

Value of preoperative three-dimensional planning software (AI-HIP) in primary total hip arthroplasty: a retrospective study

Xuzhuang Ding*, Bingshi Zhang*, Wenao Li, Jia Huo, Sikai Liu, Tao Wu and Yongtai Han 

Abstract

Objective: We performed a retrospective study to compare the accuracy of preoperative planning using three-dimensional AI-HIP software and traditional two-dimensional manual templating to predict the size and position of prostheses. The purpose of this study was to evaluate the accuracy of AI-HIP in preoperative planning for primary total hip arthroplasty.

Methods: In total, 316 hips treated from April 2019 to June 2020 were retrospectively reviewed. A typical preoperative planning process for patients was implemented to compare the accuracy of the two preoperative planning methods with respect to prosthetic size and position. Intraclass correlation coefficients (ICCs) were used to evaluate the homogeneity between the actual prosthetic size and position and the preoperative planning method.

Results: When AI-HIP software and manual templating were used for preoperative planning, the stem agreement was 87.7% and 58.9%, respectively, and the cup agreement was 94.0% and 65.2%, respectively. The results showed that when AI-HIP software was used, an extremely high level of consistency ($ICC > 0.95$) was achieved for the femoral stem size, cup size, and femoral osteotomy level ($ICC = 0.972, 0.962, \text{ and } 0.961$, respectively).

Conclusion: AI-HIP software showed excellent reliability for predicting the component size and implant position in primary total hip arthroplasty.

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Keywords

Total hip arthroplasty, AI-HIP software, artificial intelligence, preoperative planning, three-dimensional planning, implant

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Introduction

Arthroplasty is one of the most effective treatments for end-stage hip joint disease. An accurate preoperative evaluation can lead to better integration of the bone and prosthesis.^{1,2} Moreover, it can shorten the operation time; reduce intraoperative and postoperative complications such as bleeding, dislocation, prosthetic loosening, and fracture around the prosthesis; prolong the survival time of the prosthesis; accelerate recovery; and reduce the length of stay, cost of hospitalization, and legal issues arising from medical disputes.^{3–5} At present, two-dimensional (2D) templates are mostly used in clinical practice because of their simple operation; however, their accuracy is low because of the influence of X-ray magnification and the projection position.^{6,7} Although the accuracy of three-dimensional (3D) preoperative planning is clearly better than that of 2D planning, 3D software requires a long training time, and the operation steps are complex and not widely used in many hospitals. Many measurement methods of varying accuracy are available for 2D and 3D preoperative planning.^{8–10} Computed tomography (CT)-based 3D preoperative planning has relatively stable intergroup and intragroup consistency¹¹ as well as strong repeatability and accuracy.¹² Representative software packages include ZedHip and ZedKnee (LEXI Co., Ltd., Tokyo, Japan)¹¹ and HIP-PLAN (Symbios Orthopédie SA, Yverdon-les-Bains, Switzerland).¹³ However, these software programmes require manual segmentation of hip CT images, which is

more complex than 2D preoperative planning software. AI-HIP software (Beijing Changmugu Medical Technology Co., Ltd., Beijing China) is a 3D programme based on CT data for image processing. It can be used to segment CT images through the combination of artificial intelligence deep learning technology and medical big data. This preoperative planning technology has started to become more widespread but has not been assessed systematically in the field of orthopaedics. The purpose of this study was to compare the accuracy of traditional 2D manual templating measurement and 3D AI-HIP software planning to predict the size and position of prostheses. In previous studies, the accuracy of femoral stem measurements by preoperative manual or digital templating was 30% to 90%, and that of acetabular cup measurements was 50% to 90%.^{8,14–17} In contrast, the accuracy of femoral stem measurements by 3D computerization was 84% to 100%, and that of acetabular cup measurements was 80% to 100%.^{10,18–21} The hypothesis of this study was that preoperative planning by AI-HIP software is more accurate than traditional 2D manual templating technology in predicting the prosthetic size and position.

Methods

Study population

This retrospective study was performed to compare the accuracy of the prosthetic size and position for several anatomical parameters between AI-HIP planning and

traditional manual templating planning before total hip arthroplasty (THA). The reporting of this study conforms to the STROBE guidelines.²² This study was approved by the Institutional Review Board of the Third Hospital of Hebei Medical University. All investigations were conducted in conformity with ethical principles of research. Because this was a retrospective study and all patient information was deidentified before analysis, informed consent was not required.

The implant position and prosthetic size were determined by the surgeon during the surgical procedure. The preoperative imaging data were obtained after THA. The initial sample size calculation was performed as follows. According to the literature, the effective rate of the manual template method is 30% to 90% (P_0 (null proportion)=0.90). The effective rate of AI-HIP software planning in pretesting is 95% (P_1 (alternative proportion)=0.95) when the test level (α) is set at 0.05 and the permission error is set at 0.1. The required sample size calculated by PASS Software version 15.0 (NCSS LLC, Kaysville, UT, USA) was determined to be 292 patients. The number of patients included in this study ($n=316$) exceeded this value; thus, the sample size requirement for this study was met. Patients who underwent unilateral primary THA at the hip arthroplasty centre of the Third Hospital of Hebei Medical University from April 2019 to June 2020 were included. The inclusion criteria were an age of >18 years and use of a Tri-Lock femoral stem (DePuy Synthes, Raynham, MA, USA) in the primary THA. The exclusion criteria were an age of <18 years, lack of complete medical records or radiological images, complications (e.g., dislocation, infection, periprosthetic fracture, prosthesis loosening) during follow-up, and performance of hemiarthroplasty surgery. According to the above criteria, the study cohort comprised 316

patients (150 left hips, 166 right hips). We also recorded demographic characteristics such as the preoperative necrosis stage, sex, age, body mass index, and preoperative comorbidities.

Study design

All preoperative imaging examinations included an anteroposterior pelvic film and true lateral images of the hip joint, splices of the lower limbs, and a CT scan of the hip joint from the anterior superior iliac spine to the inferior trochanter of the femur at 10 cm. We measured the position of the prosthesis postoperatively on the X-ray film (Figure 1). A low-dose CT scan (SOMATOM Sensation 128; Siemens Healthineers, Erlangen, Germany) was performed. The images were anonymized before analysis. Every hospitalized patient underwent bone mineral density (BMD) examination by dual-energy X-ray. We used the t value as the main observation index for the BMD. All operations were performed via a posterolateral approach by the same group of surgeons. According to the Tri-Lock stem joint prosthesis (DePuy Synthes), the surgeon could use 13 sizes of femoral stems (0–12, intervals of 1) and 10 sizes of acetabular cups (44–62 mm, increments of 2 mm). At an average of 6 months after THA, we implemented a typical preoperative planning process. Anonymous preoperative radiographs were used for planning by both conventional manual templating and AI-HIP software. All preoperative planning and imaging measurements were completed by the same experienced orthopaedic surgeon. Two measurements were obtained, and the average value was taken as the final recorded result. To test the intraobserver reproducibility, the surgeon performed all radiographic measurements in five randomly selected patients and repeated these measurements after 2 weeks. The intraclass

