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■ **HIP**

Hip implants can restore anatomical and medialized rotation centres in most cases

A 3D TEMPLATING STUDY COMPARING FOUR IMPLANTATION STRATEGIES

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Aims

Hip arthroplasty does not always restore normal anatomy. This is due to inaccurate surgery or lack of stem sizes. We evaluated the aptitude of four total hip arthroplasty systems to restore an anatomical and medialized hip rotation centre.

Methods

Using 3D templating software in 49 CT scans of non-deformed femora, we virtually implanted: 1) small uncemented calcar-guided stems with two offset options (Optimys, Mathys), 2) uncemented straight stems with two offset options (Summit, DePuy Synthes), 3) cemented undersized stems (Exeter philosophy) with three offset options (CPT, ZimmerBiomet), and 4) cemented line-to-line stems (Kerboul philosophy) with proportional offsets (Centris, Mathys). We measured the distance between the templated and the anatomical and 5 mm medialized hip rotation centre.

Results

Both rotation centres could be restored within 5 mm in 94% and 92% of cases, respectively. The cemented undersized stem performed best, combining freedom of stem positioning and a large offset range. The uncemented straight stem performed well because of its large and well-chosen offset range, and despite the need for cortical bone contact limiting stem positioning. The cemented line-to-line stem performed less well due to a small range of sizes and offsets. The uncemented calcar-guided stem performed worst, despite 24 sizes and a large and well-chosen offset range. This was attributed to the calcar curvature restricting the stem insertion depth along the femoral axis.

Conclusion

In the majority of non-deformed femora, leg length, offset, and anteversion can be restored accurately with non-modular stems during 3D templating. Failure to restore hip biomechanics is mostly due to surgical inaccuracy. Small calcar guided stems offer no advantage to restore hip biomechanics compared to more traditional designs.

Introduction

During total hip arthroplasty, decreasing the abductor lever arm and disturbing the spatial relation between pelvis and greater trochanter should be avoided.[1-3] Anatomical cup positioning and matching femoral offset recreates the original anatomical situation. Medializing the cup while increasing femoral offset decreases load on the bearing surface and improves the abductor lever arm without modifying femoroacetabular offset.[1,4,5] This could be beneficial but requires implants with larger offsets. In practice, cup placement should be either anatomical or medialized.[6]

Hip arthroplasty systems use different strategies to restore femoral offset. Conventional stems are inserted along the proximal femoral axis and often have two or three offset options per size. Some systems have fixed offsets, while others have offsets

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Uncemented calcar-guided stems
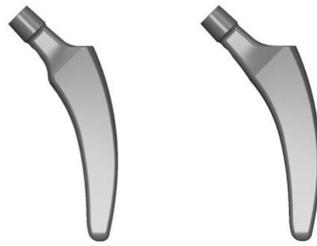
Size 4 Std   Size 4 Lat

Uncemented straight stems
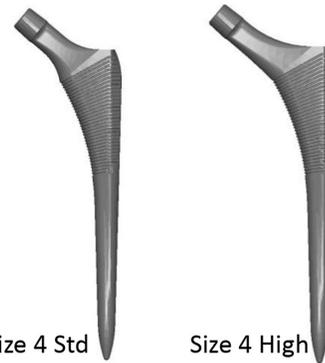
Size 4 Std   Size 4 High

Cemented undersized stems
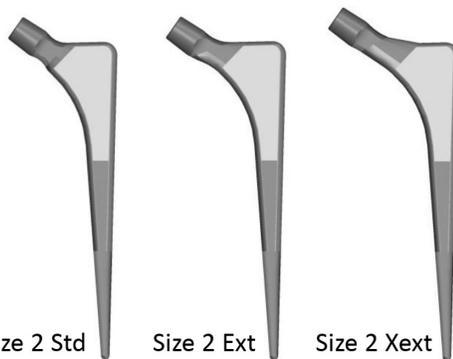
Size 2 Std   Size 2 Ext   Size 2 Xext

Cemented line-to-line stems
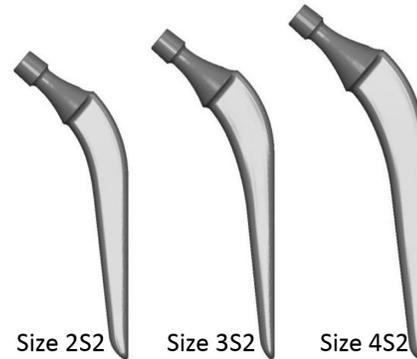
Size 2S2   Size 3S2   Size 4S2

Fig. 1

Examples of the different stem systems used in this study. Images courtesy of Mathys, DePuy Synthes and ZimmerBiomet. Ext, extended offset; High, high offset; Lat, lateralized offset; Std, standard offset, Xext, extra-extended offset.

Table I. Characteristics of the stems used in the study.

