknowledge the risk of achieving a less-than-optimal femoral version, different from the preoperative 3D CT plan.

KEYWORDS

3D planning, offset, postoperative CT, THA, uncemented stem, version

1 | INTRODUCTION

In total hip arthroplasty (THA), accurate positioning of acetabular and femoral components is important for better functionality and longevity of the implant, reducing the need of revision surgery.[1-4] Parameters such as cup inclination and version, stem version, horizontal and vertical femoral offsets have a major impact on performance,[4-6] including the range of motion,[1-3] impingement,[7] risk of dislocation,[8-10] and wear[11,12] in THA.

Recently, preoperative CT three-dimensional (3D) planning[13-16] has been used to optimize sizing, position, and orientation of components in THA. The femoral component has been underinvestigated when compared with the acetabular cup. Achieving optimal orientation is particularly important for stem version;[4,17-19] while attaining a favorable position, in terms of center of rotation (CoR) and femoral offsets, it is important to avoid leg length discrepancy (LLD) to maximize function.[20,21]

Commonly the stem orientation is planned to restore the native femoral neck version (FNV), which has a large variability between subjects, with reported values from 5.0 ± 9.6 deg to 19.8 ± 9.3 deg.[22,23] Dorr et al[24] proposed an alternative approach, where the aims are to achieve a combined anteversion of 25-50 deg, being the latter the sum of the version of the acetabulum and the femur. However, in uncemented arthroplasty, the stem is press-fitted so that its orientation is determined by the anatomy of the proximal femur. Recent reports showed an important discrepancy between the FNV and the achieved stem version after THA,[22,24–26] where the comparisons were made by measuring the angle between the femoral neck axis and the bicondylar knee axis using computerized tomography scans (CT scans).

Different methods have been used to compare the achieved stem version to the native femoral neck version, going from intraoperative robotic measurements[22] to measurements from postoperative CT scans.[27] Bargar et al[28] used 3D models from CT data to measure version more accurately by isolating only one degree of freedom for version, but no comparison has been previously done looking at the full 3D orientation of the stem. In this work, we propose a method to perform full 3D comparisons between the planned and achieved orientation and position of the femoral component in the six possible degrees of freedom.

We aimed to better understand how the press-fitting placement of uncemented femoral stems affects their orientation and position. Our primary objective was to quantify the difference between preoperative planned and postoperative achieved orientations. Our secondary objective was to quantify the discrepancy in the stem position. Our outcome measures were, respectively, discrepancy between planned and achieved (a) stem orientation angles (varus-valgus, version, anterior-posterior) and (b) stem position (CoR and offsets). Our null hypothesis was that the planned femoral stem orientation and position were not similar to the achieved.

2 | METHODS

2.1 | Study design, level of evidence, and ethical approval

We prospectively collected 3D plans generated from preoperative CTs and, following surgery, the postoperative CTs of 30 consecutive THA (17 left and 13 right hips), in 29 patients, consisting of 17 males and 13 females (median age 68 years, range 46-83 years). The surgery was performed through a posterior approach by a single consultant orthopedic surgeon who specializes in hip arthroplasty and has done more than 1000 primary and revision hip arthroplasties. A single CT-based planning platform with one design of femoral (Quadra-H System) and acetabular (Mpact System) implant was used (Medacta International SA, Castel San Pietro, Switzerland).

In the surgery, a patient-specific instrument (PSI) guide was used to cut the femoral neck. The femoral PSI guide was 3D printed to fit the contours of the femoral head-neck junction (ie, no cartilage present at this junction). Once seated, it was secured with two threaded pins. The femoral neck cut was then completed using a standard method, with the saw blade flush on the cutting surface of the guide to deliver a femoral cut at the planned angle and location. The planned cut angle was 45° from the piriformis fossa to the anatomical axis of the femur to match the etched mark on the femoral stem (also 45° to the long axis of the stem).

The femoral canal was prepared by the surgeon using the instructions for use provided by the implant manufacturer. The canal was opened using a starter reamer and femoral stem rasps, with sequentially increasing sizes, so that the etched stem marker was level with the cut surface of the femur and the rasp was secure when tested by twisting. The stem was then press-fitted and tested by twisting the implant within the femur and confirming that this did not cause movement between the stem and the bone.

The level of evidence for this paper is 2.

The study received institutional review board approval (SE16.020).

2.2 | Three-dimensional plans from preoperative computerized tomographs

The surgical plans were generated from preoperative CT scans. They aimed to restore the FNV of the affected hip and the native femoral offsets and leg length with reference to the contralateral side. The posterior condyle axis was used as the planning coordinate system for femoral version. Regarding the acetabular component, which it is out of the scope of this work, the plan aimed for an inclination of 45° and an anteversion of 30° in the anatomical definition.

2.3 | Measurement of achieved stem orientation and position

A relative comparison between the planned and the postoperatively achieved stem orientation and positions was carried out using Simpleware ScanIP (version 2018.12; Synopsys, Inc, Mountain View, CA). A number of software scripts were developed to process the stem position in the plan, from the relevant STL 3D models, and in the postoperative CT scan for each case. In this comparison, the discrepancy between planned and achieved orientation and position were measured in the six possible degrees of freedom: coronal (varus-valgus), transverse (version), and sagittal (anterior-posterior) angles for the stem orientation; and x, y, and z for the position, using the CoR of the stem for this purpose (Figure 1). The coordinate system of both datasets was aligned by using the femur as a reference.

The postoperative CT scans had slice thickness of 0.75 and a spatial resolution of 0.6 mm. The scans were corrected for metal artifacts.