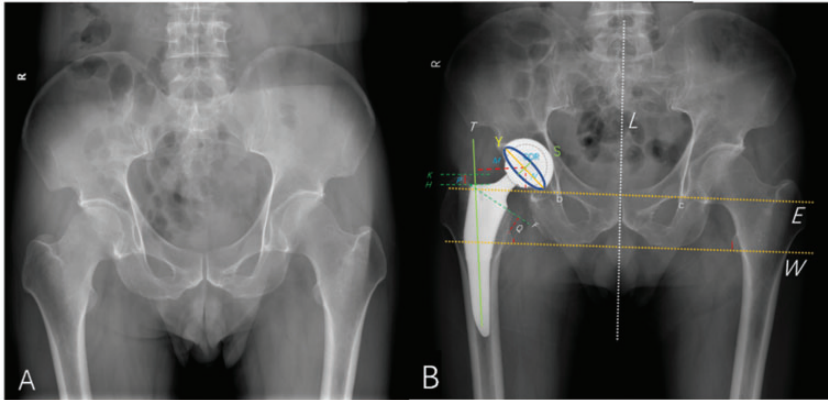


Figure 1. A 62-year-old man with necrosis of the right femoral head (Association Research Circulation Osseous stage 3). The patient underwent total hip arthroplasty. (a) Preoperative anteroposterior view. (b) Postoperative anteroposterior view with different measurement parameters. Point COR is the rotational centre of the femoral head. Points b and c are the teardrops. Line E is the connection between the teardrops. Line W is the connection of the ischial tubercle. Line M is the femoral offset. Line N is the height of the rotational centre. Line P is the shortest distance from the apex of the prosthesis to the apex of the greater trochanter, which represents the depth of the femoral component. Line F is the osteotomy line. Line Q is the shortest distance from the apex of the lesser trochanter to the position of the femoral neck osteotomy. Line S is the semi-minor axis. Line Y is the semi-major axis. The anteversion angle of the acetabular cup = $\arcsin S/Y$.

correlation coefficient (ICC) was used to assess intraobserver reliability. The results showed good reliability (ICC of >0.9 in all measurements). The prosthesis sizes and relevant parameters were recorded, including the level of the rotational centre (height of rotational centre = vertical distance from femoral head rotation centre to teardrop line), abduction angle and anteversion of the acetabulum, femoral osteotomy level (vertical distance from apex of lesser trochanter to position of femoral neck osteotomy), depth of the femoral component (distance from apex of prosthesis to apex of greater trochanter), femoral offset, and limb length discrepancy.

Preoperative planning by AI-HIP software

AI-HIP software was used for preoperative planning as follows. First, a CT image database of hip diseases was established, and a deep learning neural network was trained

for the segmentation module and 3D recognition module. Second, the original CT data of each patient in this study were inputted into the segmentation module and 3D recognition module. The pelvis and femur of each patient were divided into two parts by the segmentation module. Third, the anatomical point recognition module used the point recognition neural network of pattern recognition technology to accurately calculate the coordinates of the corresponding points, locate the key points on the bone, and output the coordinates of points such as the lesser trochanter, greater trochanter, teardrop, and anterior superior iliac spine. Finally, an automatic search engine based on a database and deep learning was used to match the optimal prosthesis and intelligently plan the perfect results.

1. Collection and establishment of CT image database of the hip joint. Hip joint CT image data were collected from more

than 2000 cases, including femoral head necrosis, femoral neck fracture, hip dysplasia, compulsory spondylitis involving both hips, other diseases, and normal hip joints. The CT scan ranged from the upper edge of the pelvis to 10 cm below the lesser trochanter of the femur, and the slice thickness was 1 mm. During shooting, the patient was in the supine position with the body in the middle of the bed surface, both thighs rotated inward, and the two toes close together. All patients' personal information was removed before inclusion in the database, and only imaging data were retained.

2. **Training of the deep learning neural network** (Figure 2). A net neural network introduced a 2D dense block structure based on the UNET model to improve the segmentation accuracy. By manually segmenting CT images with typical features of hip diseases, the contours of the hip and femoral head were manually depicted. After repeated training, the neural network could accurately identify and automatically segment the

acetabulum and femoral head. The neural network was then trained separately for different diseases, which corresponded to different segmented neural networks to achieve segmentation of different types of diseases. In the process of neural network training, a large number of anatomical position feature points were manually marked; these mainly included the anterior superior iliac spine of the pelvis, symphysis pubis, lesser trochanter of the femur, and greater trochanter of the femur. After detailed learning through artificial intelligence, the neural network could accurately identify anatomical sites and intelligently calculate important preoperative anatomical parameters of the patients.

3. **Construction of database of frequently used hip joint prostheses.** The acetabular cup, ball head, inner liner, and femoral stem of THA were collected and transformed into a 3D model by reverse engineering to build the THA prosthesis database. The PINNACLE cup, Tri-Lock stem, SUMMIT stem, and CORAIL stem (all manufactured by

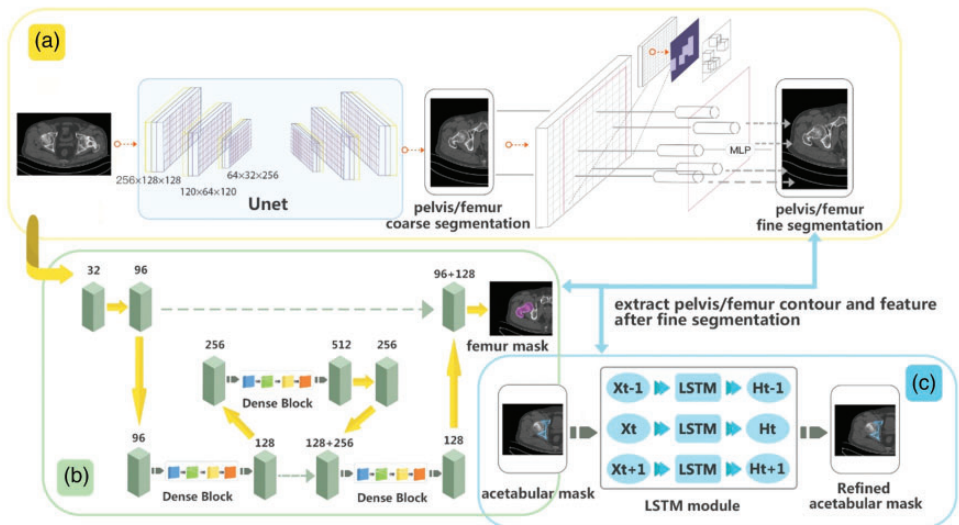


Figure 2. Schematic of the independently developed G-NET neural network for hip joint segmentation.

DePuy Synthes) were included in the database.

4. Outputting of the whole set of intelligent THA surgery plans.

The specific steps were as follows. A plain CT scan of the pelvis was acquired before the operation. The image was exported in DICOM file format. By importing the anonymous DICOM data into AI-HIP software, three-axis linkage and 3D reconstruction imaging could be generated automatically. The software utilized the algorithm to automatically remove the influence of impurities, accurately display the bone, and accurately achieve the three-axis linkage of three windows (Figure 3).

The acetabulum and femur were intelligently segmented using the above trained G-Net to achieve artificial intelligence segmentation of the acetabulum and femoral head. Next, through the increase in the

region, the region-growing algorithm was used to completely separate the pelvis and femur. This allowed for clear observation of the shape and defect of the femoral head and acetabulum and preparation for the next step of prosthesis placement (Figure 4).

