Personalized digital simulation-assisted acetabular component implantation in revision hip arthroplasty

HONG-DA LAO[1*], DA LIU[2*], BIN CHENG[3], SHU-LING LIU[4], FENG SHUANG[1], HAO LI[1], LEI LI[1] and JIANG-JUN ZHOU[1]

[1]Department of Orthopedics, The 908th Hospital of The Joint Logistics Support Force (Great Wall Hospital Affiliated to Nanchang University), Nanchang, Jiangxi 335001; [2]Department of Orthopedics, General Hospital of Western Theater Command, Chengdu, Sichuan 610038; [3]Second Department of Orthopedics, The 92962 Military Hospital, Guangzhou, Guangdong 510000; [4]Jiangxi Institute of Scientific and Technical Information, Nanchang, Jiangxi 335001, P.R. China

Received April 25, 2023; Accepted January 24, 2024

DOI: 10.3892/etm.2024.12468

Abstract. The number of artificial total hip revision arthroplasties is increasing yearly in China, and >50% of these cases have acetabular defects. Accurately locating and quantifying the bone defect is one of the current challenges of this surgery. Thus, the objective of the present study was to simulate acetabular implantation with the aid of Mimics 17.0 software (Materialise NV) in patients with loosened acetabular prosthesis, to evaluate the 'ideal acetabular center' and the 'actual acetabular center' to guide the choice of prosthesis and surgical method. From January 2017 to June 2021, the present study included 10 hips from 10 patients [seven men (seven hips) and three women (three hips)]. In all patients, the Mimics software was applied to simulate the dislocation of the femoral prosthesis and acetabular prosthesis implantation before surgery; calculate the height difference between the 'ideal acetabular center' and the 'actual acetabular center' to assess the bone defect; confirm the size of the acetabular prosthesis, abduction angle, anteversion angle and bone coverage of the acetabular cup; and measure the intraoperative bleeding and postoperative follow-up Harris score of the hip joint. After statistical analysis, the present study revealed that digital simulation assistance could improve the accuracy of hip revision acetabular prosthesis implantation, reduce postoperative shortening of the affected limb, especially for surgeons with relatively little experience in hip revision surgery, and greatly reduce the occurrence of complications such as hip dislocation because of poor postoperative prosthesis position.

Correspondence to: Professor Jiang-Jun Zhou, Department of Orthopedics, The 908th Hospital of The Joint Logistics Support Force (Great Wall Hospital Affiliated to Nanchang University), 1028 Jinggangshan Avenue, Qingyunpu, Nanchang, Jiangxi 335001, P.R. China
E-mail: zjjortho@163.com

*Contributed equally

Abbreviations: THA, total hip arthroplasty; CT, Computerized tomography; CAD, Computer-Aided Design

Key words: total hip arthroplasty, revision, acetabulum, computer simulation, Mimics, center of acetabulum

Introduction

As the global population ages, the number of primary total hip arthroplasty (THA) procedures and that of THA revision procedures is expected to increase markedly (1,2). A systematic literature review showed that hip prosthesis survival rates over 10 years ranged from 91.0-99.4% among 1,385 patients with THA in the Danish National Patient Registry from January 2004 to December 2017 (3-5), and the volume of hip revision arthroplasty in the United States increased to 10-15% of the total joint arthroplasty (6,7). The common causes of THA revision include wear of prosthetic components, mechanical loosening, hip instability and infection, among which acetabular bone defects are present in >50% cases and are difficult to locate and quantify (8). Reconstruction of acetabular bone defects is the most critical factor for successful replacement and is the most daunting challenge for THA revision (9-11).

Computer-aided technology has been successfully applied in orthopedic instrument design, materials and surgical simulation with mature technology applications (12-14). Previous studies have (15,16) used Mimics software to simulate the reconstruction of a high dislocated acetabulum, with an individualized and precise preoperative design to obtain satisfactory acetabular cup position and coverage and to avoid problems such as iliopsoas impingement. However, to the best of our knowledge, no studies have been carried out yet on computer-assisted simulation in acetabular revision. Thus, to improve the accuracy of acetabular prosthesis implantation and surgical efficiency during revision surgery, the present study admitted 10 patients with loose acetabular prosthesis revision From January 2017 to June 2021, and applied Mimics 17.0 software to preoperatively simulate the release and acetabular prosthesis implantation and determine the ideal acetabular center, actual acetabular center and acetabular prosthesis size, and obtained satisfactory acetabular prosthesis position and limb length, which are reported below.