2.4 | Plan and postoperative CT alignment

The 3D models of the plan consisted of the femur together with the appropriate size stem in the femoral canal and the head of the implant

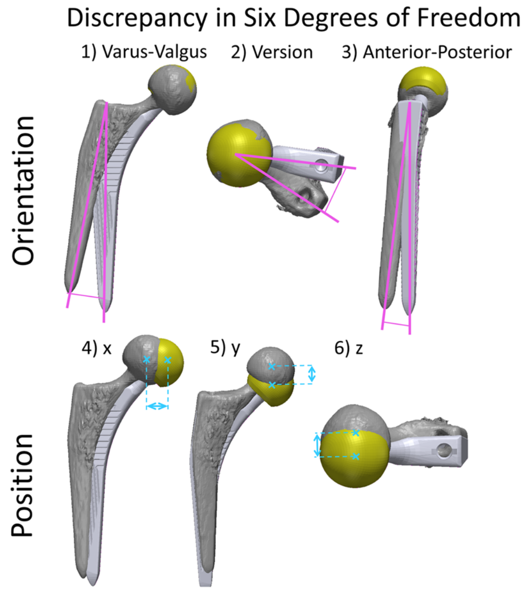

FIGURE 1 Illustration of each of the six degrees of freedom for the discrepancy between the preoperative planned and postoperative achieved stem positions. Varus-valgus (A) version (B) and anterior-posterior (C) angles for orientation; and distance in the *x*, *y*, and *z* axes for position. The shown discrepancies are for illustration pourposes [Color figure can be viewed at wileyonlinelibrary.com]

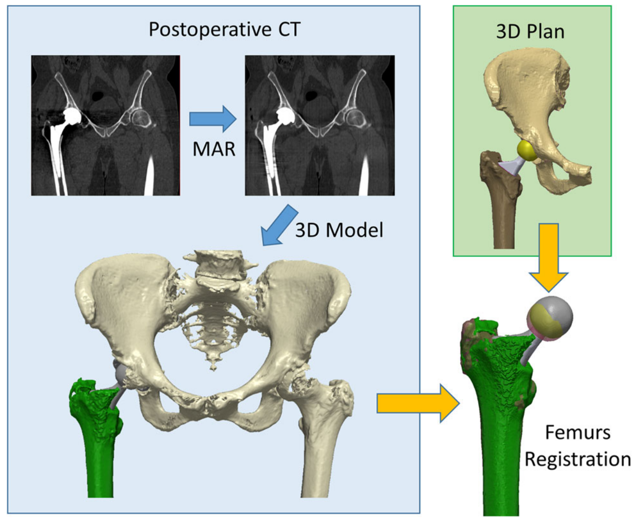

FIGURE 2 Processing chain to align the postoperative CT and the 3D plan. The CT is first processed with a Metal Artifact Reduction (MAR) algorithm, then 3D models of the bone and the implant are generated and finally, the femur is labeled. The femur and the femoral components of the plan are registered to the postoperative model of the femur. In the bottom right image, the achieved and plan femoral components are overlaid after the femur registration. 3D, three-dimensional; CT, computerized tomography [Color figure can be viewed at wileyonlinelibrary.com]

placed onto the stem. For the purpose of this study, the emphasis was placed on the femoral implant and the pelvis model was not used.

The postoperative CTs were preprocessed with the normalized metal artifact reduction algorithm[29] and then models of the hip, the femur, and the implant were generated by applying intensity thresholding and region splitting tools in Simpleware. The plan models were realigned to the CT models by registering the femurs with a two steps image registration[30] (Figure 2).

The first step consists of an automated rigid registration of the femur models, which is checked by the operator. If they consider that the image registration is not satisfactory, landmarks in the lesser trochanter are marked in both femur models and a mixed landmark-automated registration is executed. In Figure S1, we show an example where the second step was needed.

Once the datasets were aligned, a new coordinate system was defined using the stem and head models of the plan as a reference. The origin of the coordinate system was set in the center of the head. The vertical axis *y* was defined parallel to the line that joins the distal tip with the top landmark in the stem (y_p), while the horizontal axis (*x*) was the line with the direction of the projection of the origin into the stem vertical line previously defined (x_p) (Figure 3).

2.5 | Measurement of orientation discrepancy

The discrepancy between the achieved and the plan stem orientation was computed in the three possible directions: axial, coronal, and sagittal defined by the new coordinate system described in the previous section. The coronal (*XY* plane), axial (*XZ* plane), and sagittal (*ZY*) planes correspond to the varus-valgus, version, and anterior-posterior angles respectively. The definition and signs of these angles are shown in Figure 4. The achieved stem version was also computed by summing up the plan version and the discrepancy angle.

To estimate the achieved orientation, the vertical and horizontal axes of the achieved stem were computed in the same way as for the planned stem (Figure 3), which we call y_a and x_a, respectively.

The version angle discrepancy was computed by projecting the x_a axis into the *XZ* plane and estimating the angular difference with the plane stem axis (x_p). A positive (+) angle was used to indicate a more anteverted achieved stem.

For the varus-valgus angle, the vertical stem axis y_a was projected into the coronal *XY* plane and the angular difference with y_p was computed. A positive (+) angle was used to indicate a valgus stem respect to the plan.

For the anterior-posterior angle, the y_a axis was projected into the *ZY* plane and the angular difference with y_p was calculated. In Figure 4, the three angles are shown where the axes of the planned stem are shown with gray lines, the axes of the achieved stem in red lines, and the projection of the latter in the planes of the new coordinate system in a green line.

2.6 | Measurement of position discrepancy

The postoperative CoR was used to assess the positioning of the stem. The CoR is a surrogate measurement of the top of the stem