Brand	Fixation	Implantation strategy	Size	Offset options, mm	Neck lengths, mm	NS angle, °
Optimys	Uncemented	Calcar-guided	24	Standard, +5	-4, 0, +4, +8	135
Summit	Uncemented	Along femoral axis	20	Standard, +5	+1.5, +5, +8.5, +12	130
CPT	Cemented undersized	Along femoral axis	18*	Standard, +5, +10†	-3.5, 0, +3.5, +7	120, 125*§
Centris	Cemented canal filling	Along femoral axis	17‡	Proportional	-4, 0, +4, +8	133

*Including the CPT Small and X-Small sizes.
†The CPT extra-extended stem increases offset by 10 mm and leg length by 5 mm compared to the corresponding standard implant.
‡Including the Centris Dysplasia version of the stem.
§Neck shaft angle of the CPT stem: Small and X-Small 120°, other sizes 125°.
NS angle, neck shaft angle.

proportional to stem size. Femoral offset can be altered by choosing an offset option within a stem size, and by modifying the stem insertion depth and varying the head's neck length accordingly. This moves the hip rotation centre along a fixed neck-shaft angle.[2]

Calcar-guided stems are inserted in varus in varus hips and in valgus in valgus hips. As such, compared to conventional implants, a single calcar-guided stem could cover a larger offset range and might restore offset more often.[7]

During hip arthroplasty, anatomical variation[8-18] and surgical inaccuracy can cause poor restoration of hip biomechanics.[19-21] In a study by Erivan et al,[7] using standard and short calcar-guided stems, femoral offset inaccuracies over 10 mm were seen in 14% and 18% of patients, respectively. Several authors report leg length discrepancies > 10 mm in 3% of hips using intraoperative measurements,[22] in 10% with navigation and in 16% to 32% without.[19] Compared to the contralateral hip and without navigation, differences in global offset ≥ 10 mm were seen in 10% of patients,[21] with some cases > 25 mm.[20]

We used 3D templating to evaluate if failure to restore biomechanics in hips without major deformity

Table II. The patients' demographic and biomechanical characteristics of the 49 femora from which CT scans were obtained.

Patients' characteristics	Data
Sex, M:F	28:21
Mean age, yrs (SD, range)	67.0 (14.0, 27.0 to 88.5)
Mean length, cm* (SD, range)	166.9 (8.9, 143.0 to 186.0)
Mean weight, kg* (SD, range)	77.4 (19.4, 44.8 to 144.0)
Mean BMI, kg/m²* (SD, range)	27.7 (6.3, 15.3 to 51.9)
Biomechanical characteristics anatomical rotation centre	
Mean offset, mm (SD, range)	42.7 (5.9, 30.2 to 54.1)
Mean femoral length, mm† (SD, range)	396.3 (28.4, 333.2 to 472.0)
Mean anteversion, °‡ (SD, range)	21.1 (8.2, 3.6 to 43.4)
Biomechanical characteristics medialized rotation centre	
Mean offset, mm (SD, range)	47.8 (5.9, 35.2 to 59.1)
Mean femoral length, mm† (SD, range)	397.0 (28.3, 333.9 to 472.7)
Mean anteversion, °‡ (SD, range)	21.3 (8.2, 3.6 to 43.3)

*Calculated based on 44/49 available data.
†Femoral length was measured between the hip rotation centre and the middle of the interepicondylar line.
‡Femoral anteversion was the angle between the interepicondylar line and the x-z plane.

Table III. Offset range within one stem size and for the whole stem system.

Stem type	Min OR within one size, mm	Max OR within one size, mm	Total OR, mm
Uncemented calcar-guided stem	13.5	13.5	38.0
Uncemented straight stem	14.1	16.1	26.1
Cemented undersized stem	9.0	18.0	30.0
Cemented line-to-line stem	8.7	8.9	25.9

OR, offset range.

is attributable to a lack of implants and compared four implantation strategies.

Methods

Implants. We used 3D Computer-assisted Design (CAD) templates provided by the manufacturers and representing four primary femoral hip systems (Figure 1) with different implantation strategies (Table I): 1) uncemented calcar-guided stems with two offset options (Optimys, Mathys, Switzerland), 2) uncemented straight stems with two offset options (Summit, DePuy Synthes, USA), 3) cemented undersized stems (Exeter philosophy) with three offset options (CPT, ZimmerBiomet, USA), and 4) cemented line-to-line stems (canal-filling Kerboull philosophy) with proportional offset options (Centris, Mathys, Switzerland). For each implant, we used the neck lengths available for 36 mm ceramic heads.

CT scan segmentation. We selected 49 high-resolution CT scans of hips without major deformity, performed to investigate vascular problems. Datasets were cropped to the left femur and segmented with Mimics software (Materialise, Belgium) based on thresholding and manual fine-tuning.

Coordinate system. Segmented femora were imported in 3-matic (Materialise, Belgium) and the hip rotation centre was identified by optimal sphere fitting to the femoral head. To identify the proximal femoral axis, we optimally fitted a conical cylinder to the intramedullary cavity starting 20 mm and ending 120 mm below the level of the tip of the lesser trochanter.