Materials and methods

Patient information. This study included 10 patients who underwent hip revision at Nanchang and Yingtan hospitals of The 908th Hospital of the Joint Logistic Support Force (Great Wall Hospital Affiliated to Nanchang University) from January 2017 to June 2021. The ethical approval number was approval no. Hospital Medical Service (2017)13. Each patient included in this study provided written informed consent. The present study included 10 hips of 10 patients [mean age, 31-61 (44.2±10.1) years; seven men (seven hips) and three women (three hips)]. All patients had loose or broken acetabular prostheses, two had initial replacement femoral neck fracture and eight had osteonecrosis of the femoral head. The time between initial replacement and revision surgery ranged from 1 to 15 (5.2±4.3) years. Preoperative shortening of the affected limb was evaluated by orthogonal pelvis radiography and computed tomography (CT) from 15 to 35 (25.1±6.3) mm. Patients underwent preoperative radiography and 3D CT to clarify the fusion of the acetabulum and acetabular component and the acetabular bone volume and quality. Magnetic resonance imaging (MRI) was repeated to rule out infection in patients with a history of previously infected fusion. However, because of significant artifacts associated with outdated models of prosthetics, not all cases could undergo MRI to rule out infection. For patients in whom infection could not be excluded by MRI, the present study primarily relied on the following methods for infection assessment: i) Preoperative levels of C-reactive protein and erythrocyte sedimentation rate should both not exceed 40; and ii) if infection was suspected during the operation, frozen section was taken for pathological examination (neutrophil <5 per high-power field) to rule out infection.

Simulated surgery and intraoperative and perioperative management

Imaging data collection. Hardware: 64-row spiral CT (LightSpeed VCT 64) from GE Healthcare Life Sciences; Thinkpad T460 (I5; 16G; 1TB; NVIDIA GeForce940/2GB; Lenovo Group). Software: Win10 64-bit Professional (Microsoft Corporation); Mimics 17.0 (Materialise NV); Solidworks 2011 SP0.0 (Dassault Systèmes SE). Patients underwent pelvic scanning (including the hip and upper femur) with the following parameters: Layer thickness, 0.625 mm; 120 kV; and 240 mA.

Pre-operative 3D CT reconstruction. The preoperative CT image data were saved in Digital Imaging and Communications in Medicine format and imported into Mimics software. The thresholding function button in Mimics software was used to create a bone window mask and generate a 3D model of the pelvis. The 'Cut with Polyplane' function was used to create a Polyplane (CP1) at the anterior and posterior edges of the initial acetabulum. The osteophytes of the femur were removed using the Split function to simulate the femoral prosthesis dislocation and to establish the acetabular model. Subsequently, 2-3 'spheres' of different diameters were created in Medcad to simulate the reaming of the acetabulum and to confirm that they reached the cancellous bone surface at all three levels, sagittal, coronal and transverse. After confirming the 'spheres' diameter, the Boolean calculation was performed to obtain the model of the acetabulum after reaming. The corresponding diameter of the spherical acetabular model was established in Solidworks according to the hole made in the acetabulum. The model was saved in the stereolithography format and imported into Mimics. It was placed into the osteotomy acetabulum through movement and rotation to retain the appropriate size of the acetabulum. A coverage rate of >75% was considered eligible (17). There are two concepts involved in the operation, namely the 'ideal acetabular center' and 'actual acetabular center'. The ideal acetabular center is calculated by Sphere simulation based on the reference of the contralateral acetabular center, while the actual acetabular center is the position that needs to be reamed to the cancellous bone surface when the original acetabular component is removed. The ideal acetabular center combined with bone graft or tantalum implant was used. If the height difference was <10 mm, the actual acetabular center combined with lengthening of the femoral ball head was used (Fig. 1).

Surgical method. The patient was placed in the lateral decubitus position and general anesthesia was induced. Via a posterolateral approach to the hip joint, the femoral neck, large trochanter and minor trochanter and the femoral prosthesis were exposed, making sure to protect the sciatic nerve. Upon fully loosening the acetabulum and large trochanter and minor trochanter, the acetabulum and the femoral prosthesis were exposed. It was repeatedly confirmed that the femoral stem was still loose; if not, we continued to loosen and dislocate the lateral femoral prosthesis to the top of the outer acetabulum to provide sufficient space for the removal of the acetabular prosthesis. After loosening the edge of the acetabular prosthesis, the scar on the edge of the acetabular prosthesis was removed to expose the bony border, subsequently we tapped with a special curved osteotome close to the edge of the acetabular prosthesis to separate it from the acetabular bone. This separation step was performed gently to avoid removing too much cancellous bone or causing an acetabular fracture. After removing the prosthesis and referring to the size of the preoperative simulated acetabular cup, the acetabulum was reamed to 2-3 sizes smaller than the preoperative simulated size, using the 'wall-holding' method when reaming the acetabulum, starting from the position of the transverse ligament. After the acetabular scar was basically removed, the reverse acetabulum reamer was used when it was close to the size of the preoperative simulation. The maximum size of the acetabulum reamer did not exceed the maximum size of the preoperative simulation. Finally, the appropriate acetabular cup was placed, and C-arm fluoroscopy was used to confirm that the position of the prosthesis was correct and then sutured layer by layer.