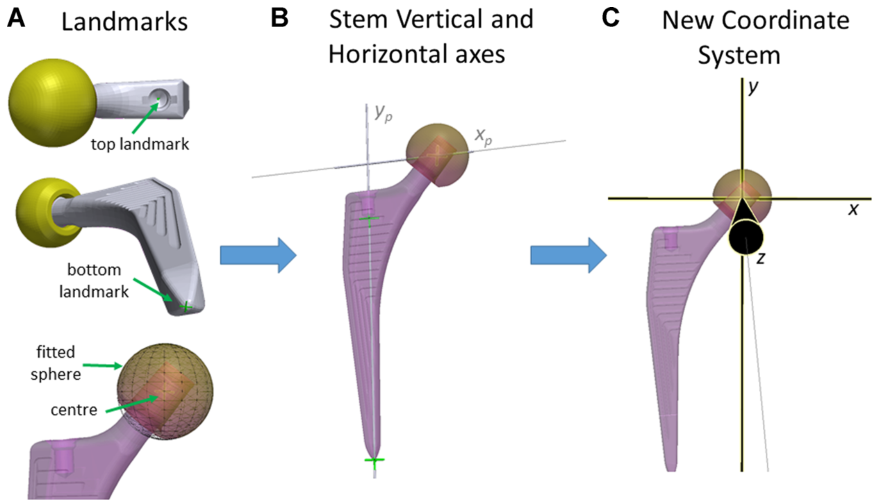

FIGURE 3 Definition of a new coordinate system. The stem top mark, the distal tip and the center of the head are used as landmarks (A), to define the vertical y_p and horizontal x_p stem axis (B). The new coordinate system is defined with the origin in the center of the head, the new *x*-axis is x_p, the *y*-axis is the line parallel to y_p that passes through the origin and *z* is orthogonal to *x* and *y* (C) [Color figure can be viewed at wileyonlinelibrary.com]

neck. The CoR was obtained by computing the center of a fitted sphere to the head of the implant. When the head was able to be split from the cup (see Figure 2), a region of interest over the head was used to fit a sphere, while a sphere was extrapolated from the visible head surface for all the other cases (Figure 5). For the *x*-axis, a positive discrepancy was used for an achieved head shifted medially respect to the plan, irrespectively of the hip side. For the *y*-axis, a positive discrepancy was used for a superiorly achieved head.

2.7 | Measurement of femoral offsets discrepancy

The achieved horizontal and vertical femoral offsets (HFO and VFO, respectively) are mainly dependent on the position of the stem that was described in the previous subsection. We measured the HFO for both the preoperative plan and the postoperatively achieved stem to have a better insight of the impact of the position discrepancy on this important parameter. The plan HFO was obtained by measuring the distance between the head center and its projection into the vertical stem axis (y_p). The achieved HFO was obtained using the same method but with the center of the achieved head position, while still using the plan vertical axis as it represents the anatomical femoral axis. The VFO discrepancy was measured by obtaining the distance between the projected CoR points.

2.8 | Validation, reproducibility, and reliability analysis

The processing chain of the proposed method relies mainly in automated steps that reduce the inter- and intraobserver variability of the results. However, the operator still needs to create landmarks to define the stem axes and to assist the image registration when the automated algorithm is not completely accurate. We have identified and analyzed the steps where the user input could potentially impact on the results.

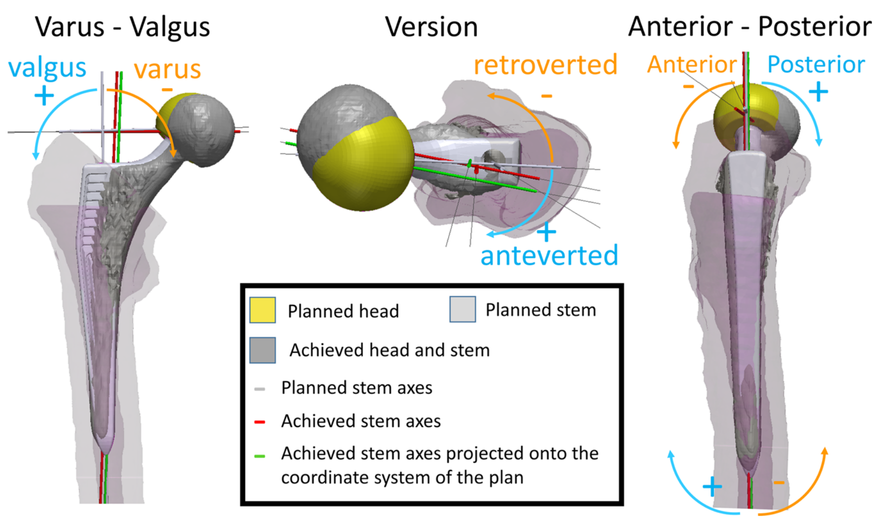

FIGURE 4 Measured angle discrepancies. The axes of the achieved stem (red lines) are projected into the planes of the plan coordinate system (green lines) and the angular difference respect to the plan axes (gray lines) are measured. Coronal plane: varus-valgus angle. Axial plane: version angle. Sagittal plane: anterior-posterior angle [Color figure can be viewed at wileyonlinelibrary.com]

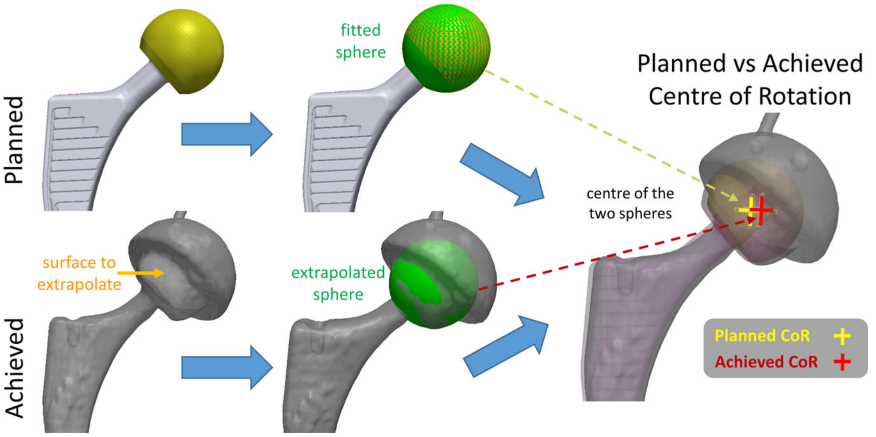

FIGURE 5 Estimation of the center of rotation for the plan (top row) and achieved (bottom row) femoral components. A sphere is fitted to the planned head, while a sphere is extrapolated in the achieved head when the head cannot be split from the cup. On the right, planned and achieved stems are overlaid and the center of the two spheres are shown [Color figure can be viewed at wileyonlinelibrary.com]

- Image registration: after the automated image registration, the user checks visually the alignment of both femur 3D models. If the user considers that the alignment can be improved, they can add landmarks to assist the image registration. This is the step where the observer could introduce a higher variability.
- Estimation of the CoR: in this step, a sphere is fitted to the implant head based on user input. For the plan head, a region of interest covering the full head is used and therefore it does not introduce any observer error. However, for the achieved head, a sphere is fitted to a surface painted by the user on the stem head, which is user-dependent and more variable when the head cannot be split from the cup, as shown in Figure 5. This would introduce a mild observer variability, mainly in the stem position but secondarily in the orientation.
- Definition of the horizontal and vertical stem axes: in this step, the user creates points in the stem top mark and the distal tip. These landmarks have low variability as they are very easy to identify.