We defined the orthogonal xyz-coordinate system in relation to the proximal femur. The origin of the coordinate system was set in the anatomical or medialized hip rotation centre. The positive z-axis (femoral lengthening/shortening) pointed along the longitudinal axis of the proximal femur in superior direction. The positive x-axis (offset) and y-axes (anterior/posterior translation) were oriented in the medial and posterior direction respectively. The x-axis was located in the plane defined by the hip rotation center and the longitudinal axis of the proximal femur, the y-axis was perpendicular to that plane. The medialized rotation centre simulated medializing the cup by 5 mm along the x-axis and increasing the stem offset accordingly.

The longitudinal axis of conventional stems was defined as the central axis of a conical cylinder fitted on the distal straight part of the stem. The longitudinal axis of calcar-guided stems was defined as a line through the distal stem tip and perpendicular to the tangent plane of that tip.

Templating procedure. Virtual templating was performed by importing 3D-CAD files of the implants in 3-matic and Mimics software. We used the scripting functionality of the software to size the implants, aiming at restoring both hip rotation centres. For conventional stems, the software aligned the longitudinal stem axis with the proximal femoral axis. For calcar-guided stems, the software aligned the medial border of the stem along the calcar region of the medullary canal.[23] As this step was automated, it was perfectly reproducible.

Uncemented calcar-guided, uncemented straight, and cemented line-to-line stems were sized to fill the medullary cavity and to provide cortical contact without removing cortical bone. This left few options to position the stem. Cemented undersized stems were one size smaller than the largest insertable broach, allowing some positioning freedom within the cement mantle. We chose the neck length of the head that restored both hip rotation centres at its best. The initial stem size, neck length, and stem position provided by the software was optimized by an orthopaedic trainee (EDW) and fine-tuned by experienced hip surgeon (TS). Both individuals checked and agreed on the implant size, the neck length, and the final stem position.

Outcome measures. Femoral length was defined on CT scans between the hip rotation centre and the middle of the interepicondylar line. Femoral anteversion was the angle between the interepicondylar line and the x-z plane.
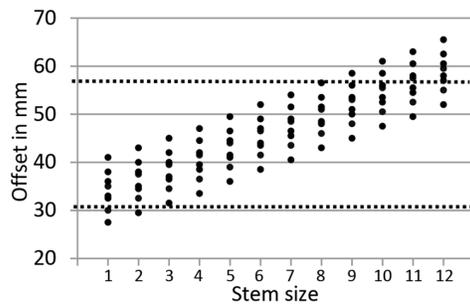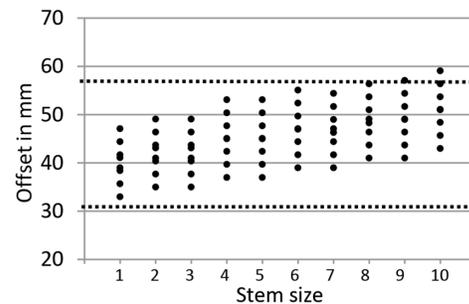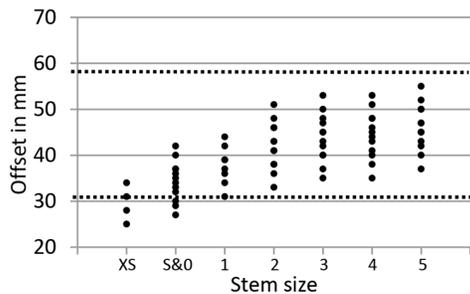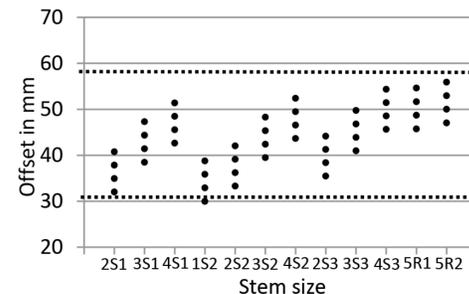
Fig. 2

Offset range of the different stem systems used in this study. The dotted lines delimit the femoral offset range including the anatomical and medialized hip rotation centre.

For each stem, we calculated offsets based on manu-facturers' data and available neck lengths for 36 mm ceramic heads. The offset range, i.e. the difference between the smallest and largest offset, was calculated for each hip system and within each stem size.

For all simulations, we recorded stem size, offset, and neck length. We also noted the angle between the longitudinal stem axis and the proximal femoral axis and measured the distance between the achieved and the targeted rotation centre. That distance was expressed as offset (along the x-axis), anteroposterior (along the y-axis), and proximal-distal distance (along the z-axis). For each stem system, we report the number of cases where the rotation centre could not be restored within 5 mm. That threshold is thought to be clinically significant.[3]

Statistical analysis. Continuous ratio scale variables were reported as means, standard deviations (SDs), minima (Min) and maxima (Max). Hip systems were compared with a one-way analysis of variance (ANOVA) or a one-way repeated ANOVA. When significant differences were found, Tukey's honesty significant difference (HSD) pair-wise tests or paired t-tests were performed to investigate the origin of the difference. Ordinal variables were ana-lyzed with a Wilcoxon signed-rank test and categorical variables with a chi-squard test followed by a post-hoc analysis with adjusted residuals, when independence was significant.