Perioperative management. Cefazolin sodium (1.0 g) were administered routinely 30 min preoperatively and no more than 48 h postoperatively. Preoperative intravenous drip of 0.5 of injectable tranexamic acid, with 20 ml saline dissolved in 0.5 g tranexamic acid was injected into the drainage tube after closing the incision, and the drainage tube was clamped shut for 2 h and then released. The drainage tube was removed within 48 h postoperatively. Postoperative low molecular-weight heparin sodium anticoagulation was performed. Muscle strength training of hip abductors and other muscles

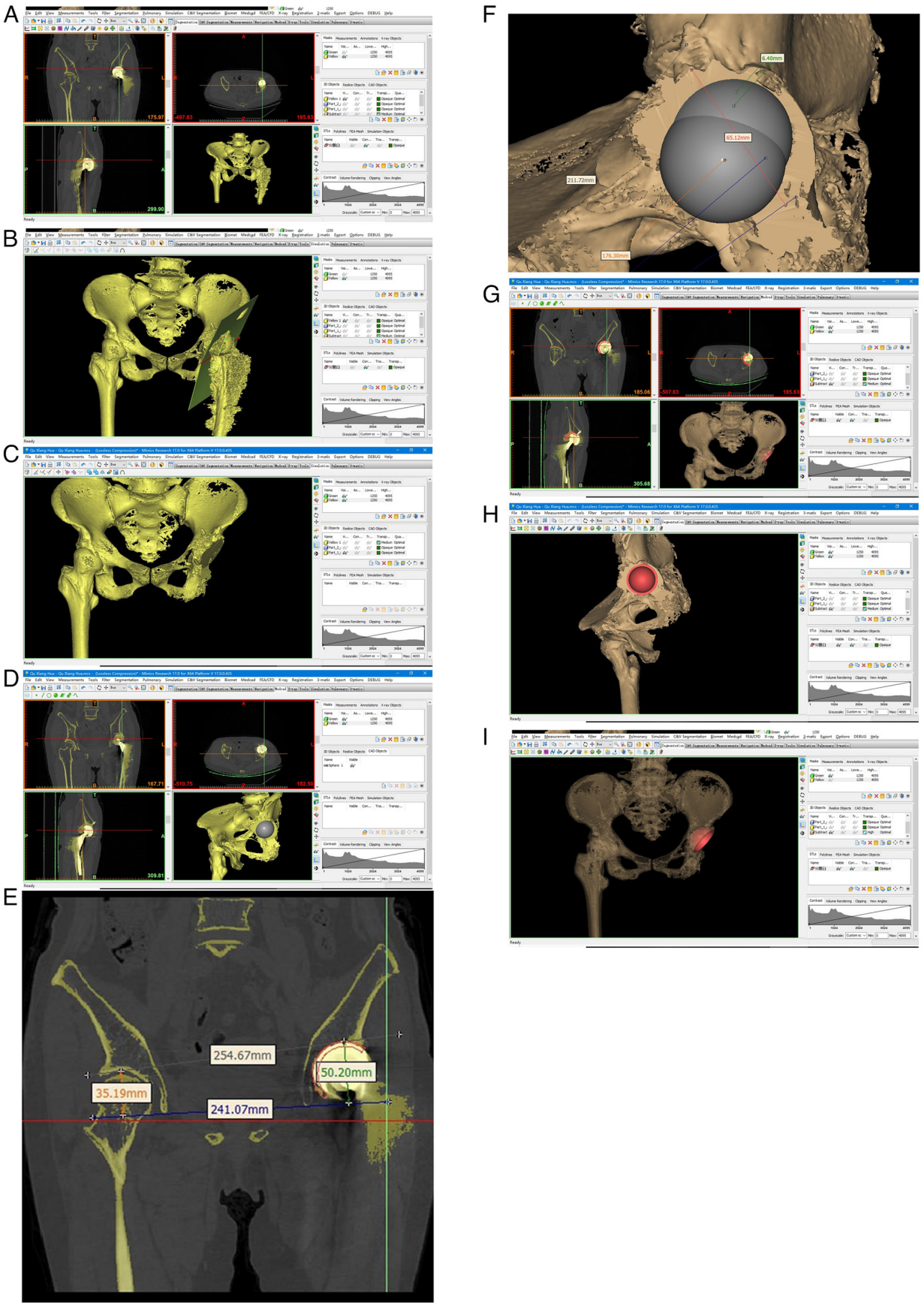

Figure 1. (A) Simulated implantation of an acetabular prosthesis: 3D models generated from bone values under thresholding. (B) Simulation of the decomposition model through the Cut function CP1. (C) After dislocation of the femoral prosthesis. (D) Importing acetabular model; (E) Confirming the center of the acetabular cup through the healthy acetabulum in three images in sagittal, coronal and transverse views. (F) Confirming the height difference between the actual acetabular cup and the ideal acetabular cup center. (G) Selecting the appropriate sphere for the Boolean operation to derive the acetabular model and place the corresponding size acetabular cup. (H) Confirmation of the anteversion angle, abduction angle and bone coverage of the acetabular cup. (I) Final simulated orthopantomogram is obtained.

Table I. Pre-operative and post-operative follow-up data for each case.