Artificial intelligence can learn a large number of manually labelled feature points and automatically identify the related anatomic positions of the affected hip (mainly the anterior superior iliac spine of the pelvis, pubic symphysis, lesser trochanter of the femur, and greater trochanter of the femur) and automatically measure the acetabular diameter, femoral medullary cavity diameter, femoral neck–stem angle, and other parameters. According to the anterior pelvic plane composed of the bilateral anterior superior iliac spine and pubic symphysis, we were able to automatically identify the hip-related anatomical

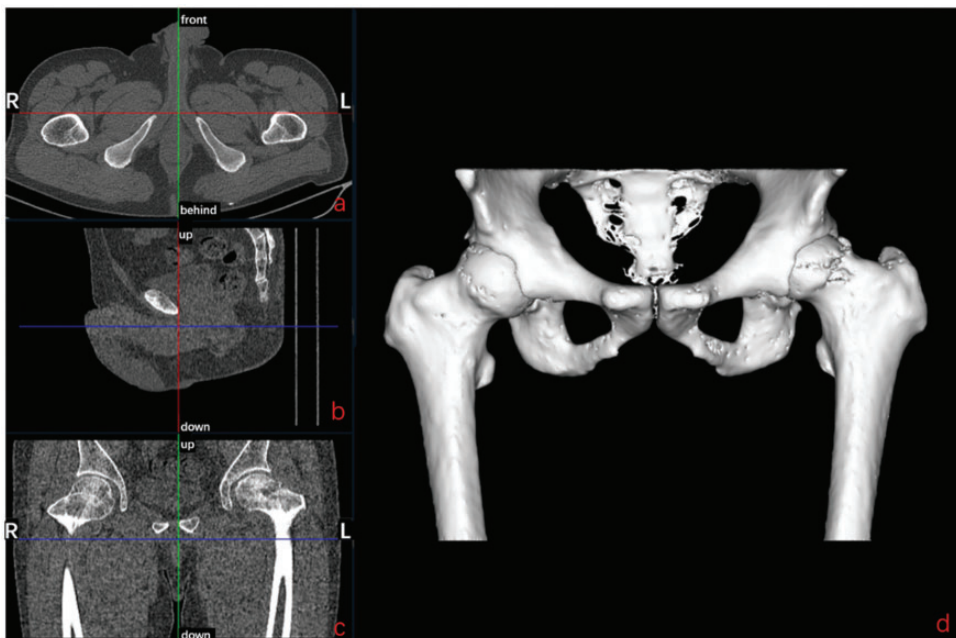


Figure 3. Three-dimensional reconstruction of the hip joint with views of the transverse section, sagittal plane, and coronal plane. (a) Transverse axial plane. (b) Sagittal axial plane. (c) Coronal axial plane. (d) Three-dimensional reconstruction.

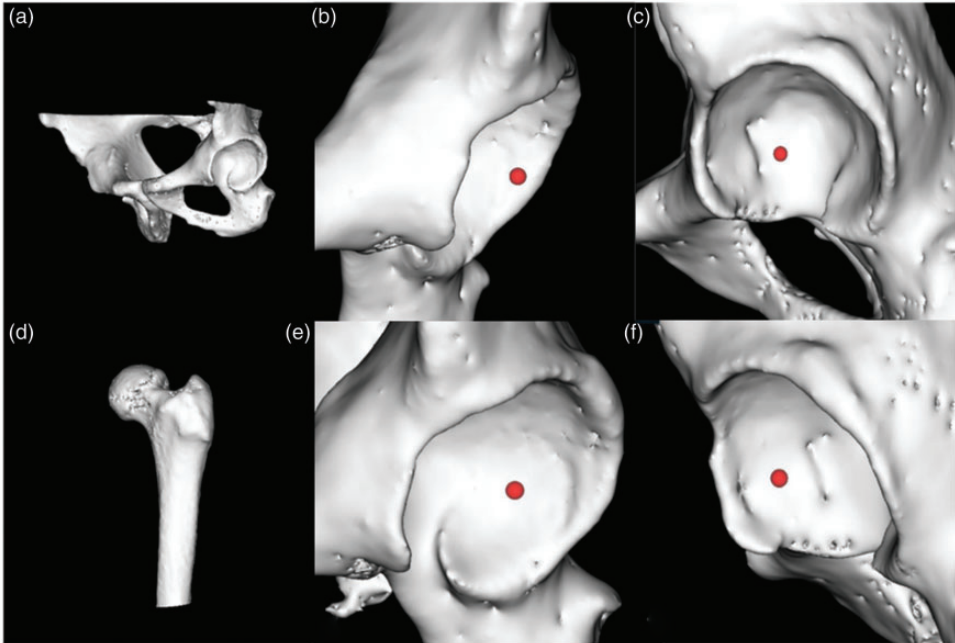


Figure 4. Segmentation result of the G-NET neural network. The red point represents the rotating centre of the femoral head. (a) Acetabular bone with intelligent segmentation. (b) Femoral bone with intelligent segmentation. (c–f). Acetabular morphology from different perspectives.

positions. The pelvis was corrected to the neutral position to prepare for matching the prosthesis model and angle according to the identified anatomical site. The preoperative femoral offset, combined offset, and leg length discrepancy were calculated to provide a reference for the surgeons (Figure 5).

Several landmarks were demarcated on the acetabular side of the CT image. The landmarks were fitted into a sphere with the radius of the acetabulum, and the type of prosthesis was determined according to this value. By training the artificial intelligence neural network system, the position and size of the cup were automatically recognized based on learning the artificial mark point. After the pelvic correction was completed in the early stage, the acetabular cup prosthesis was placed with abduction of 45° and anteversion of 15°

according to the pelvic coordinate system after correction. The contour line of the imported prosthesis was displayed on the original CT image. The planner could fine-tune the position, model, and angle of the cup prosthesis as needed. According to the coverage of bone on the surface of the cup prosthesis, the system calculated and displayed the bone coverage rate of the cup prosthesis in real time through the coincidence rate of the prosthesis and bone (Figure 6).

Based on the diameter of the medullary cavity, the appropriate femoral stem was matched according to the length difference of the lower limbs and the eccentricity before and after the operation. After the position of the femoral stem rotation centre was determined, the femoral stem rotation centre and the cup rotation centre were intelligently matched, and the femoral

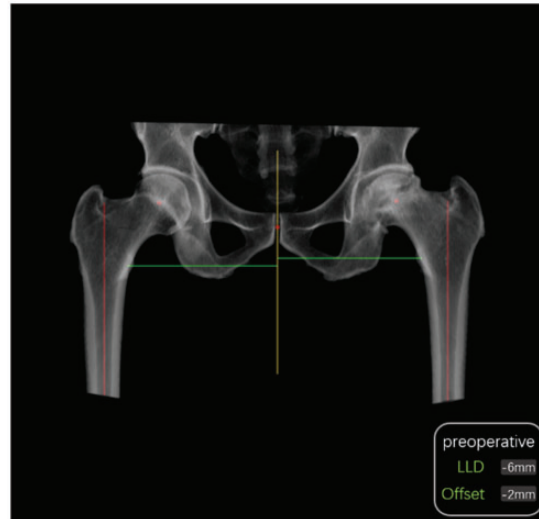


Figure 5. Automatic correction of the pelvis and measurement of the leg length discrepancy and the combined offset.