Statistical analysis was performed with Microsoft Excel and the Real Statistics Resource Pack software release 3.2.1. We considered p-values < 0.05 as statistically significant.

Ethical approval. This study was approved by the ethical committee of the Universitair Ziekenhuis Brussel, Brussels, Belgium (B.U.N. B143201525335).

Results

Femora and stem characteristics. In 49 patients, we ana-lyzed demographics and calculated biomechanical pa-rameters taking the anatomical and a 5 mm medialized hip rotation centre into account (Table II). The overall off-set range, including both rotation centres, was 28.9 mm (30.2 mm to 59.1 mm). Femoral length and anteversion had a global range of 138.8 mm and 40° respectively. None of the femora presented major deformities.

Offset ranges (Table III) assume that stems are inserted along the proximal femoral axis as conventional stems should be positioned. However, as uncemented calcar-guided stems are inserted along the calcar in a varus, valgus, or neutral position, their effective offset range could be larger.

The mean offset reachable with a 36 mm ceramic head (Figure 2), was significantly smaller for cemented under-sized stems than for uncemented calcar-guided and

Uncemented calcar-guided stems

Uncemented straight stems

Cemented undersized stems

Cemented line-to-line stems
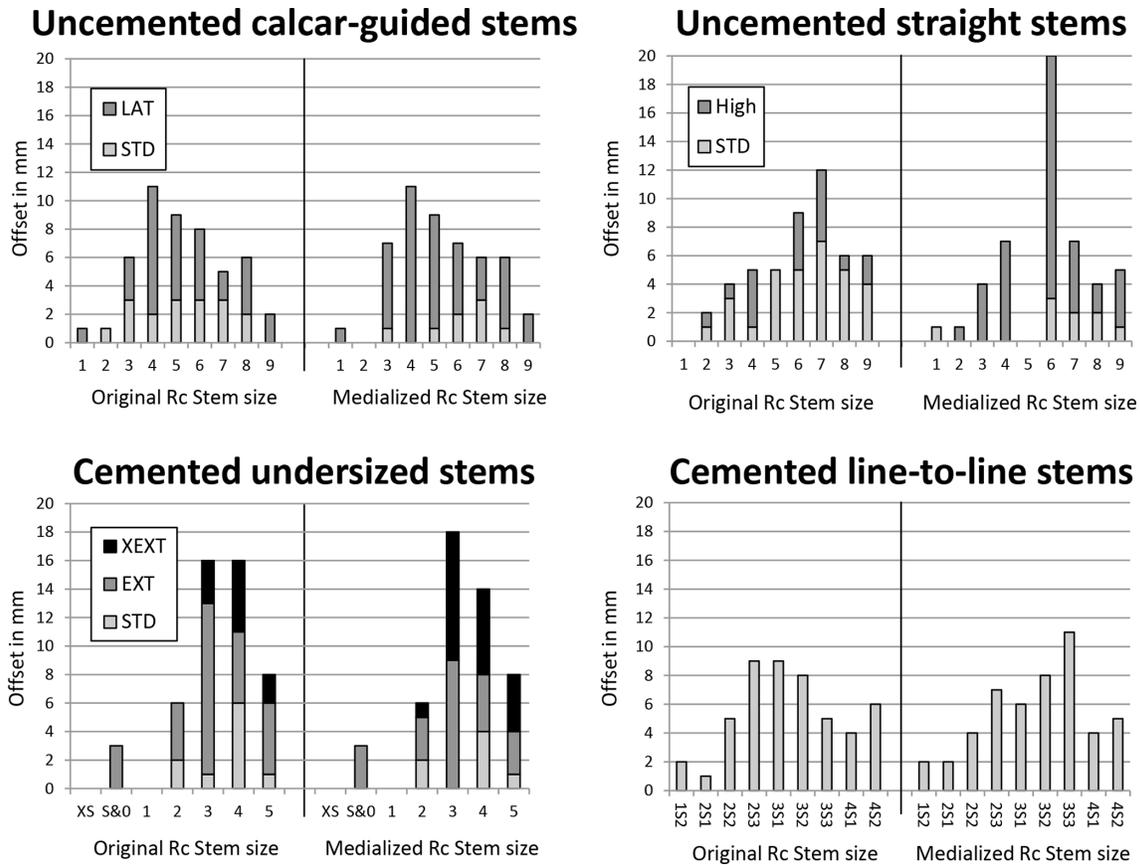
Fig. 3

Stem sizes of the different stem systems used to reconstruct the anatomical and medialized hip rotation centre. EXT, extended offset; High, high offset; LAT, lateralized offset; STD, standard offset; XEXT, extra-extended offset.

Table IV. Angle between the axis of the proximal femur and the stem.