We ran a reproducibility test by doing intra- and interobserver analysis.[31] For the intraobserver analysis, the same operator repeated the measurements of the 30 cases, more than a month apart. To assess the interobserver variability, ten cases were randomly selected and measured by a second operator. In these tests, we also included the implant femoral offset that was defined as the distance from the center of the implant head to the stem vertical axis for both achieved and planned stem models.

Finally, we used the femoral version to validate the method using the same 10 cases randomly selected for the interobserver analysis. We compared the femoral anteversion, which we obtained by adding the version discrepancy to the plan version, with the postoperative version measured with the method developed by Murphy.[32]

2.9 | Data analysis

The mean, median, standard deviation, interquartile range (IQR), minimum, and maximum values were estimated for the six degrees of freedom and the femoral offsets. Due to the importance of the version angle and the horizontal femoral offset, a linear regression model was fit to the data to look for a linear relationship between the planned and achieved parameters. The coefficient of determination (R^2) was used to indicate the level of correlation. In addition, a Bland-Altman analysis was done, where the discrepancy on each of these two parameters was compared with the values of the plan.

For the reproducibility and reliability analysis, the intraobserver variability was quantified by calculating the mean and standard deviation of the difference between the two measurements performed by the same operator; while for the interobsever variability, we used the difference between one measurement of the main observer and the only measurement of the second user. A one-way analysis of variance was used to obtain the intraclass correlation (ICC) for both inter- and intraobserver measurements.[33] We focused our analysis on the version and femoral offset.

3 | RESULTS

We recorded satisfactory surgical outcomes with no intraoperative femoral fracture (the most relevant intraoperative complication for uncemented stems), which was confirmed on postoperative CT. There was one dislocation that occurred as a result of excessive range of motion: deep hip flexion at 5 weeks postoperative, it was treated with one closed reduction procedure and the patient achieved full return to all activities with a maximum Oxford Hip Score of 48 at 12 months postoperative. The patient did not have further surgery. We present the discrepancy between planned and achieved femoral stem orientation (varus-valgus, version, and anterior-posterior) and position (CoR, HFO, and VFO).

3.1 | Femoral stem orientation (varus-valgus, version, and anterior-posterior)

The mean (±SD) discrepancy for the varus-valgus angle of the stem was −1.1 ± 1.4 deg (median = −1.1 deg; IQR −2.5-0.3 deg;

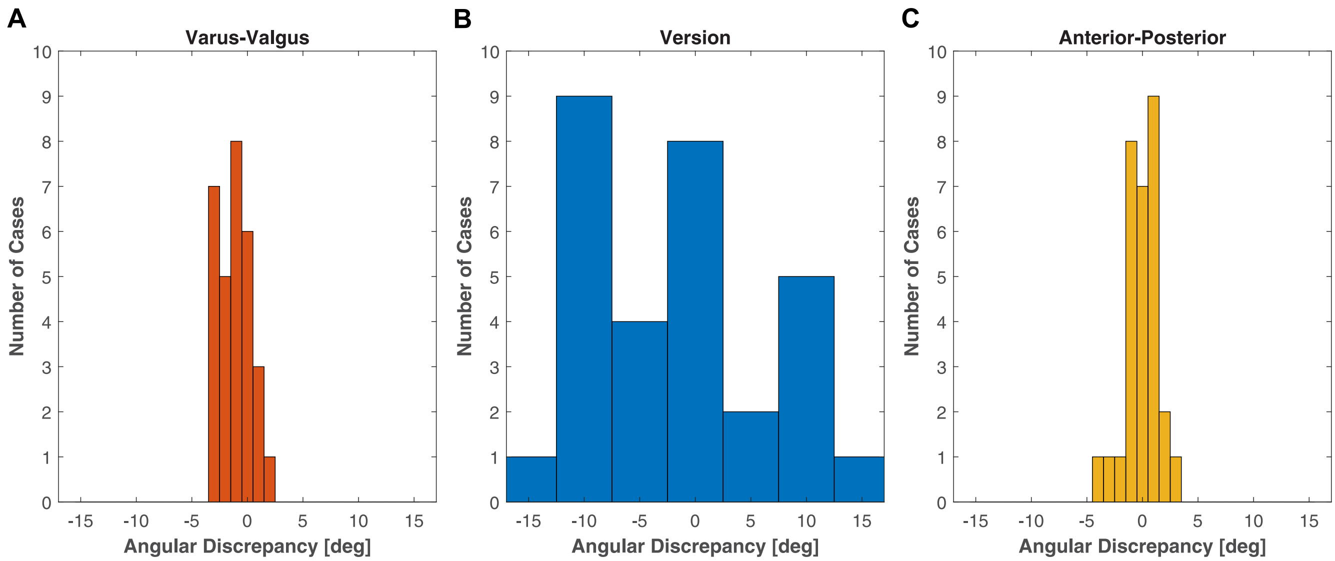

FIGURE 6 Angular discrepancy (in degrees) histograms for the (A) varus-valgus, (B) version, and (C) anterior-posterior orientations. The same range of values was used in the three cases but with a bin width adjusted to the variability of each variable [Color figure can be viewed at wileyonlinelibrary.com]

min = −3.2 deg, max = 1.8 deg); 24 out of 30 stems were varus with respect to the plan. The mean (±SD) discrepancy of the version angle was −1.5 ± 7.8 deg (median = −2.1 deg; IQR −8.1-7.2 deg; min = −14.5 deg, max = 14.3 deg). Twelve stems were positioned with a more anteverted angle than in the plan, while 18 were retroverted when compared to the plan. Finally, the mean (±SD) anterior-posterior angle discrepancy was 0.1 ± 1.5 deg (median = 0.4 deg; IQR −0.7-1.1 deg; min = −3.7 deg, max = 3.2 deg). Histograms with the discrepancy in the three angular orientations are shown in Figure 6.