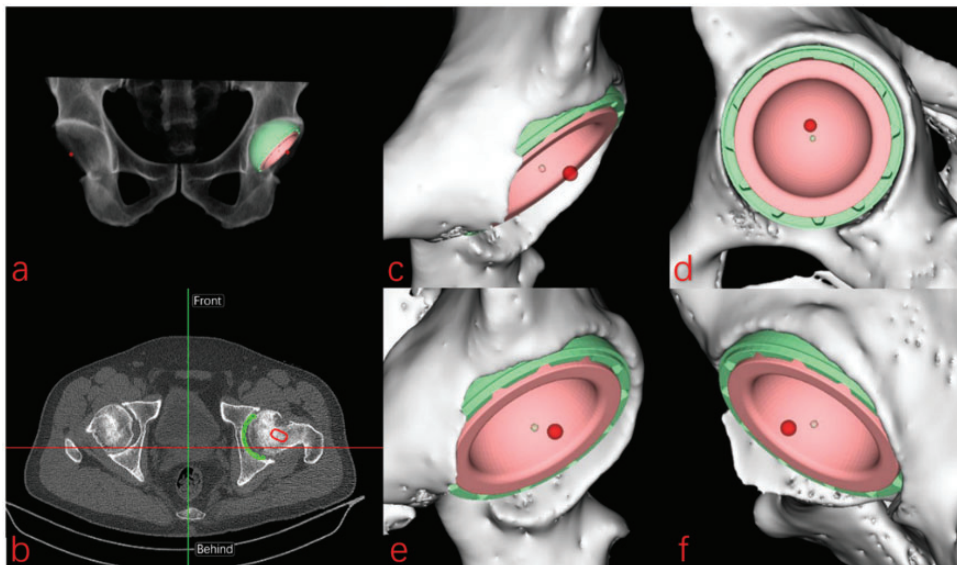


Figure 6. Prediction of the best position for the acetabular prosthesis. The red point represents the rotating centre of the femoral head. (a) Intelligent placement of acetabular cup prosthesis. (b) Transverse axial plane of computed tomography scan. (c–f) Acetabular cup from different perspectives.

stem prosthesis contour was displayed on the original CT image. The planner could adjust the position, model, and varus angle of the femoral stalk as needed. According

to the changes in anatomic landmarks identified in the early stage, the joint eccentricity and leg length difference of both lower limbs after femoral stem prosthesis

placement were calculated in real time and displayed (Figure 7).

After the femoral prosthesis was placed, the affected femur was subjected to simulated osteotomy according to the prosthesis osteotomy line. The planner could adjust the position of the prosthesis before the osteotomy to adjust the height and angle of the osteotomy. During the osteotomy, the height from the osteotomy line to the upper edge of the lesser trochanter was displayed in real time (Figure 8). Finally, preoperative planning was completed, and several significant related parameters were displayed.

Preoperative planning by regular manual templating

All patients who underwent regular manual templating were evaluated by anteroposterior views of the pelvis and hip, anteroposterior radiographs of the lower limbs, and a true lateral view of the hip before surgery and at 6 weeks postoperatively. All X-rays were performed in our department on the same calibrated X-ray machine with the same patient in a standardized standing position. The X-ray magnification was determined. The operator performed manual planning according to the traditional film manual

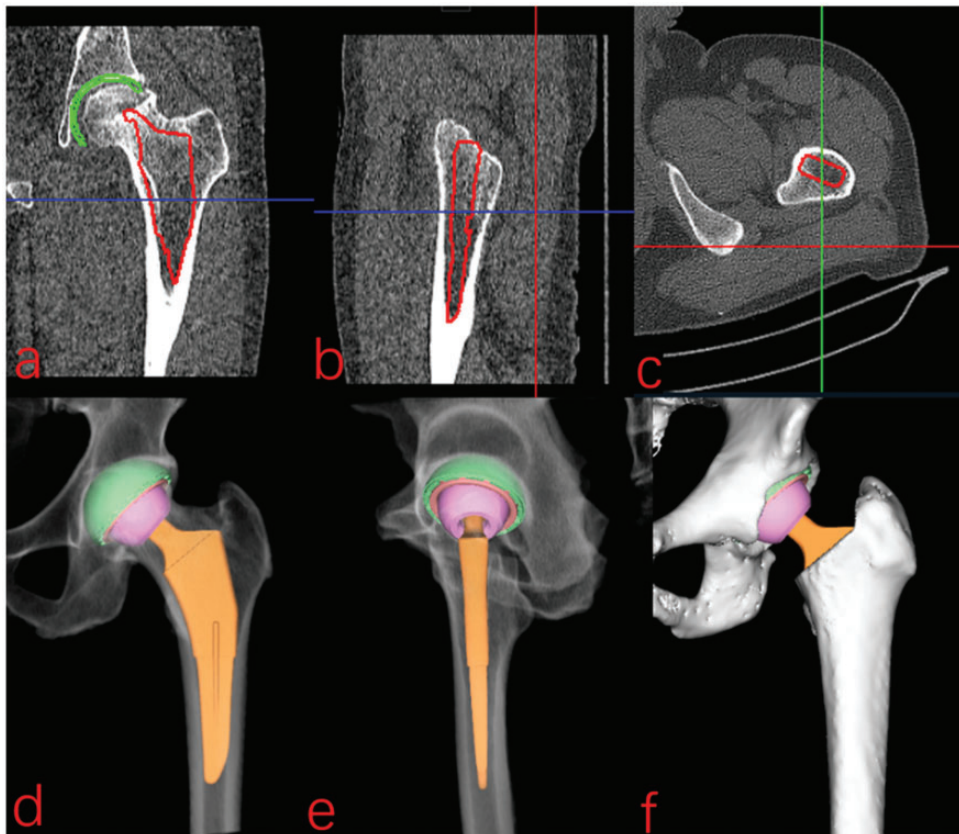


Figure 7. Prediction of the best position for the femoral prosthesis. (a) Coronal axial plane. (b) Sagittal axial plane. (c) Transverse axial plane. (d) Anteroposterior view of femoral component placement. (e) Lateral view of femoral component placement. (f) Complete simulation of femoral stem placement.

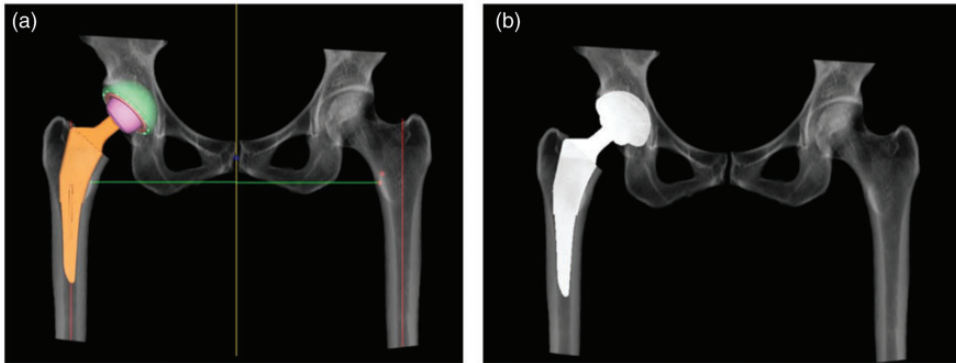


Figure 8. The final result of the preoperative plan. (a) AI-HIP software planning. (b) AI-HIP software planning with X-ray.

templating measurement method; the measurements included the prosthetic size and related indices such as the level of the rotational centre, abduction angle and anteversion of the acetabulum, femoral osteotomy level, depth of the femoral component, femoral offset, and limb length discrepancy.