Stem type	Mean anatomical rotation centre, ° (SD; range)	Medialized rotation centre, ° (SD; range)
Uncemented calcar-guided stem	2.3 (1.9; 0.0 to 7.0)	2.2 (1.8; 0.0 to 7.0)
Uncemented straight stem	1.5 (0.9; 0.0 to 4.5)	1.3 (0.8; 0.0 to 3.9)
Cemented undersized stem	0.3 (0.8; 0.0 to 3.7)	0.4 (0.8; 0.0 to 3.9)
Cemented line-to-line stem	0.5 (0.9; 0.0 to 3.8)	0.6 (1.1; 0.0 to 4.4)

uncemented straight stems (p < 0.001, ANOVA; Tukey's HSD pairwise tests).

Implants and stem alignment. For all but cemented line-to-line stems, we used significantly more lateralized implants to restore the medialized rotation centre than to restore the anatomical centre (all p < 0.016, Wilcoxon signed-rank test for paired samples). For cemented line-to-line stems this could not be evaluated as offset varied with stem size. Stem sizes used to restore both rotation centres were not significantly different (all p > 0.065, Wilcoxon signed-rank test for paired samples) (Figure 3).

The neck lengths used to restore the medialized hip rotation centre was significantly larger for uncemented calcar-guided, cemented undersized and cemented line-to-line stems (all p < 0.001, Wilcoxon signed-rank test for

paired samples), but not for uncemented straight stems (p = 0.267, Wilcoxon signed-rank test for paired samples).

In both settings, uncemented calcar-guided stems had the largest angle between the proximal femoral axis and the stem axis (Table IV). Of the conventional stems, uncemented straight implants showed the largest malalignment (both p < 0.001, ANOVA; Tukey's HSD pairwise tests).

Restoring the anatomical hip rotation centre. All four hip systems restored the anatomical rotation centre within an average of 2.5 mm and within 5 mm in 184/196 (93.9%) of the simulations (Table V). The number of outliers (distance > 5 mm) did not differ between systems (p = 0.069, chi-squared test). Cemented undersized stems restored the anatomical rotation centre more accurately than both uncemented calcar-guided and uncemented straight stems (p < 0.001, ANOVA; Tukey's HSD pairwise tests).

The distance between the anatomical and the templated rotation centre was broken down along the x, y, and z axes. The anteroposterior deviation (y-axis), which is related to the hip anteversion, was small (mean (absolute value)): 0.2 mm (SD 0.5)) and was not significantly different between hip systems (p = 0.129, ANOVA).

Table V. Distance and difference in offset and leg length between the original and the restored hip rotation centre for the four hip systems.

Stem type	Distance, mm*	Distance > 5 mm†	Δ offset, mm‡	Δ offset > 5 mm†	Δ leg length, mm‡	Δ leg length > 5 mm†
Uncemented calcar-guided stem	2.4 (1.9, 0.3 to 8.0)	6	1.6 (1.6, 0.0 to 6.8)	2	1.5 (1.3, 0.0 to 5.1)	1
Uncemented straight stem	1.8 (1.3, 0.2 to 6.1)	2	1.2 (1.0, 0.1 to 5.2)	1	0.9 (0.8, 0.0 to 2.5)	0
Cemented undersized stem	0.8 (0.9, 0.1 to 4.3)	0	0.7 (0.8, 0.00 to 4.2)	0	0.3 (0.6, 0.0 to 4.0)	0
Cemented line-to-line stem	1.7 (2.1, 0.0 to 12.0)	4	1.2 (1.7, 0.0 to 8.8)	3	0.9 (1.4, 0.0 to 8.2)	1

*Mean (SD, range).
†Number of outliers (distance > 5 mm) out of 49 subjects.
‡Difference in offset and leg length (mean of absolute values (SD, range)) in mm.
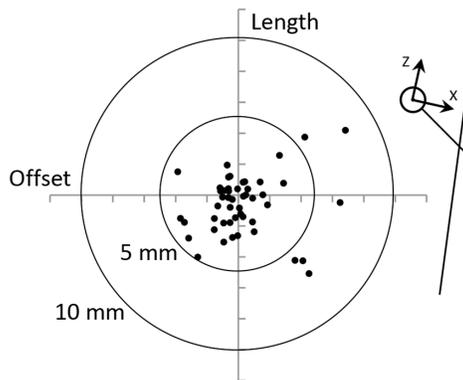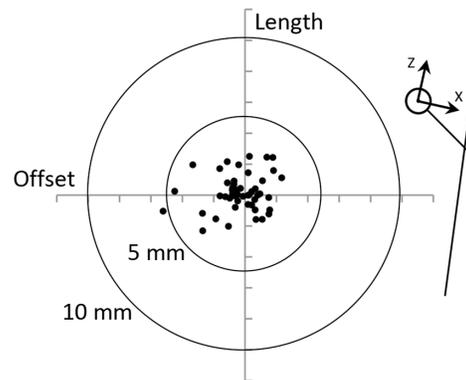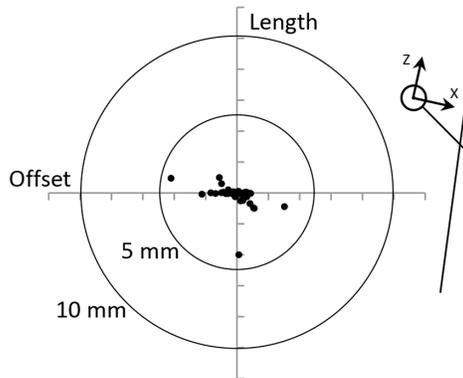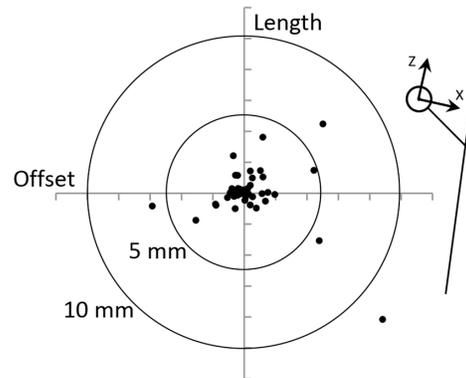
Fig. 4