Case	Sex	Age, years	Medical history, years	Type of primary acetabular component	Shortening (pre-op), mm	Acetabular center difference, mm	Paprosky type	Shortening (Post-op), mm[a]	Intraoperative bleeding, ml	Operation duration, min	Follow-up time, months	Abduction angle, °	Anteversion angle, °	Acetabular coverage, %	Harris score		
															Pre-op	3 months (Post-op)	12 months (Post-op)
1	M	32	1	Zweymuller biocon cup	25	11	I	5	450	90	48	40	10	88.9	15	45	90
2	M	46	2	Beijing AiKang APT A-Cup	18	15	I	2	275	80	37	41	15	94.4	16	42	87
3	M	44	3	Beijing Montagne KG	20	8	I	2	350	70	24	39	13	77.8	22	56	85
4	M	48	4	Zweymuller biocon cup	22	12	I	5	275	85	21	40	18	70.0	28	61	80
5	M	49	2	Beijing AiKang APT A-Cup	31	15	II	7	400	80	16	38	20	80.6	23	43	81
6	F	42	8	Beijing Montagne KG	15	20	II	-5	350	80	13	32	17	83.3	19	39	90
7	M	56	15	Zweymuller biocon cup	27	25	III	8	300	85	15	45	18	86.1	16	54	80
8	F	61	5	Strykle Osteonics Crossfire	28	6	I	1	250	70	12	39	16	91.7	25	47	78
9	M	31	3	Zweymuller biocon cup	30	16	II	-3	350	80	18	43	15	97.2	21	48	91
10	F	33	9	Beijing AiKang APT A-Cup	35	5	I	-6	325	70	31	40	16	82.2	24	37	92

[a]The negative sign in this column indicates that the affected limb is longer compared with the healthy side.