Preoperative planning evaluation index

The numbers of prostheses of different sizes and with different femoral conditions (such as different BMDs or different Dorr types) among those preoperatively planned and those actually used were counted. Planning was considered “correct” if the planned size of the femoral stem and acetabular cup was completely consistent with the actual application size. If the planned size was within ± 1 size, it was considered “accurate”; otherwise, it was considered inaccurate. The deviation of certain preoperatively planned parameters from the actual postoperative plan was calculated (level of the rotational centre, abduction angle and anteversion of the acetabulum, femoral osteotomy level, depth of the femoral component, femoral offset, and limb length discrepancy). The consistency of the component sizes and related parameters, such as the level of the rotational centre, abduction angle and anteversion of the

acetabulum, femoral osteotomy level, depth of the femoral component, femoral offset, and limb length discrepancy, was compared.

Statistical analyses

Statistical analyses were performed using IBM SPSS Statistics for Windows, Version 24.0 (IBM Corp., Armonk, NY). Continuous variables are expressed as mean \pm standard deviation, and categorical variables are expressed as frequency. If the data followed a normal distribution, the characteristics were compared using Student’s t test; otherwise, a nonparametric test was used, such as the Mann–Whitney U test. The chi-square test was used for comparisons between categorical variables. The chi-square test was also used to assess the difference in accuracy when the two preoperative planning methods were used for the different BMDs and Dorr types. The patients were divided into several subgroups according to the BMD around the hip joint (normal BMD, T-score of -1 to 1 ; osteopenia, T-score of -2.5 to <-1 ; and osteoporosis, T-score of <-2.5) and Dorr classification (Dorr A, canal flare index of >4.7 to <6.5 ; Dorr B, canal flare index of 3.0 to 4.7 ; and Dorr C, canal flare index of <3.0). Chi-square tests were used to

compare the preoperative planning accuracy between these subgroups. To evaluate the prosthetic size and position reproducibility, the interobserver ICC was calculated for both planning techniques. In addition to the ICC, absolute differences in cup and stem size were evaluated.

A P value of <0.05 was considered statistically significant.

Results

Demographic information

In total, 316 patients (192 men and 124 women) were included in the study. The mean age at the time of the operation was 50.68 ± 12.64 years (range, 24–82 years), and the mean body mass index was 25.07 ± 3.20 kg/m² (range, 17.78–34.60 kg/m²). A total of 166 patients underwent surgery on the right side, and 150 patients underwent surgery on the left side. Of the 316 patients, 73 patients had hypertension, 21 had diabetes, 56 had cardiovascular disease, 12 had neurological disease, and 8 had rheumatism. The primary diagnosis was osteonecrosis of the femoral head in 234 hips, developmental dysplasia of the hip in 50, osteoarthritis in 10, ankylosing spondylitis in 7, rheumatoid arthritis in 8, and an old femoral neck fracture in 7. The patients' general information is shown in Table 1.

Evaluation of prosthetic size

In terms of acetabular component size selection, the acetabular component that was actually used included nine sizes (44–60 mm, increments of 2 mm). We found significant differences between AI-HIP planning and manual template planning ($P < 0.05$) when we used 44-, 46-, 48-, 50-, 52-, and 54-mm acetabular cups in the surgery. Most cases of increased agreement occurred when AI-HIP software was

Table 1. General information of patients undergoing total hip arthroplasty

General information	Values
Age, years	50.68 ± 12.64
Sex	
Male	192
Female	124
BMI, kg/m ²	25.07 ± 3.20
Side	
Left	150
Right	166
Diagnosis	
Osteonecrosis of the femoral head	234
Osteoarthritis	10
Old femoral neck fracture	7
Ankylosing spondylitis	7
Rheumatoid arthritis	8
Developmental dysplasia of the hip	50
Comorbidities	
Hypertension	73
Diabetes	21
Cardiovascular disease	56
Neurological disease	12
Rheumatism	8

N = 316. Data are expressed as n or mean \pm standard deviation.

BMI, body mass index.

used for preoperative planning (90.0% vs. 55.0%, 90.5% vs. 57.1%, 98.5% vs. 64.7%, 97.0% vs. 69.7%, 99.1% vs. 73.6%, and 88.5% vs. 53.8%). The other cup sizes were not significantly different between the two preoperative planning methods. In terms of femoral component size selection, the femoral component that was actually used included 13 sizes (0–12, intervals of 1). We found significant differences between AI-HIP planning and manual template planning ($P < 0.05$) when we used femoral stem sizes of 1, 2, 3, 4, 5, 6, and 7 in the surgery. Most cases of increased agreement occurred when AI-HIP software was used for preoperative planning (85.7% vs. 46.4%, 92.7% vs. 60.0%, 92.9% vs. 61.9%,

95.0% vs. 72.5%, 92.9% vs. 64.3%, 94.0% vs. 66.0%, and 83.3% vs. 43.3%). The other stem sizes were not significantly different between the two preoperative planning methods. Overall, there were significant differences in the complete agreement rate of the component sizes when AI-HIP software was used for preoperative planning: the stem showed 87.7% vs. 58.9% agreement, and the cup showed 94.0% vs. 65.2% agreement ($P < 0.05$). Detailed information regarding the evaluation of the prosthetic size between the two planning methods is shown in Table 2.

We found significant differences between AI-HIP planning and manual template planning ($P < 0.05$) when the patients showed a normal BMD, osteopenia, and osteoporosis. Increased agreement was found when AI-HIP software was used for stem preoperative planning (93.3% vs. 66.1%, 84.2% vs. 55.8%, and 76.8% vs. 42.9%). Similar to the BMD, an obvious advantage was observed when AI-HIP software was used for preoperative planning with the different proximal femur types determined according to the Dorr A, Dorr B, and Dorr C classification (91.7% vs. 58.3%, 92.7% vs. 64.1%, and 74.4%

Table 2. Comparison of stem and cup sizes between actual and planned results.