Target plot representing the best possible restoration of the anatomical hip rotation centre using different stem systems. The inner circle represents 5 mm from the target, the outer centre 10 mm. As a left hip was used, left represents increased offset and up represents lengthening of the leg.

There was only one outlier (uncemented straight stem: 6.1 mm).

Target plots (Figure 4) show how each hip system restored offset (x-axis) and leg length (z-axis). Uncemented calcar-guided stems were less successful in restoring offset than cemented undersized stems (p = 0.009, ANOVA; Tukey's HSD pairwise tests). Other comparisons were not significant (Table V). Offset could be restored within 5 mm in 96.9% of the simulations and this did not differ between hip systems (p = 0.329, chi-squared test).

Overall, mean leg length discrepancies and differences between hip systems were small (Table V). Cemented undersized stems performed best, while uncemented calcar-guided stems performed worst (p < 0.001, ANOVA; Tukey's HSD pairwise tests). Leg length could be restored within 5 mm in 99.0% of cases and this did not differ between hip systems (p = 0.568, chi-squared test).

Restoring the medialized hip rotation centre. All hip systems restored the medialized rotation centre within a mean of 3.2 mm and within 5 mm in 91.8% of the simulations (Table VI). Uncemented calcar-guided stems

Table VI. Distance and difference in offset and leg length between the medialized and the restored hip rotation centre for the four hip systems.

Stem type	Distance, mm*	Distance > 5 mm†	Δ offset, mm‡	Δ offset > 5 mm†	Δ leg length, mm‡	Δ leg length > 5 mm†
Uncemented calcar-guided stem	3.1 (2.5, 0.4 to 11.6)	8	2.4 (2.3, 0.0 to 11.5)	6	1.5 (1.5, 0.0 to 7.2)	2
Uncemented straight stem	1.9 (1.3, 0.2 to 6.8)	1	1.2 (1.2, 0.1 to 6.4)	1	1.1 (0.9, 0.1 to 4.9)	0
Cemented undersized stem	1.2 (1.6, 0.1 to 8.1)	2	1.0 (1.5, 0.0 to 8.0)	2	0.5 (0.5, 0.0 to 2.0)	0
Cemented line-to-line stem	2.6 (2.5, 0.1 to 11.1)	5	1.9 (2.2, 0.1 to 10.9)	3	1.4 (1.5, 0.0 to 5.8)	1

*Mean (SD, range).
†Number of outliers (distance > 5 mm) out of 49 subjects.
‡Difference in offset and leg length (mean of absolute values (SD, range)) in mm.
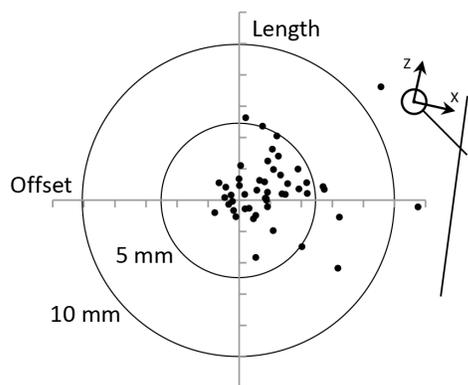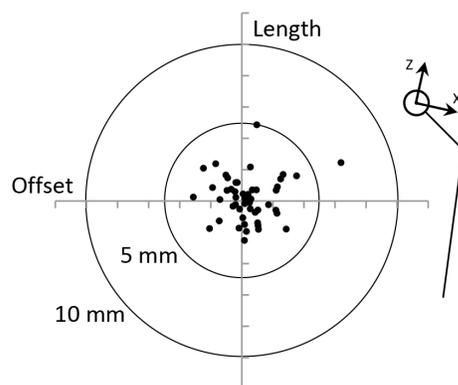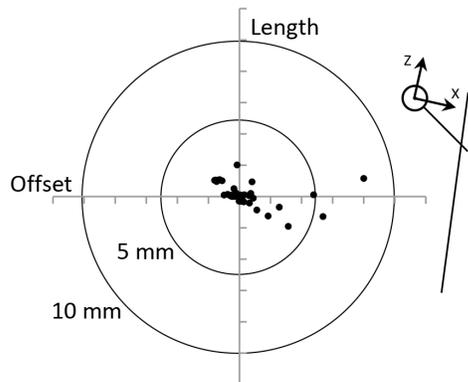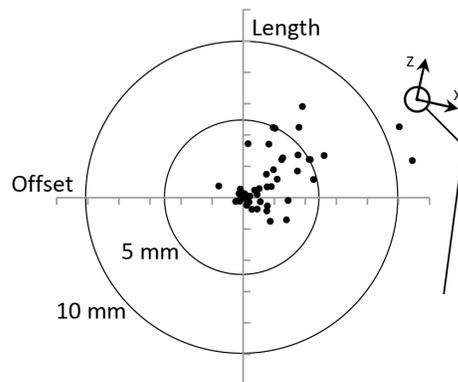
Fig. 5