3.2 | Femoral stem version

The mean (±SD) achieved version was 14.1 ± 10.2 deg (median = 14.5 deg; IQR 8.9-19.4 deg; min = −4.5 deg, max = 39.2 deg). The planned version was 15.9 ± 9.8 deg (median = 15.8 deg; IQR 8.5-21.0; min = 0, max = 41). In Figure 7A, the achieved version is plotted as a function of the plan. A linear regression modeled was fitted to the data, showing a moderate positive correlation (R^2=.48; P < .001) due to the high variability in the achieved version. In Figure 7B, a Bland-Altman analysis is

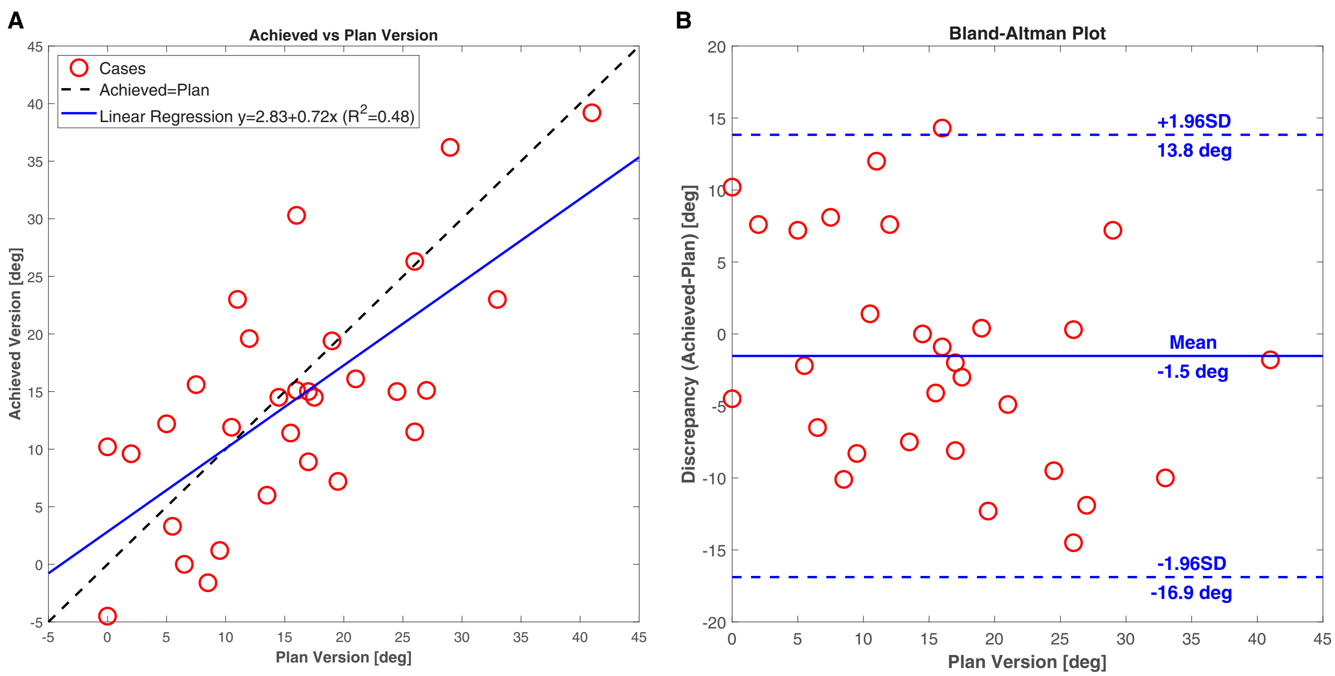

FIGURE 7 A, Achieved version as a function of the version of the plan. The case for achieved = plan is shown in a dashed line and a linear regression in a solid line. B, Bland-Altman plot of the version. The planned version is used as a reference in the x-axis, while the error is shown in the y-axis [Color figure can be viewed at wileyonlinelibrary.com]

shown where the high variability can be observed. A 95% confidence interval of [-16.9, 13.8] deg was obtained for version discrepancy.

3.3 | Femoral stem position (CoR)

The mean (±SD) discrepancy in the position of the stem, using the CoR, was 6.6 ± 4.0 mm (median = 5.4 mm; IQR: 3.6-8.9 mm; min = 2.2 mm, max = 17.4 mm). When analyzing the discrepancy in each direction, the mean (±SD) values were 2.3 ± 3.6 mm (median = 2.3 mm; IQR 0.3-4.2 mm; min = -5.5 mm, max = 10.3 mm), 0.2 ± 2.3 mm (median = 0.4 mm; IQR: -1.9-2.2 mm; min = -5.9 mm, max = 4.1 mm), and 1.1 ± 6.0 mm (median = 0.7 mm; IQR -3.5-4.7 mm; min = -9.5 mm, max = 16.0 mm) in the x, y, and z directions, respectively. In Figure 8A, a plot of the discrepancy values in the horizontal and vertical directions is shown, as these parameters would have impact in the femoral offsets and leg length. For clarity, the achieved positions of the tip of the implants are shown with blue crosses overlaid to a stem and head with an 18-mm radius (Figure 8B).

3.4 | Femoral offsets (HFO and VFO)

The achieved HFO was in average 2.2 ± 2.8 mm greater than in the plan (median = 2.2 mm; IQR 0.4−4.5 mm; min = −2.9 mm, max = 8.3 mm). In Figure 9A, the achieved HFO is shown as a function of the plan HFO. A strong linear correlation (R^2 = .83, P < .001) was found between the achieved and planned HFOs, where the relationship between achieved and planned offsets was 1.25 instead of the ideal 1.0. In Figure 9B, a Bland-Altman analysis of the HFO discrepancy is shown, using the HFO of the plan as a reference. Both plots show that the achieved HFO was in most of the cases greater than in the plan, which also agrees with the observed medial shift of the COR as this would increase the HFO. We found a moderate statistically significant positive correlation between the horizontal discrepancy in the CoR and the HFO (m = 0.89, R^2=.49, P < .001). A 95% confidence interval of [−3.2, 7.7] mm was obtained for the HFO discrepancy.