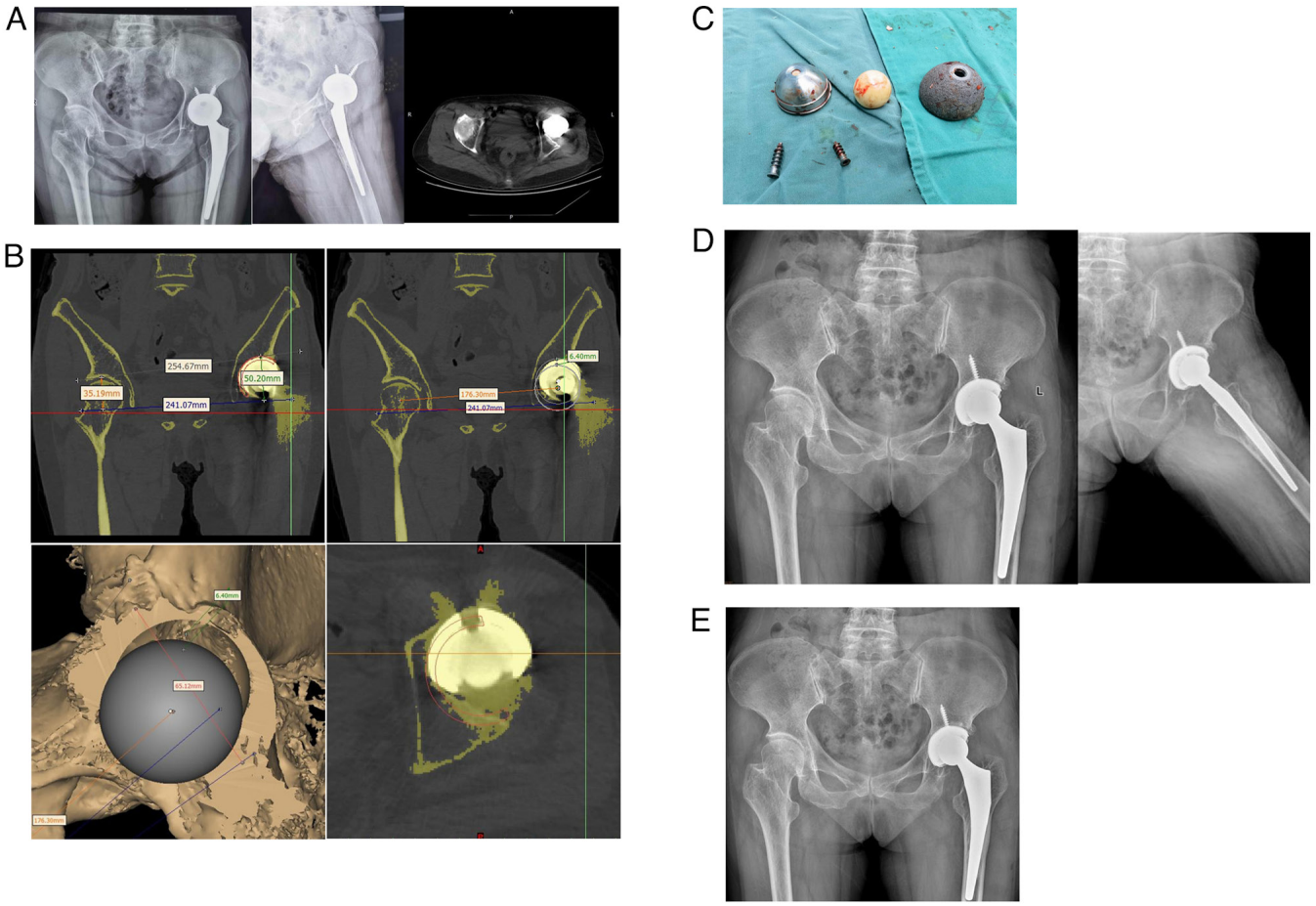

Figure 2. (A) Typical case: The patient was a 61-year-old woman who presented with a loose flip of the acetabular lateral prosthesis 5 years after total hip arthroplasty for a femoral neck fracture (first surgery with a Stryker all-ceramic prosthesis). At 5 years after femoral neck fracture surgery, radiography and computerized tomography both suggested loosening of the lateral acetabular prosthesis and acetabular flip to the anterior acetabulum, which was assessed as a Paprosky type I bone defect with preoperative measurement of 28-mm shortening of the affected limb. (B) According to the methodology of the present paper, Mimics 17.0 software was used to preoperatively simulate the surgery, and the maximum outer diameter of the acetabular prosthesis could not exceed 52 mm (coverage rate, 91.7%), and the ideal acetabular center was 6-mm lower compared with the actual reamed acetabular cup. Moreover, the actual reamed acetabular center was planned to be selected intraoperatively, while the long ceramic ball head of the same brand was replaced to avoid shortening of the affected limb. (C) During the operation, the acetabular side prosthesis was completely removed with very little bone destruction. The acetabular prosthesis of 52-mm diameter was replaced according to the preoperative plan, and a large ceramic ball head of plus 7 mm was selected. (D) On the postoperative review radiograph, the affected limb was shortened by ~1 mm, and the acetabular prosthesis was well positioned with an abduction angle of 39˚ and an anteversion angle of 16˚. (E) Radiographs were repeated 12 months after surgery and were in good position.

was started after awakening from anesthesia, and standing was assisted by a walker 48 h postoperatively.

Observation items. The operation time, intraoperative bleeding and Harris hip score (18) at 3 months and 12 months after surgery were recorded, and the postoperative acetabular anteversion and abduction angles were measured according to the Pradhan method (19).

Statistical analysis. The statistical analysis was conducted using SPSS 25.0 software (IBM Corp.), and the measurement data are presented as mean ± standard deviation. To assess the normal distribution of the data, we performed the Shapiro-Wilk test and examined the associated P-values for all test items, which indicated a normal distribution. Repeated measures analysis of variance (ANOVA) was employed to evaluate Harris scores at three consecutive time points post-enrollment, with within-subject effect testing applied when Mauchly's sphericity assumption was met. Post hoc tests for Harris scores before operation, at 3 months, and at 12 months after operation were conducted using Bonferroni correction. $P<0.05$ was considered to indicate statistically significant differences, and a two-tailed hypothesis test with a 95% confidence interval was utilized.

Results

All patients were followed-up for 12-48 (23.5±11.8) months. No postoperative dislocation or infection of the prosthesis occurred, and one case had numbness of the lateral calf skin due to incomplete injury of the sciatic nerve caused by intraoperative pulling, which was treated with mecobalamin (0.5 g three times a day) and the patient recovered 3 months after surgery.

Postoperative acetabular cup abduction angle (39.7±3.4˚), anteversion angle (15.8±2.8˚), abduction angle and anteversion angle were within Lewinnek's safety (20) range in all cases. Preoperative limb shortening was 25.1±6.3 mm,

intraoperative ideal acetabular center and actual acetabular center difference was 13.3±6.3 mm and postoperative limb shortening was 1.6±4.9 mm. Postoperative acetabular cup bone coverage was 85.2±8.2%; the preoperative Harris hip score points were 20.9±4.3, at 3 months post-operation it was 47.2±7.7 points and at 12 months post-operation it improved to 85.4±5.3 points; bleeding volume was 332.5±61.3 ml; and operative time was 79.0±7.0 min (Table I) The typical cases are illustrated in Fig. 2. There was a statistically significant overall difference in preoperative, 3 months postoperative and 12 months postoperative Harris hip scores (repeated measures ANOVA; F=245.23; P<0.001). There were statistically significant differences in hip Harris scores before and after operation, 3 months and 6 months after operation (P<0.001; Table II).

Table II. Comparison of preoperative (n=10), 3 months postoperative (n=10) and 12 months postoperative (n=10) Harris scores of patients.

		Repeated measures analysis of variance	
Group	Harris score	F	P-value
Preoperative	20.9±4.3	245.23	<0.001
3 months postoperative	47.2±7.7[a]		
12 months postoperative	85.4±5.3[a,b]		

[a]P<0.001 compared with preoperative; [b]P<0.001 compared with 3 months postoperative.