Target plot representing the best possible restoration of the medialized hip rotation centre using different stem systems. The inner circle represents 5 mm from the target, the outer centre 10 mm. As a left hip was used, left represents increased offset and up represents lengthening of the leg.

had more outliers than the other systems (p = 0.043, chi-squared test; p = 0.016, post-hoc analysis with adjusted residuals). Other comparisons were not significant (all p > 0.071, post-hoc analysis with adjusted residuals). Cemented undersized stem restored the medialized rotation centre more accurately than both uncemented calcar-guided and cemented line-to-line stems (p < 0.001, ANOVA; Tukey's HSD pairwise tests)

The anteroposterior distance between targeted and achieved rotation centres (y-axis) was small (mean (absolute value): 0.2 mm (SD 0.4)), did not exceed 5 mm, and

was not significantly different between hip systems (p = 0.129, ANOVA).

Uncemented calcar-guided stems were less successful in restoring offset than cemented undersized and uncemented straight stems (p = 0.001, ANOVA; Tukey's HSD pairwise tests) (Figure 5, Table VI). Offset could be restored within 5 mm in 93.9% of cases, with no significant differences between hip systems (p = 0.174, chi-squared test).

Mean leg length discrepancy and differences between hip systems were small (Table VI). Cemented undersized

Table VII. CT scan-based measurements of femoral offset.

Study	Number of cases	Femoral offset, mm	Offset range, mm
This study	49	Anatomical 30.2 to 53.1; Medialized 35.2 to 58.1	Within one group 23.9; Overall 28.9
Yi et al[14] (2019)*	100	Average: 38.4 in male Average: 35.6 in female	SD: 4.7 in male SD: 4.4 in female
Wegrzyn et al[12] (2018)	151	Average: 45	SD: 5
Wells et al[13] (2017)†	50	Average: 37	SD: 4
Dimitriou et al[15] (2016)	61	Average: 37.6	SD: 5.2
Arnould et al[16] (2015)	75	32 to 54	22
Terrier et al[4] (2014)	15	32 to 55	23
Merle et al[9] (2014)	345	26.9 to 66.2	39.3
Lechler et al[17] (2014)	25	34 to 71	37
Preininger et al[10] (2012)	200	28 to 54	26
Atkinson et al[8] (2010)	100	37 to 68	31
Pasquier et al[18] (2010)	61	31 to 55	24
Sariali et al[11] (2009)	223	32 to 59	27

*In Chinese population.
†Dysplastic hips.
SD, standard deviation.

stems performed better than other systems (p < 0.001, ANOVA; Tukey's HSD pairwise tests). Leg length could be restored within 5 mm in 98.5% of cases with no significant differences between hip systems (p = 0.293, chi-squared test).

Anatomical versus medialized hip rotation centres. Overall, it was easier to restore hip rotation centres and offsets in the anatomical compared to the medialized situation (p < 0.001, both one factor repeated ANOVA). However, mean differences were small (0.5 mm (SD 2.1) and 0.5 mm (SD 1.9), respectively) and differences were only significant for uncemented calcar-guided and cemented line-to-line stems (p < 0.034, all paired t-tests).

All but uncemented calcar-guided stems restored leg length better when aiming at the anatomical compared to the medialized rotation centre (p < 0.001, one factor repeated ANOVA). Similarly, differences were small (0.2 mm (SD 1.4)) and only significant for cemented line-to-line stems (p = 0.037, paired t-test).

Discussion

This study investigated how four femoral hip systems could restore anatomical and a 5 mm medialized hip rotation centres. Based on 392 simulations in 49 femora, we concluded that all systems could restore both rotation centres within 5 mm in the majority of none deformed femora (83.7% to 100%). As such, in the absence of major deformity, failure to restore hip anatomy is generally attributable to surgical inaccuracy, rather than lack of femoral implants. Therefore, in most cases, the need for modular necks is questionable. This is confirmed in a clinical study without computer navigation,[20] where neck modularity did not improve leg length discrepancy or offset restoration.

Overall, medialized hip rotation centres were more difficult to restore than anatomical ones, and offset was more difficult to restore than leg length. To reconstruct medialized rotation centres, we used more lateralized stems and longer necks. However, stem sizes were similar.