Component	Size	Actually used	AI-HIP agreement	Standard templating agreement	χ^2	P
Acetabular component						
	44 mm	20	18 (90.0%)	11 (55.0%)	6.144	0.013
	46 mm	21	19 (90.5%)	12 (57.1%)	6.035	0.014
	48 mm	68	67 (98.5%)	44 (64.7%)	25.926	<0.001
	50 mm	66	64 (97.0%)	46 (69.7%)	17.673	<0.001
	52 mm	106	105 (99.1%)	78 (73.6%)	29.122	<0.001
	54 mm	26	23 (88.5%)	14 (53.8%)	7.589	<0.001
	56 mm	4	1 (25.0%)	0 (0.0%)	1.143	0.285
	58 mm	4	0 (0.0%)	1 (25.0%)	1.143	0.285
	60 mm	1	0 (0.0%)	0 (0.0%)	–	–
	Total	316	297 (94.0%)	206 (65.2%)	80.657	<0.001
Femoral component						
	0	15	14 (93.3%)	10 (66.7%)	3.333	0.068
	1	28	24 (85.7%)	13 (46.4%)	9.639	0.002
	2	41	38 (92.7%)	25 (60%)	11.577	0.001
	3	42	39 (92.9%)	25 (61.9%)	12.863	<0.001
	4	40	38 (95%)	29 (72.5%)	7.440	0.006
	5	42	39 (92.9%)	27 (64.3%)	10.182	0.001
	6	50	47 (94.0%)	33 (66%)	12.250	<0.001
	7	30	25 (83.3%)	13 (43.3%)	10.335	0.001
	8	18	13 (72.2%)	8 (44.4%)	2.857	0.091
	9	4	0 (0%)	1 (25%)	1.143	0.285
	10	3	0 (0%)	1 (33.3%)	1.200	0.273
	11	1	0 (0%)	0 (0%)	–	–
	12	2	0 (0%)	1 (50%)	1.333	0.248
	Total	316	277 (87.7%)	186 (58.9%)	66.886	<0.001

N = 316; chi-square test. Statistically significant P values are indicated by boldface type. The concordance rate of components is shown in parentheses.

vs. 46.5%). We found that the precision of the stem for the medullary cavity of Dorr A and Dorr B femurs had increasingly similar results when AI-HIP planning was used. Detailed information regarding the evaluation of stem size with different BMDs and morphologies of the proximal femur (Dorr types) between the two planning methods is shown in Tables 3 and 4. AI-HIP planning showed significant differences among the three groups of different BMDs ($\chi^2 = 12.075$, $P = 0.002$). There was also a significant difference between the normal BMD and osteoporosis groups of patients when AI-HIP planning was used ($\chi^2 = 11.827$, $P = 0.001$). Similarly, there were significant differences among the three groups of different BMDs when template planning was used ($\chi^2 = 9.825$, $P = 0.007$). There was also a significant difference between the normal BMD and osteoporosis groups of patients when template planning was used ($\chi^2 = 9.394$, $P = 0.002$).

The stem size was planned within one size (within 2 mm) of the actual size in 298 of 316 (94.3%) patients who underwent

AI-HIP planning and in 250 of 316 (79.1%) patients who underwent manual templating ($P < 0.05$). The cup size was planned within one size (within 2 mm) in 308 of 316 (97.5%) patients who underwent AI-HIP planning and in 267 of 316 (84.5%) patients who underwent manual templating ($P < 0.05$). Stem size predictions were within two sizes for AI-HIP planning and within three sizes for manual templating planning. Cup size predictions were within two sizes for AI-HIP planning and within three sizes for manual templating planning. Detailed information is provided in Table 5.

Evaluation of prosthetic position

The estimated prosthetic positions of both preoperative planning methods were also investigated in this study, including the level of the rotational centre, abduction angle and anteversion of the acetabulum, femoral osteotomy level, depth of the femoral component, femoral offset, and limb length discrepancy. The level of the rotational centre was closer to the actual

Table 3. Comparison of accuracy of AI-HIP and templating planning with different BMDs of patients.

BMD	Number of patients	AI-HIP agreement*	Template agreement [#]	χ^2	P
Normal BMD	165	93.3% (154/165)	66.1% (109/165)	37.924	<0.001
Osteopenia	95	84.2% (80/95)	55.8% (53/95)	18.271	<0.001
Osteoporosis	56	76.8% (43/56)	42.9% (24/56)	13.410	<0.001
Total	316	87.7% (277/316)	58.9% (186/316)	66.866	<0.001

N = 316; chi-square test.

T-score = difference between BMD of tested person and peak value of bone in normal young people of same sex. Normal BMD, T-score of -1 to 1; osteopenia, T-score of -2.5 to <-1; and osteoporosis, T-score of <-2.5. The concordance rate of the component is shown in parentheses.

*The AI-HIP agreement was significantly higher in patients with normal BMD than in those with osteoporosis. The three groups with different BMDs were not all equal. AI-HIP planning showed significant differences for the three groups of different BMDs ($\chi^2 = 12.075$, $P = 0.002$). A P value of <0.05 was considered significant. There was a significant difference between the normal BMD and osteoporosis groups of patients when AI-HIP planning was used ($\chi^2 = 11.827$, $P = 0.001$). A P value of <0.0167 was considered significant.

[#]The template agreement was significantly higher in patients with normal BMD than in those with osteoporosis. The three groups with different BMDs were not all equal. Template planning showed significant differences among the three groups of different BMDs ($\chi^2 = 9.825$, $P = 0.007$). A P value of <0.05 was considered statistically significant. There was a significant difference between the normal BMD and osteoporosis groups of patients when template planning was used ($\chi^2 = 9.394$, $P = 0.002$). A P value of <0.0167 was considered statistically significant.

BMD, bone mineral density.

Table 4. Comparison of accuracy of AI-HIP and templating planning with different bone morphologies of the proximal femoral medullary cavity (according to Dorr classification).

Dorr classification	Number of patients	AI-HIP agreement*	Template agreement [#]	χ^2	P
Dorr A	24	91.7% (22/24)	58.3% (14/24)	7.111	0.008
Dorr B	206	92.7% (191/206)	64.1% (132/206)	49.889	<0.001
Dorr C	86	74.4% (64/86)	46.5% (40/86)	14.009	<0.001
Total	316	87.7% (277/316)	58.9% (186/316)	66.866	<0.001

N = 316, chi-square test.

Dorr A, canal flare index of >4.7 to <6.5; Dorr B, canal flare index of 3.0 to 4.7; and Dorr C, canal flare index of <3.0. The concordance rate of the component is shown in parentheses.

*The AI-HIP agreement was significantly higher for the Dorr B classification than the osteoporosis group. The three groups with different Dorr classifications were not all equal. AI-HIP planning showed significant differences for the three groups of Dorr classifications ($\chi^2 = 19.166$, $P < 0.001$). A P value of <0.05 was considered significant. There was a significant difference between patients with Dorr B classification and Dorr C classification when AI-HIP planning was used ($\chi^2 = 18.361$, $P < 0.001$). A P value of <0.0167 was considered significant.

[#]The three groups with different Dorr classifications were not all equal. Template planning showed significant differences among the three groups of Dorr classifications ($\chi^2 = 7.734$, $P = 0.021$). A P value of <0.05 was considered significant. There was a significant difference between patients with Dorr B classification and Dorr C classification when template planning was used ($\chi^2 = 7.734$, $P = 0.005$). A P value of <0.0167 was considered significant.

Table 5. Comparison of concordance rate of stem and cup sizes when planned and actual results were “accurate” or “inaccurate”.