Discussion

Loosening of the prosthesis after hip arthroplasty often causes pain, resulting in limited walking and thus disuse osteoporosis (21-23). Revision hip arthroplasty has high risks and a number of variables, making it a difficult operation in joint surgery (24). Inadequate preoperative and tools preparation can easily lead to catastrophic intraoperative consequences, such as massive bone loss, acetabular fracture and acetabular prosthesis sinking into the pelvis (25,26). Understandably, acetabular reconstruction is one of the major difficulties of this operation. The aim of acetabular reconstruction is to restore the anatomical center of the hip joint and construct a peri-acetabular support band to bring the new acetabular prosthesis into full contact with the acetabular bone and maintain long-term stability and durability, and to minimize the bone defects formed in the replacement (27-30). However, the risk of a poor acetabular cup mounting position due to unclear anatomical landmarks and inaccurate positioning during hip revision is high, and the use of the traditional reaming acetabular positioning method requires a high level of surgical skill and clinical experience (31). Moreover, it is relatively difficult to accumulate surgical experience and hone skills given the small number of cases, too many intraoperative variables and a long learning curve (25-27).

Preoperative 3D analysis simulates the surgery to help preoperatively fully understand the morphological characteristics of the acetabulum, assess the degree of bone loss and select the appropriate size acetabular prosthesis (32-34). Zeng *et al* (35) have performed preoperative 3D simulated surgery in Mimics for patients with congenital hip dislocation with high dislocation, but it requires a high level of operating skills. Sugano *et al* (36) report the use of an intraoperative acetabular Computer-Aided Design (CAD) device to improve the accuracy of acetabular cup implantation, but its diffusion was affected by the expensive device and relatively cumbersome intraoperative operation. Zhang *et al* (37) used a positioning-guidance assisted technique for intraoperative acetabular reaming in patients with congenital hip dislocation. This technique is accurate in positioning and easy to operate intraoperatively, but it is relatively difficult to produce and design, because the design of the guide template requires CAD software operating skills and experience. Wu *et al* (38) designed a self-developed CAD/rapid prototyping/intraoperative positioner system to simulate acetabular cup prosthesis implantation, and used self-developed digital light processing 3D printer-light-curing surface-forming technology to match and position the acetabular positioner claw tip with the external orifice edge of the model to guide the direction of acetabular reaming. However, because the directional rod operation occupies a certain space, the intraoperative operation requires a large surgical area to be exposed and is not suitable for surgery to preserve the femoral prosthesis.

Our group previously used the Mimics software for simulations to assess acetabular prosthesis size, bone defects and acetabular prosthesis coverage in hip dysplasia cases, but in acetabular prosthesis revision, the bone defects resulting from acetabular prosthesis removal need to be considered when reconstructing the simulated surgery owing to the influence of the original acetabular prosthesis (39,40). Therefore, the present research will help to judge the size of the bone defect after prosthesis implantation based on the difference between the ideal acetabular center and the actual acetabular center, to choose whether to add a pad or to solve the problem of limb shortening by replacing the ceramic ball head, which is relatively simple and easy to operate and promote the use of. The present study also used the method provided by previous studies (17,27) to assess the bone coverage of the new acetabular prosthesis after removal of the loosened acetabular prosthesis. Since the femoral stem prosthesis was not removed in any of the cases in this group, the present study replaced the plus-sized ball heads or padded blocks as appropriate according to the height difference between the ideal acetabular center and the actual acetabular center, and ground the acetabulum to match the large ball head of 32 mm or ≥38 mm in diameter as much as possible to compensate for the limb shortening owing to the bone defect. All patients in this group had intraoperative loosening of the acetabular lateral prosthesis. Because of the gentle intraoperative operation, the degree of intraoperative acetabular lateral bone defect due to surgical technique was mild, so none of the pads were used. In addition, the postoperative shortening was reduced to within 0.5 cm, and all patients were satisfied

with the postoperative results. Due to the limited number of patients in this category, the present study collected a relatively small number of cases. Currently, the present study is just a preliminary experimental report, so a control group has not been established. More data will be gathered in the future to enhance the study.

In conclusion, the use of digital simulation assistance can improve the accuracy of hip revision acetabular prosthesis implantation and reduce postoperative shortening of the affected limb. Especially for surgeons with relatively little experience in hip revision surgery, it provides a reference for the reasonable placement of the prosthesis and greatly reduces complications such as hip dislocation because of poor postoperative prosthesis position. However, because of the small number of cases in the present study and the absence of cases with bone defects of >3 cm, the effectiveness of the method could not be verified in such cases.

Acknowledgements

Not applicable.

Funding

The present study was supported by The PLA's High-level Talents Independently Projects [grant no. (2022)17-02] and Subject of Health Commission of Jiangxi Province (grant no. 20203826).

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Authors' contributions

JJZ, HDL, DL, BC, FS, HL, SLL and LL analyzed the data and edited the manuscript. JJZ, HDL, DL and BC helped to perform the follow-up and to collect patients' data. JJZ, DL and FS confirm the authenticity of all the raw data. All authors read and approved the final manuscript.