The mean (±SD) VFO discrepancy was 0.1 ± 2.2 mm greater than in the plan (median = 0.4 mm; IQR −1.7-1.6 mm; min = −6 mm, max = 4.4 mm). The VFO discrepancy was highly correlated with the vertical discrepancy in the CoR (m = 1.0, R^2=.96, P < .001).

3.5 | Validation, reproducibility, and reliability analysis

For the validation, the difference between the version measured with our method and Murphy's method was in average 0.22 deg with a standard deviation of 2.4 deg (median = 0.15 deg; IQR −0.8-0.4 deg; min = −2.6 deg, max = 6 deg). There was a very good agreement between the two measurements, except for one outlier with six degrees of difference.

In Table 1, the results for the reproducibility and repeatability tests are presented. We achieved good intraobserver (repeatability) and interobserver reproducibility for the main variables assessed in this work: version discrepancy and HFO. In every case, the ICC was higher than 0.98. The standard deviation for version discrepancy and HFO differences was lower than 1.4 deg and 1.1 mm, respectively. In Figure 10A, we show a Bland-Altman plot for the version discrepancy difference between the repeated measurements for the main user, where a very good agreement was found for most of the cases. Figure 10B shows a very good correlation between the two

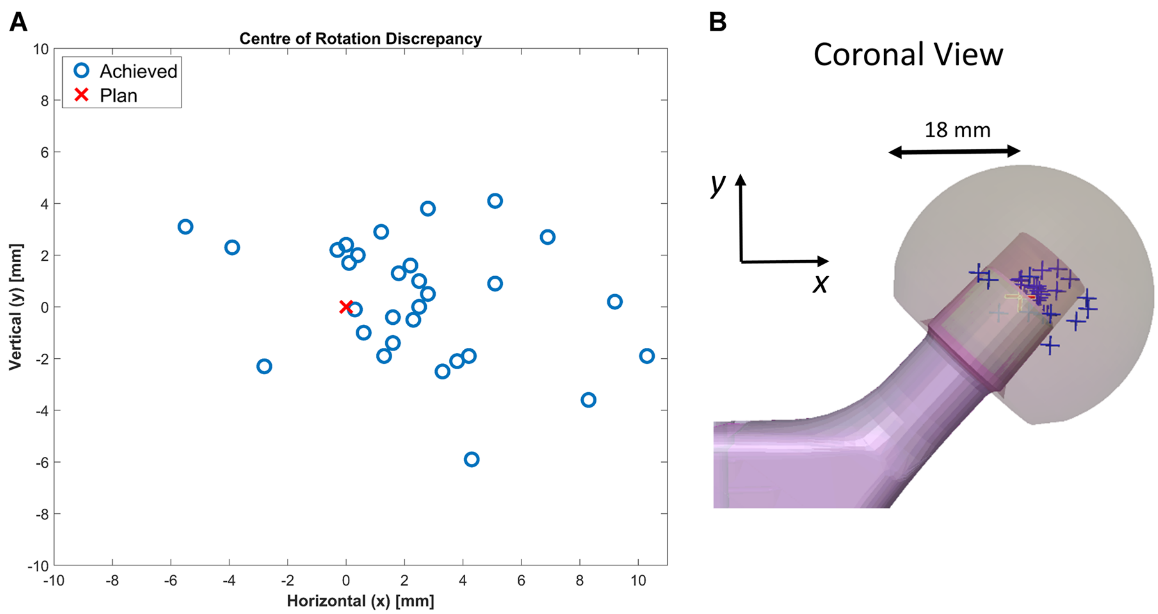

FIGURE 8 A, Discrepancy between the achieved and planned position of the stem for the 30 cases of the study, using the center of rotation as a reference. B, The 30 achieved positions are shown with blue crosses in a coronal view overlaid with a right stem and an 18-mm radius head [Color figure can be viewed at wileyonlinelibrary.com]