Comparison	Stem		Cup	
	AI-HIP vs. surgery	Template vs. surgery	AI-HIP vs. surgery	Template vs. surgery
±0–1 size (Accurate)	298/316 (94.3%)	250/316 (79.1%)	308/316 (97.5%)	267/316 (84.5%)
±2–3 size (Inaccurate)	18/316 (5.7%)	66/316 (20.9%)	8/316 (2.5%)	49/316 (15.5%)
P	<0.001		<0.001	

N = 316, chi-square test. The concordance rate of the components is shown in parentheses.

position in the AI-HIP planning than in the regular manual template planning (0.611 ± 0.364 vs. 0.743 ± 0.534 mm, $P = 0.004$). AI-HIP planning also showed advantages over traditional manual templating in terms of the abduction angle ($0.576^\circ \pm 0.670^\circ$ vs. $1.104^\circ \pm 0.759^\circ$, $P = <0.001$) and anteversion ($0.184^\circ \pm 0.489^\circ$ vs. $0.601^\circ \pm 0.585^\circ$, $P = <0.001$) of the acetabular shell. In addition to preoperative planning for the acetabular component, AI-HIP could calculate the depth of the femoral stem (0.908 ± 1.014 vs. 1.341 ± 1.460 mm, $P = <0.001$) and osteotomy level ($0.747 \pm$

0.540 vs. 0.953 ± 0.511 mm, $P = <0.001$) more accurately than regular manual templating. The femoral offset, which indicates the force arm of the abductor, was also closer to the actual value in AI-HIP planning than in traditional manual templating (0.968 ± 1.210 vs. 1.133 ± 1.202 mm, $P = <0.001$). Finally, the limb length discrepancy could be more accurately estimated when AI-HIP planning was performed (0.470 ± 0.729 vs. 0.730 ± 0.740 mm, $P = <0.001$). Detailed information regarding the evaluation of the prosthetic position between the two planning methods is shown in Table 6.

Table 6. Comparison of position of prosthesis between actual used and planning results.

	AI-HIP vs. surgery	Template vs. surgery	Z	P
HRC	0.611 ± 0.364	0.743 ± 0.534	-2.917	0.004
Abduction angle of acetabulum	0.576 ± 0.670	1.104 ± 0.759	-9.158	<0.001
Anteversion of acetabulum	0.184 ± 0.489	0.601 ± 0.585	-10.314	<0.001
Depth of femoral component	0.908 ± 1.014	1.341 ± 1.460	-4.222	<0.001
FOL	0.747 ± 0.540	0.953 ± 0.511	-4.855	<0.001
Femoral offset	0.968 ± 1.210	1.133 ± 1.202	-4.274	<0.001
LLD	0.470 ± 0.729	0.730 ± 0.740	-9.525	<0.001

N = 316, Mann-Whitney U test.

AI-HIP vs. surgery = absolute value of the difference between AI-HIP and actual use.

Template vs. surgery = absolute value of the difference between regular templating and actual use.

HRC, height of rotational centre (vertical distance from the femoral head rotation centre to the teardrop line); FOL, femoral osteotomy level (vertical distance from the apex of the lesser trochanter to the position of the femoral neck osteotomy); LLD, limb length discrepancy.

Depth of femoral component = vertical distance from the apex of the greater trochanter to the shoulder of the femoral stalk.

ICCs between different preoperative planning methods

ICCs were used to evaluate the homogeneity between the actual prosthetic size and position and the preoperative planning method. The results showed an extremely high level of consistency ($ICC > 0.95$) regarding the femoral stem size ($ICC = 0.972$), acetabular cup size ($ICC = 0.962$), and femoral osteotomy level ($ICC = 0.961$) when AI-HIP planning was performed. A high level of consistency ($ICC > 0.90$) was also identified for the level of the rotational centre ($ICC = 0.909$), abduction angle ($ICC = 0.908$) and anteversion ($ICC = 0.924$) of the acetabulum, depth of the femoral component ($ICC = 0.911$), and femoral offset ($ICC = 0.916$) when AI-HIP planning was performed. Moreover, for regular manual template planning, a high level of consistency could be achieved only at the osteotomy level ($ICC = 0.941$). A moderate level of consistency ($ICC < 0.85$) was achieved in limb length discrepancies regardless of the planning method, but the ICC was higher when AI-HIP planning was performed. Generally, all

the ICCs for AI-HIP planning were higher than those for regular manual template planning. The ICCs of the two different planning methods are shown in Table 7.

Discussion

Preoperative planning is crucial for the success of THA and satisfactory postoperative hip joint function recovery, especially for junior surgeons and difficult patients.¹⁴ In our study, traditional manual templating based on plain X-ray examinations was compared with modern preoperative planning (i.e., 3D planning based on CT with artificial intelligence technology). Because similar reports are rare, only patients with satisfactory outcomes and correct prosthetic sizes and positions were included in this study. The criteria for “satisfaction” were a Harris score of >90 , Engh score showing good stability of the femoral prosthesis, good placement position of the prosthesis component of the femur and acetabulum in the postoperative X-ray image, and no complications (such as dislocation, infection, periprosthetic fracture, or prosthesis

Table 7. ICCs for the two methods.

	Cup	HRC	Abduction angle	Anteversion of acetabulum	Stem	Depth of femoral component	FOL	Femoral offset	LLD
AI-HIP planning	0.962	0.909	0.908	0.924	0.972	0.911	0.961	0.916	0.843
Templating planning	0.814	0.860	0.889	0.863	0.898	0.854	0.941	0.894	0.789

Data are presented as the ICCs.

Depth of femoral component = vertical distance from the apex of the greater trochanter to the shoulder of the femoral stalk.

ICC, intraclass correlation; HRC, height of rotational centre (vertical distance from the femoral head rotation centre to the teardrop line); FOL, femoral osteotomy level (vertical distance from the apex of the lesser trochanter to the position of the femoral neck osteotomy); LLD, limb length discrepancy.

loosening) in the postoperative follow-up. By investigating these patients, we were mainly concerned about the consistency between traditional manual templating and AI-HIP planning.

In contrast to other studies, we compared not only the consistency of the prosthesis size but also the position parameters of two different preoperative planning methods. Good prosthesis placement is important for patients to achieve long-term prosthesis survival. The contralateral side should be used as the standard for measurements of the operative side, and the activity of the contralateral hip joint should be restored as much as possible. Our results showed significantly higher consistency of both prosthetic size selection and prosthetic implantation position when AI-HIP planning was performed than when traditional manual templating was performed. This result indicates that preoperative planning using AI-HIP software might be more accurate than traditional preoperative manual templating. In terms of acetabular component planning, we found that AI-HIP software could accurately calculate the acetabular component diameter and implantation angle as well as the level of the rotation centre. These key parameters are crucial for the stability of the acetabular shell.²³ Moreover, appropriate acetabular component abduction and

anteversion angles help to maintain the stability of the hip joint prostheses and avoid dislocation. Our results demonstrated that the superiority of AI-HIP software in preoperative planning was reflected not only in the implantation of the acetabular prostheses but also in guiding the correct implantation of the femoral prostheses. In particular, the correct osteotomy position cup size and femoral stem size were chosen (ICC > 0.95). Therefore, the application of AI-HIP software for preoperative planning might help to decrease the incidence of intraoperative periprosthetic femoral fractures, which might be a consequence of the implantation of oversized stems or excessively deep stem implantation levels. Furthermore, in addition to accurate estimation of the medullary canal diameter and prosthetic size, calculation of the anteversion and Ranawat angle could also be accomplished using AI-HIP software. The latter might be crucial for reducing the incidence of postoperative dislocation. The stability of a prosthesis mainly includes two aspects: joint stability, which represents the potential incidence of joint dislocation after surgery, and implant stability, which represents the risk of prosthetic loosening. Joint stability is mainly determined via the angle of combination anteversion, and implant stability is assessed by the match between the bone socket and the prosthesis.