Ethics approval and consent to participate

Ethics committee approval for use of individual participant data was granted by the ethics committee of the 908th Hospital of Joint Logistic Support Force of PLA to this study [approval no. Hospital Medical Service (2017)13]. Signed written informed consent was obtained from the patients and/or guardians.

Patient consent for publication

Consent for publication of the patients' data and images was obtained from patients or their relatives.

Competing interests

The authors declare that they have no competing interests.

References

1. Schwartz AM, Farley KX, Guild GN and Bradbury TL Jr: Projections and epidemiology of revision hip and knee arthroplasty in the united states to 2030. J Arthroplasty 35 (Suppl): S79-S85, 2020.
2. Marsh M and Newman S: Trends and developments in hip and knee arthroplasty technology. J Rehabil Assist Technol Eng 8: 2055668320952043, 2021.
3. Darrith B, Courtney PM and Della Valle CJ: Outcomes of dual mobility components in total hip arthroplasty: A systematic review of the literature. Bone Joint J 100-B: 11-19, 2018.
4. Hauer G, Heri A, Klim S, Puchwein P, Leithner A and Sadoghi P: Survival rate and application number of total hip arthroplasty in patients with femoral neck fracture: An analysis of clinical studies and National arthroplasty registers. J Arthroplasty 35: 1014-1022, 2020.
5. Larsen JB, Mechlenburg I, Jakobsen SS, Thilleman TM and Søballe K: 14-year hip survivorship after periacetabular osteotomy: A follow-up study on 1,385 hips. Acta Orthop 91: 299-305, 2020.
6. Kurtz SM, Ong KL, Lau E and Bozic KJ: Impact of the economic downturn on total joint replacement demand in the United States: Updated projections to 2021. J Bone Joint Surg Am 96: 624-630, 2014.
7. Chapman RM, Van Citters DW, Chapman D and Dalury DF: Higher offset cross-linked polyethylene acetabular liners: Is wear a significant clinical concern? Hip Int 29: 652-659, 2019.
8. Petis SM, Kubista B, Hartzler RU, Abdel MP and Berry DJ: Polyethylene liner and femoral head exchange in total hip arthroplasty: Factors associated with long-term success and failure. J Bone Joint Surg Am 101: 421-428, 2019.
9. Koob S, Scheidt S, Randau TM, Gathen M, Wimmer MD, Wirtz DC and Gravius S: Biological downsizing: Acetabular defect reconstruction in revision total hip arthroplasty. Orthopade 46: 158-167, 2017 (In German).
10. Miettinen HJ, Miettinen SS, Kettunen JS, Jalkanen J and Kröger H: Revision hip arthroplasty using a porous tantalum acetabular component. Hip Int 31: 782-788, 2021.
11. Garcia-Rey E, Saldaña L and Garcia-Cimbrelo E: Impaction bone grafting in hip re-revision surgery. Bone Joint J 103-B: 492-499, 2021.
12. Lewinnek GE, Lewis JL, Tarr R, Compere CL and Zimmerman JR: Dislocations after total hip-replacement arthroplasties. J Bone Joint Surg Am 60: 217-220, 1978.
13. Zhou JJ, Zhao M, Liu D, Liu HY and Du CF: Biomechanical property of a newly designed assembly locking compression plate: Three-Dimensional finite element analysis. J Healthc Eng 2017: 8590251, 2017.
14. Shen X, Tian H, Li Y, Zuo J, Gao Z and Xiao J: Acetabular revision arthroplasty based on 3-Dimensional reconstruction technology using jumbo cups. Front Bioeng Biotechnol 10: 799443, 2022.
15. Yang Y, Liao W, Yi W, Jiang H, Fu G, Ma Y and Zheng Q: Three-dimensional morphological study of the proximal femur in Crowe type IV developmental dysplasia of the hip. J Orthop Surg Res 16: 621, 2021.
16. Chen JX, Yu ZY, Cheng QX, Fu MQ, Shi BN, Yang J, Zhou JJ and Zhao M: Application of personalized digital analog assisted acetabular prosthesis precise implantation in Crowe typeIand IIhip dysplasia. China J Orthop Trauma 35: 605-609, 2022 (In Chinese).
17. Silber DA and Engh CA: Cementless total hip arthroplasty with femoral head bone grafting for hip dysplasia. J Arthroplasty 5: 231-240, 1990.
18. Lakhotia D and Agrawal U: Functional outcome of uncemented total hip replacement in low socioeconomic group using modified harris hip score: A prospective midterm Follow-Up study. Cureus 15: e50005, 2023.
19. Pradhan R: Planar anteversion of the acetabular cup as determined from plain anteroposterior radiographs. J Bone Joint Surg Br 81: 431-435, 1999.
20. Takemoto N, Nakamura T, Kagawa K, Maruhashi Y, Sasagawa T, Funaki K, Aikawa T and Yamamoto D: Clinical outcomes of total hip arthroplasty with the anterolateral modified Watson-Jones approach for displaced femoral neck fractures. Geriatr Orthop Surg Rehabil 13: 21514593221134800, 2022.
21. Fröschen FS, Schell S, Wimmer MD, Hischebeth GTR, Kohlhof H, Gravius S and Randau TM: Synovial complement factors in patients with periprosthetic joint infection after undergoing revision arthroplasty of the hip or knee joint. Diagnostics (Basel) 11: 434, 2021.