The cemented undersized stem with three offset options restored both rotation centres most accurately. Several undersized cemented polished tapered stems showed similar good results in a 2D templating study.[24] This was attributed to the freedom of stem positioning within the cement and the three offset options of our stem. Moreover, the horizontal neck-shaft angle (120° to 125°) produced a within-size and global offset range up to 18 mm and 30 mm, respectively. Yet, that offset range remained low compared to our population, especially when aiming at the medialized rotation centre (Figure 2).

The uncemented straight stem with two offset options performed well despite a smaller within-size and overall offset range. Mandatory cortical bone contact restricted insertion positions, but this was not a problem as the offset range was right within the targeted range (Figure 2). In our study, we used 63.3% of standard stems (Figure 3) and this compares well to clinical practice (75.5%).[25]

The cemented line-to-line stem with proportional offsets performed less well due to small within-size and overall offset ranges. Moreover, only 17 stem sizes were available and line-to-line cementing restricted stem positioning. This resulted in 10% of outliers and could have clinical consequences.[3] Additionally, we found proportional offset options more difficult to template.

The short uncemented calcar-guided stem underperformed in restoring both rotation centres. Moreover, the medialized rotation centre had 16% of outliers. These findings are surprising, as the system has the largest number of stem sizes (24) and, the largest (38 mm) well-distributed offset range (Figure 2). We believe this is due to their need for calcar contact. 2D templating studies suggested that a varus insertion in a varus hip, and a valgus insertion in a valgus hip, could favour offset reconstruction in extreme cases.[26,27] However, preserving the neck and maintaining close calcar contact limited control of insertion depth along the femoral axis. As such, it was more difficult to manage leg length and fine-tune offset by varying neck length as we did with the other systems. In clinical practice, calcar-guided stems can cause relevant offset and/or leg length discrepancies,[7,26] and intra-operative radiographs are mandatory.[28] On the other hand, the short-curved Fitmore stem (ZimmerBiomet, USA), with four neck-shaft angles and 14 sizes each, achieved a better combined offset and leg length reconstruction compared to straight stems.[20] Moreover, in a comparative series of 100 patients,[7] short stems restored offset better than standard stems. However, the accuracy

achieved during surgery was inferior to that of our simulations. This suggests that surgical technique could be the weak link, and more so for standard stems than for calcar-guided stems.[7]

Nevertheless, difficulties to restore hip anatomy with short calcar-guided stems should be addressed during implant design. These stems could benefit from a larger choice of sizes, a larger within-size offset range and more neck length options. In 12% to 16% of outliers, modular necks could be considered. However, issues with stem-neck junctions should be tackled first. Alternatively, a cemented version of the stem could improve implantation freedom, making stem positioning less dependent on calcar contact.

Although we aimed at realistic simulations, our study suffers from weaknesses. Firstly, we templated a limited number of healthy hips. Osteoarthritic hips could differ in morphology and deformity was not included. However, our hips had offsets within the range found in literature, excluding extreme cases (Table VII). Secondly, we cannot be sure that our simulations are reproducible in clinical practice. However, CT scan-based 3D templating has proven reliable,[29,30] and virtual implantations were fine-tuned by an experienced hip surgeon (TS) and were agreed on by two doctors (TS, EDW). Although the hip surgeon had clinical experience with three of the hip systems, he lacked experience with the uncemented calcar-guided stem that performed less well. We also templated with 36 mm ceramic heads and with an accuracy that would be difficult to achieve in clinical practice.[7,26] We realize that some patients might have a cup size that would not accept large heads. However, we chose to use the largest range of neck lengths, avoiding skirted heads. Thirdly, we only investigated four hip systems. As such, our results cannot be extrapolated to other designs. However, we chose four different implantation and sizing philosophies, trying to cover the most commonly used implantation strategies.

In conclusion, based on 3D templating with four stem types, we could restore the anatomical and medialized hip rotation centre within 5 mm in 83.7% to 100% of non-deformed hips. As such, failure to restore anatomy is often due to surgical inaccuracy rather than lack of implants and, modular necks are not needed in most cases.

Cemented undersized and uncemented straight stems performed best. Small uncemented calcar-guided stems presented no advantage, on the contrary. We hypothesize that the close calcar contact needed for stability limited stem positioning and was unfavorable. However, that same lack of freedom, combined with a large number of implant sizes, could explain good results in clinical practice.

We advise templating, especially when using calcar-guided stems. If, based on templating, hip anatomy cannot be restored, another hip system should be considered. Otherwise, surgeons should focus on reproducing the preoperative plan as that is probably the weakest link.

Take home message

- Cemented and uncemented hip implants allow to restore offset, leg length, and anteversion in the vast majority of non-deformed hips. Modular hip implants are not needed in the majority of cases.
- Undersized cemented stems with three offset options perform best in restoring hip biomechanics.
- Small calcar guided stems do not offer an advantage compared to standard implants, on the contrary, failure to restore hip biomechanics is more often due to surgical inaccuracy than lack of implants.

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