Our next research question concerned how AI-HIP software improves the accuracy of preoperative planning. It is very difficult to determine the transverse diameter of the acetabulum on regular anteroposterior X-ray films. However, using 3D reconstruction technology, AI-HIP software can accurately calculate the transverse diameter of the acetabulum. This ability is important for determining the acetabular component size intraoperatively. Besides its high consistency in acetabular component planning, AI-HIP showed great advantages when femoral component planning was performed. This might have occurred because when traditional manual templating is performed by 2D plain X-ray examination, the rotation of the lower limb can largely compromise the accuracy of preoperative planning.¹⁰ The anteversion of the femoral neck varied among different patients in the present study. A plain X-ray image is the projection of a 3D structure. The neck–shaft angle and the actual medullary canal diameter might be inaccurately estimated on plain X-ray films.²⁴ Furthermore, the variation in femoral neck anteversion in different populations imposes difficulty in achieving accurate calculations with the traditional manual templating method. However, this problem can be easily overcome with AI-HIP software because of its 3D capabilities.

When using AI-HIP software for common prosthetic components, the accuracy of the planned acetabular cup size is higher than the accuracy of the planned femoral stem size. We obtained a result analogous to that of other studies: The accuracy of the stem was slightly lower than that of the cup (87.7% vs. 94.0%). Two recent studies using CT methods showed extremely high accuracy in predicting the stem size (100%) and cup size (94%–96%).^{13,19} Because these studies were performed prospectively, they have a potential bias resulting in higher accuracy

than the present study in that the preoperatively planned value is more likely to be adopted by the surgeon during the actual THA procedure, particularly if the patient falls between sizes. Our planned stem size is more accurate than that in some previous reports, probably because we used the same prosthesis for all patients.^{10,18} Several studies have shown that the accuracy of stem planning on digital X-rays ranges from 30% to 90% and that the accuracy for cup planning ranges from 50% to 90%, and some studies have shown better accuracy for the stem and others for the cup.^{16,17,25,26} The 2D stem planning accuracy measured in the present study (58.9%) was at the lower end of the reported range, and the cup planning accuracy (65.2%) was in the middle of the reported range.

We found reduced effectiveness in predicting the use of large acetabular cup components regardless of how we used the two preoperative planning methods. In our study, three large acetabular cups (56- and 58-mm cups were used for four patients, and only one 60-mm acetabular cup was used) were used in nine patients. Because the sample size of the large acetabular cup was too small to be representative, it is difficult to distinguish whether the accuracy of the two measurement methods was related to the use of a large acetabular cup. To further explore the factors influencing femoral stem implantation, we also compared the accuracy of stems when using AI-HIP and manual templating planning for patients with different BMDs or different Dorr types.²⁷ We found that as the quality of the BMD decreased, the accuracy of the predicted stem decreased. The rate of agreement of stem prediction for patients with excellent bone quality was higher than that for patients with osteoporosis, regardless of whether AI-HIP planning or manual templating planning was used. Thus, a femoral stem that is one or two sizes larger

intraoperatively than preoperatively planned for patients with osteoporosis can provide initial stability. These findings indicate that based on the existing imaging examination level, we cannot completely eliminate the interference of BMD in preoperative planning. In addition, an advantage was found when AI-HIP software was used to predict the accuracy of the stem with Dorr A and Dorr B types compared with Dorr C. We found that the lower accuracy of the stem for patients with Dorr C femurs might have been caused by the design of the prosthesis. The Tri-Lock stem (DePuy Synthes) is a short cementless prosthesis that is more suitable for patients with Dorr A and Dorr B proximal femoral medullary cavities.²⁸ We also found that patients with Dorr C femurs who underwent THA using the Tri-Lock stem prosthesis were more likely to have valgus alignment of the femoral stem.

Eight patients with severe osteoporosis and four with Dorr C femurs used a stem that was two sizes larger than that planned by AI-HIP. Five patients with a history of hip surgery on the femoral side used a stem that was two sizes smaller than that planned by AI-HIP. This indicates that local osteoporosis or osteosclerosis will affect the selection of the prosthesis size in the process of femoral stem implantation, and correct prosthesis selection can avoid intraoperative periprosthetic fracture or postoperative prosthesis loosening. Increased accuracy of AI-HIP planning can be achieved by combining 3D reconstruction technology and BMD measurement. We believe that low accuracy may also be related to the lower use of marginally sized prosthesis components when THA surgery is performed. Interestingly, when using an actual sized 44-mm cup or size 0 stem, relatively high accuracy planning can be performed. AI-HIP can accurately measure the size of the femoral medullary cavity and is especially sensitive to morphological changes in the

proximal femur. Simultaneously, the Tri-Lock stem prosthesis with a 300- μ m Gription coating on the proximal side can provide initial and long-term stability. Greater attention was given to the left and right diameters of the proximal femoral medullary cavity in the preoperative planning. However, a thicker coating impacts the anteroposterior diameter of the medullary cavity, making the actual implantation size of the prosthesis smaller than that planned by AI-HIP.²

The 2D manual templating with conventional radiographs is the most commonly used technique for preoperative planning before THA; however, the low accuracy of component sizing with cementless implants has promoted the development of digital 2D and 3D planning methods. The 3D planning system based on artificial intelligence-assisted THA is able to perform intelligent segmentation and deep learning without considering the influence of individual anatomy and location on the X-ray magnification coefficient, leading to accurate determination of the implant size and location.

The principle of AI-HIP is database-based deep learning. As sample sizes increase, AI-HIP planning will become more accurate, and personalized customization will be achieved while meeting standardization. AI-HIP planning has reached a high level of accuracy compared with other 3D planning software; however, it is still limited by several factors in the primary stage, such as the use of only specific prostheses. With the continued development of this technology, increasingly diverse kinds of prostheses will be provided in future. The images of AI-HIP import analysis in the present study included only the hip joint and proximal femur, which had been considered by artificially combining lower limb splices. In summary, AI-HIP planning software exhibits high accuracy and is a reliable artificial intelligence-based

preoperative assistant. We will also discuss the effect of AI-HIP on shortening the operation time, reducing blood loss, and promoting rapid recovery in another article.

Limitations

This study had several limitations. First, only one stem was used in this study; thus, the conclusions of our study are only applicable to Tri-Lock prostheses. For other prostheses, the accuracy of AI-HIP software preoperative planning requires further research and careful treatment. Additionally, the prostheses used were limited to DePuy Synthes products, and the range of the prosthesis selection was small. With the continuous improvement of artificial intelligence systems, we will add more femoral prostheses in future research to conduct more comprehensive research. Second, the sample size of large-diameter acetabular shells for actual use in surgery was not sufficient, so it was difficult to identify differences in the consistency of the two preoperative planning methods. We will continue to expand the number of cases and further study the accuracy of AI-HIP for components of different sizes. When the sample size is sufficient, this problem will be resolved. Third, our study was retrospective, and the results of AI-HIP preoperative planning were not used to guide surgery. Finally, the BMD was not calculated using AI-HIP software and was used for the assessment of prosthetic mechanical stability. Therefore, the evaluation of mechanical stability might not be as accurate as it would be with other software designed to calculate the BMD and evaluate mechanical stability.

Conclusions

AI-HIP software showed excellent reliability for predicting the component size and

implant position in primary THA. It provides significantly higher accuracy in predicting the implant size and position than traditional manual templating in primary THA.

Declaration of conflicting interest

The authors declare that there is no conflict of interest.

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