22. Bondarenko S, Filipenko V, Badnaoui AA, Ashukina N, Maltseva V, Lazarenko I and Schwarzkopf R: Periacetabular bone changes after total hip arthroplasty with highly porous titanium cups in patients with low bone mass. Wiad Lek 75: 1629-1633, 2022.
23. Kweon SH, Park JS and Park BH: Sarcopenia and its association with change of bone mineral density and functional outcome in old-aged hip arthroplasty patients. Geriatr Orthop Surg Rehabil 13: 21514593221121377, 2022.
24. Harris WH: The three revolutions in acetabular revision surgery for total hip replacement: 1. Definite and 2. Probable. Chir Organi Mov 88: 1-13, 2003.
25. Quinlan ND, Werner BC, Brown TE and Browne JA: Risk of prosthetic joint infection increases following early aseptic revision surgery of total hip and knee arthroplasty. J Arthroplasty 35: 3661-3667, 2020.
26. Grosso MJ, Kozaily E, Cacciola G and Parvizi J: Characterizing femoral and acetabular bone loss in two-stage revision total hip arthroplasty for infection. J Arthroplasty 36: 311-316, 2021.
27. Cosyn J, Eghbali A, Hanselaer L, De Rouck T, Wyn I, Sabzevar MM, Cleymaet R and De Bruyn H: Four modalities of single implant treatment in the anterior maxilla: A clinical, radiographic, and aesthetic evaluation. Clin Implant Dent Relat Res 15: 517-530, 2013.
28. Chiarlone F, Zanirato A, Cavagnaro L, Alessio-Mazzola M, Felli L and Burastero G: Acetabular custom-made implants for severe acetabular bone defect in revision total hip arthroplasty: A systematic review of the literature. Arch Orthop Trauma Surg 140: 415-424, 2020.
29. von Lewinski G: Custom-made acetabular implants in revision total hip arthroplasty. Orthopade 49: 417-423, 2020 (In German).
30. Wirtz DC, Jaenisch M, Osterhaus TA, Gathen M, Wimmer M, Randau TM, Schildberg FA and Rössler PP: Acetabular defects in revision hip arthroplasty: A therapy-oriented classification. Arch Orthop Trauma Surg 140: 815-825, 2020.
31. Giaretta S, Lunardelli E, Di Benedetto P, Aprato A, Spolettini P, Mancuso F, Momoli A and Causero A: The current treatment of hip arthroplasty revision: A systematic review of the literature. Acta Biomed 94: e2023092, 2023.
32. Maldonado DR, Go CC, Kyin C, Rosinsky PJ, Shapira J, Lall AC and Domb BG: Robotic Arm-assisted total hip arthroplasty is more cost-effective than manual total hip arthroplasty: A markov model analysis. J Am Acad Orthop Surg 29: e168-e177, 2021.
33. Weber M, Witzmann L, Wieding J, Grifka J, Renkawitz T and Craiovan B: Customized implants for acetabular Paprosky III defects may be positioned with high accuracy in revision hip arthroplasty. Int Orthop 43: 2235-2243, 2019.
34. Myers CA, Huff DN, Mason JB and Rullkoetter PJ: Effect of intraoperative treatment options on hip joint stability following total hip arthroplasty. J Orthop Res 40: 604-613, 2022.
35. Zeng Y, Lai OJ, Shen B, Yang J, Zhou ZK, Kang PD, Pei FX and Zhou X: Three-dimensional computerized preoperative planning of total hip arthroplasty with high-riding dislocation developmental dysplasia of the hip. Orthop Surg 6: 95-102, 2014.
36. Sugano N: Computer-assisted orthopaedic surgery and robotic surgery in total hip arthroplasty. Clin Orthop Surg 5: 1-9, 2013.
37. Zhang YZ, Chen B, Lu S, Yang Y, Zhao JM, Liu R, Li YB and Pei GX: Preliminary application of computer-assisted patient-specific acetabular navigational template for total hip arthroplasty in adult single development dysplasia of the hip. Int J Med Robot 7: 469-474, 2011.
38. Wu PH, Liu ZT and Zhang YQ: Pre-clinical application of self-developed computer assisted design/rapid prototyping and guidance system to assist precise acetabular component placement: A pilot study. Chin J Orthop Trauma 19: 323-328, 2017.
39. Li P, Tang H, Liu X, Chen Z, Zhang X, Zhou Y and Jin Z: Reconstruction of severe acetabular bone defects with porous metal augment in total hip arthroplasty: A finite element analysis study. Proc Inst Mech Eng H 236: 179-187, 2022.
40. Kocak S and Sekercioglu T: Experimental and numerical static failure analyses of total hip replacement interfaces. Proc Inst Mech Eng H 233: 1183-1195, 2019.