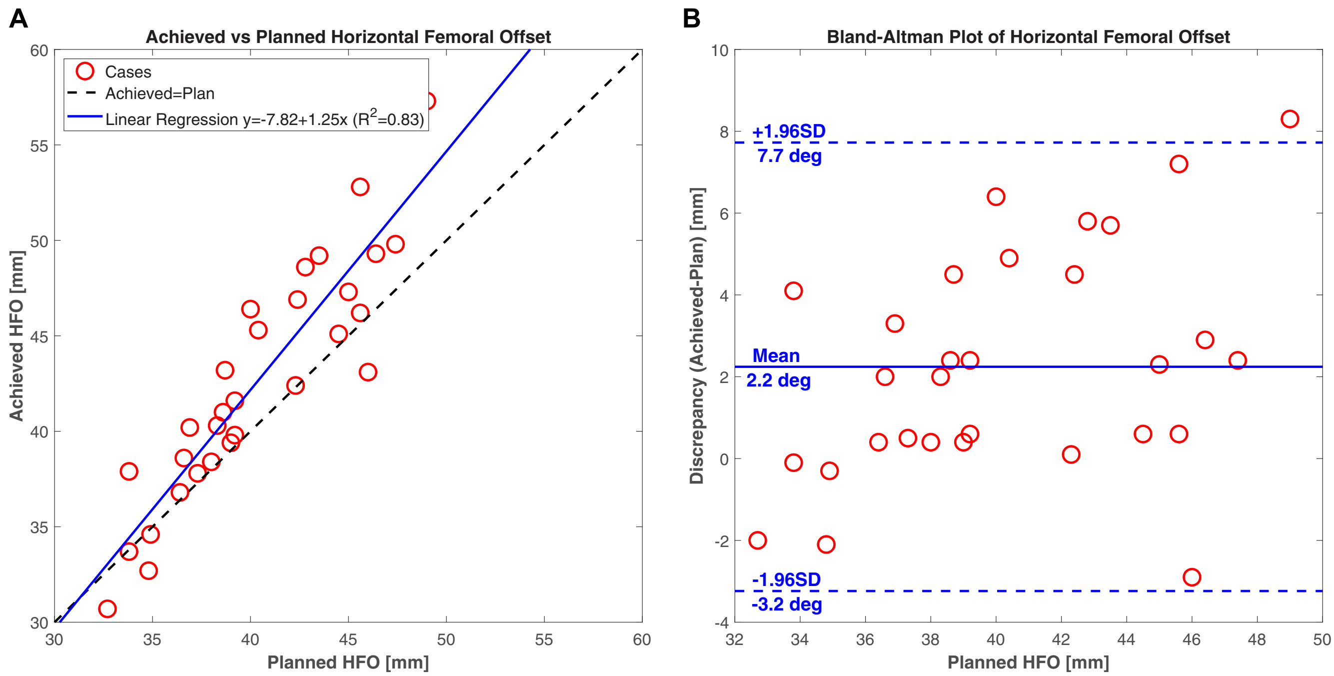

FIGURE 9 A, Achieved vs planned horizontal femoral offset for the 30 measured cases, achieved = plan is shown in a dashed line and a linear regression fitted to the measured data in a solid line. B, Bland-Altman analysis of the achieved horizontal femoral offset, on the *x*-axis the planned HFO, in the *y*-axis the discrepancy between achieved and planned values. HFO, horizontal femoral offset [Color figure can be viewed at wileyonlinelibrary.com]

intraobserver measurements (circles) and also for the interobserver measurements (crosses).

4 | DISCUSSION

This is the first study to quantify the discrepancy between planned and achieved femoral stem orientation and position in all six degrees of freedom in contemporary, uncemented THA using pre- and post-operative CT scans. We found that the mean (±SD) discrepancy was low for: vertical positioning (0.1 ± 2.3 mm) and therefore VFO (0.1 ± 2.2 mm); and the varus-valgus −(1.1 ± 1.4 deg) and anterior-posterior (0.1 ± 1.6 deg) orientations. The discrepancy was higher for femoral version (−1.4 ± 8.2 deg), although the achieved version was moderately correlated to the plan. There was a moderate discrepancy in the horizontal positioning (2.5 ± 3.5 mm) and HFO (2.2 ± 2.8 mm).

The clinical relevance of this work is for surgeons and surgical planning engineers. Both groups should be apprised of the unpredictability of achieving the planned femoral stem version of an uncemented femoral stem from the preoperative 3D CT plan. These results are dependent on the surgical planning engineer, the surgeon, the software used for planning, the stem design, and the measurement error of the postoperative analysis.

We have proposed and implemented a method that quantifies the discrepancy between the achieved femoral component position in THA to the 3D operative plan in its six degrees of freedom: *x*, *y*, and *z* components of the CoR; and the coronal (varus-valgus), axial (version), and sagittal (anterior-posterior) angular orientations. The method aligns the preoperative 3D plan to a postoperative CT using

TABLE 1 Reproducibility and reliability results

Analysis	Variable	Mean difference	SD difference	ICC
Intraobserver (N = 30)	Version	−0.1 deg	1.3 deg	0.99
	HFO	−0.3 mm	0.8 mm	0.99
	Planned stem offset	0.0 mm	0.6 mm	0.99
	Achieved stem offset	0.0 mm	0.3 mm	1.0
Interobserver (N = 10)	Version	−0.5 deg	1.4 deg	0.99
	HFO	-0.2 mm	1.1 mm	0.98
	Planned stem offset	−0.5 mm	1.1 mm	0.96
	Achieved stem offset	−0.2 mm	0.4 mm	0.99

Abbreviations: HFO, horizontal femoral offset; ICC, intraclass correlation.
In Table 1, we also present results for the horizontal offset of the stem, which shows that the landmarks to define the stem axes have very low variability.

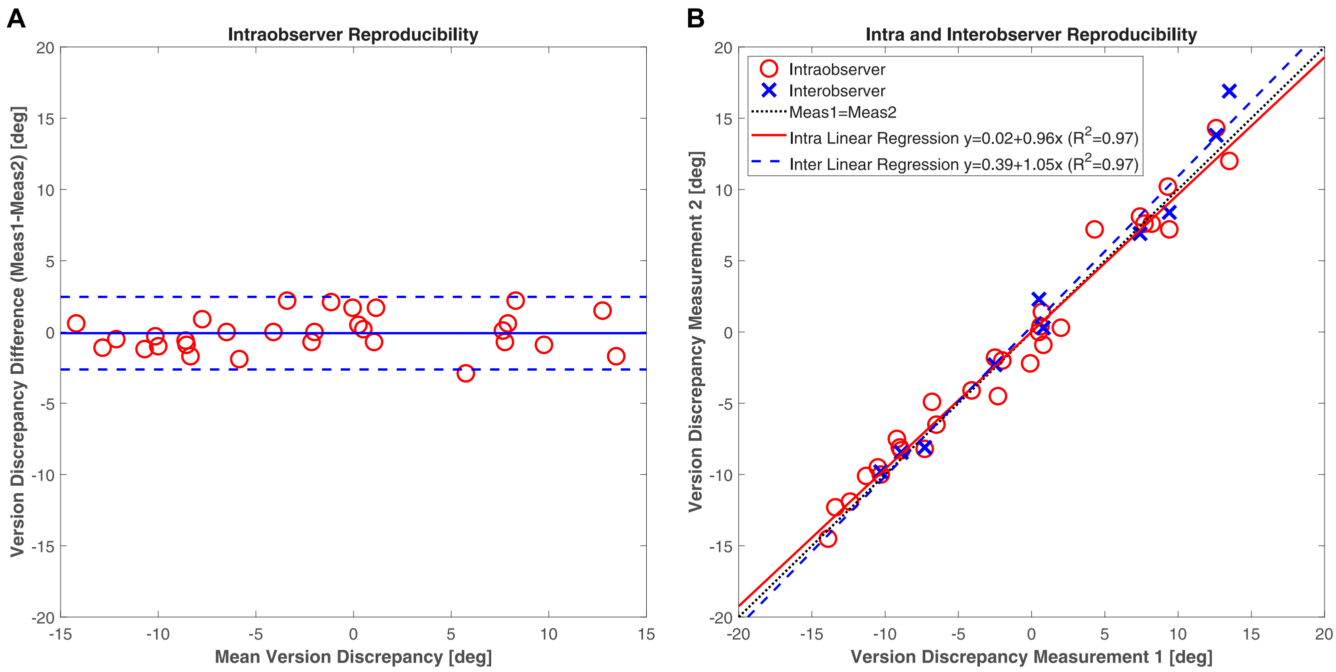

FIGURE 10 Intra- and interobserver results. A, Bland-Altman analysis of the version discrepancy for the 30 measured cases. B, Comparison of the two measurements involved in the inter- and intraobserver analysis. In circles, the 30 measurements done by the same operator (*x*-axis, first measurement; *y*-axis, second measurement). In crosses, the 10 measurements performed by a second operator are plot against the measurements from the main operator [Color figure can be viewed at wileyonlinelibrary.com]

the femur as a reference. In addition to be able to get a full comparison in the full six degrees of freedom, it has the advantage of not requiring the knee joint in the postoperative CT reducing the total radiation dose.

The main limitation of the proposed method is that it relies on a successful registration of the femur between the plan and the postoperative CT, which has metal artifacts. However, this was addressed by using metal artifacts reduction techniques and the use of landmarks in those cases that the image registration was not satisfactory as in Figure S1. The automated registration without landmarks not always could achieve perfect alignment due to residual metal artifacts and small differences in the femoral neck osteotomy level between the plan and postoperative 3D models. The method proved to be reliable, as shown in the intraobserver and interobserver analysis. For the validation test, good agreement was found between the version angle measured with our method and the Murphy method, although the difference between both methods was higher than in the reproducibility analysis. Differences between both methods were expected as in our measurements we completely isolate the degree of freedom for version, while in the Murphy method, the version is measured on axial CT slices not necessarily aligned with the stem version plane.

A further limitation of our study is that all the THAs were performed by a single surgeon and one specific implant geometry. However, other works have previously compared the FNV with the postoperative version and similar discrepancy values were obtained using other methodologies to assess version.[22-28] For example, Marcovigi et al[22] reported a standard deviation of 9.7 deg for the achieved stem version, with a discrepancy of 1.6 ± 9.8 deg respect to the FNV, while we obtained a version discrepancy of −1.4 ± 8.2 deg. These results would indicate that the press-fit position of uncemented stems is unlikely to match the plan version and restore the FNV; and that surgeon factors have low impact on the achieved version of the uncemented stem. These results are in line with the minimal surgeon control of the orientation of uncemented stems. Given the importance of the stem version angle to obtain good functionality and avoid dislocation or impingement,[17,18] special attention would be needed when deciding to use an uncemented stem. For this reason, planning a combined version between the acetabular and femoral components would be more appropriate. Ranawac and Maynard[34] introduced the concept of combined version and proposed a fixed value for the sum of the cup and stem version; later, Dorr et al[24] proposed an optimal zone for the combined anteversion that ranges from 25 deg to 50 deg. The option of using a femur first approach,[35-37] where the cup is positioned relative to the stem to achieve a satisfactory combined version, should be considered. However, a satisfactory intraoperative measurement tool is needed for this purpose.

Regarding the second outcome of this work, we showed that the achieved position for the tip of the stem was shifted in average 2.5 ± 3.5 mm medially and 0.2 ± 2.3 mm superiorly in the horizontal and vertical axes, which would impact in the femoral offsets and leg LLD. A higher discrepancy was observed in the *z*-axis, but this was related to the higher variability of the version angle, since the *z* coordinate of the CoR respect to the femur is mainly dictated by the version angle.

The VFO discrepancy was lower and, unsurprisingly, explained by the vertical discrepancy in the CoR. The HFO was increased postoperatively in average 2.3 mm (in 80% of the cases, the HFO was larger than in the plan) and had a moderate correlation with the medial displacement of the stem respect to the plan. Because in our study, we only included cases where the head used was the same as in the plan, the changes in the femoral offsets were exclusively dictated by the stem orientation and position. Based on the classification done by Cassidy et al,[38] we found that 24 cases had a normal offset (discrepancies between −5 and 5 mm), six increased offsets, and none of them had a decreased offset. In addition, the correlation between the HFO and the horizontal discrepancy agrees with the analysis done by Dastane et al,[21] where the hip offset reconstruction was directly related to the position of the hip CoR.

5 | CONCLUSION

We proposed a comparison method that can quantify discrepancies between the planned and achieved stem orientation and position of a THA in its six degrees of freedom, using a 3D plan and a postoperative CT. This study shows that the preoperatively measured and planned stem orientation and the position was never achieved in this series of uncemented THAs. The discrepancy was high for the femoral version, although the achieved version moderately correlated to the plan. Surgeons should be cautious with their expectation of achieving the femoral stem version of an uncemented femoral stem from the preoperative 3D CT plan. The positioning of the stem affected mainly the horizontal femoral offset, which on average was 2 mm larger than in the plan, but with low impact as most of the cases achieved a normal HFO.

ACKNOWLEDGMENTS

This research study was funded by The Maurice Hatter Foundation, the RNOH Charity, the Rosetrees Trust, and the Stoneygate Trust, and supported by researchers at the National Institute for Health Research University College London Hospitals Biomedical Research Centre.

AUTHOR CONTRIBUTIONS

MAB, JH, and AH contributed to the research design. MAB, JH, ADL, and AH were involved in data collection. MAB, JH, ADL, and AH contributed to the writing and revision of the manuscript. All coauthors have read the manuscript and agreed with the contents of it.

ORCID

Martin A. Belzunce http://orcid.org/0000-0001-6085-484X

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Belzunce MA, Henckel J, Di Laura A, Hart A. Uncemented femoral stem orientation and position in total hip arthroplasty: A CT study. *J Orthop Res*. 2020;38: 1486–1496. https://doi.org/10.1002/jor.24627