Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Computer-assisted femoral head reduction osteotomies an approach for anatomic reconstruction of severely deformed Legg-Calvè-Perthes hips

Philipp Fürnstahl
Uniklinik Balgrist
Fabio A. Casari (fabio.casari@balgrist.ch)
Uniklinik Balgrist https://orcid.org/0000-0002-9530-4861
Joëlle Ackermann
Eidgenossische Technische Hochschule Zurich
Magda Marcon
Uniklinik Balgrist
Michael Leunig
Schulthess Klinik
Reinhold Ganz
Inselspital Universitatsspital Bern

Research article

Keywords: Femoral head reduction osteotomy, FHRO, LCPD-hip, Perthes

Posted Date: July 23rd, 2020

DOI: https://doi.org/10.21203/rs.3.rs-37205/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Version of Record: A version of this preprint was published on November 18th, 2020. See the published version at https://doi.org/10.1186/s12891-020-03789-y.

Abstract

Background: Legg–Calvé–Perthes (LCP) is a common orthopedic childhood disease leading to a deformity of the femoral head and to an adaptive deformity of the acetabulum. The altered joint biomechanics can result in early joint degeneration requiring total hip arthroplasty. In 2002 Ganz et al. introduced the femoral head reduction osteotomy (FHRO) as a direct joint-preserving treatment. The procedure remains one of the most challenging in hip surgery. Computer-based 3D preoperative planning and patient-specific navigation instruments have been successfully used to reduce technical complexity in other anatomies. The goal of this study was to evaluate the feasibility and anatomic reconstruction of such an approach for FHRO.

Methods: In this pilot study 6 LCP patients were treated by FHRO in multiple centers between May 2017 and June 2019. Based on patient-specific 3D models of the hips, the surgeries were simulated in a step-wise fashion. Patient-specific intstruments tailored to FHRO were designed 3D-printed and used in the surgeries for navigating the osteotomies. The results were assessed radiographically and time and costs recorded.

Results and Interpretation: The clinical feasibility of our approach for FHRO surgery has been demonstrated. The results showed significant improvement compared to the preoperative situation. The sphericity index improved postoperatively by 20% ($p=0.028$), the postoperative head diameter differed by only 1.8% ($p = 0.043$) from the contralateral side and Stulberg classification improved from 4.33 poor coxathrosis outcome to 1.5 good outcome ($p = 0.026$). The average time (minutes) for preliminary analysis, computer simulation, and patient-specific instrument design was 63 (±48), 156 (±64), and 105 (±68.5), respectively. All operations were performed by experienced surgeons, still three complications occurred, showing that FHRO remains one of the most complex hip surgeries, even with computer assistance; however none was directly related to simulation or navigation technique.

Background

Legg–Calvé–Perthes is an orthopedic childhood disease caused by a disturbance of the blood supply of the femoral head. With a lifetime risk of about one in 1200 children, LCP disease can be considered as one of the most common hip disorders in young children (2). The pathology presents itself at the age of 4 to 8 years, but it may take five to ten years until the full deformity has manifested. (2-5) Avascular necrosis of the femoral head develops in the first phase of the pathology. Later, the head of the femur is progressively deformed as a result of fatigue fractures caused by the repetitive forces acting on the joint during daily activities. The new contour of the head resembles a mushroom with a central dent (6) or a saddle(7) having a significant three-dimensional (3D) component(8). The horizontal diameter is extra-large (coxa magna), the neck is short and the greater trochanter is high riding [Fig. 1]. The dysmorphic head induces adaptive changes of the acetabulum in form of a secondary acetabular dysplasia (9), leading to impaired hip function and pain(10) due to intra- and extracapsular impingement(8), hinged abduction (11, 12) and early joint degeneration(9, 10).

Conservative treatment possibilities are load restricition, physiotherapy and orthoses, but these have been found to be ineffective (5). Possible surgical options after healed LCP include adductor tenotomy(13), osteochondroplasty (14), valgus-extension intertrochanteric osteotomy(14, 15), and acetabular osteotomy(16, 17), but these approaches perform a bone correction distant from the actual deformity. In one third of the patients, pain and stiffness reach unbearable levels due to early joint degeneration. Femoral head reduction osteotomy remains as the only joint-preserving surgical treatment option. (1, 6, 8, 18–20)

Ganz performed the first FHRO in 2002 and published it in 2009 [Fig. 2] (1). The procedure aims at restoring the sphericity of the femoral head as much as possible. The osteotomies separate the head into a mobile lateral fragment, a central, necrotic and a stable medial part. (1, 6, 18) The pathologically extended central part is resected and the lateral fragment is carefully reduced. In the majority of cases, a concurrent reorientation of the acetabulum by pericatebular osteotomy (PAO) (21) is needed to restore the joint containment and stability(8).

Careful and detailed preoperative planning of the procedure is necessary(14), but state-of-the-art planning is limited to conventional imaging using biplanar radiographs, MRI and CT. (8, 20) Surgeons have to rely on simplified two-dimensional measures to make a decisions about the size of the resection and the direction of the osteotomies. For this reason a final decision can only be made intraoperatively and the surgeon has no other choice than performing the most difficult femoral head osteotomies in a freehand fashion. (8)

We have developed a new technique combining computer simulation, for preoperative planning, and additive manufacturing, for surgical navigation with patient-specific instrument, with the goal to perform FHRO in a more controlled way. Purpose of this study was to report first results if remodeling of the physiologic anatomy is feasible and about safety of the new technique in the treatment of 6 patients.

Materials And Methods

In this pilot study 7 patients between nine and eighteen years of age were treated by FHRO with the new technique between May 2017 and October 2019. Aim of this study was to evaluate feasibility, safety and reconstruction outcome. All except one patient, the parents or the legal guardian provided informed consent to this study, who was excluded. Three of the patients were male and three were female. Ethical approval was obtained by the ethical committee of the Canton Zurich. Inclusion criteria were pain and restricted hip motion, severe deformity of the femoral head and an intact peripheral cartilage with a central necrosis. Preoperative computer simulation of the surgery was performed for each patient and patient-specific instruments (PSI) to precisely execute the bony cuts were designed and manufactured. Surgeries were performed in different centers by four senior hip surgeons who had experience in FHRO surgeries.

Preoperative computer simulation

CT scans of the patients hips were obtained in supine position and anterior-posterior hip orientation according to a specifically designed protocol (MyOsteotomy CT protocols, Medacta International, Castel San Pietro, Switzerland). The CTs were acquired with an axial resolution of 1 mm slice thickness using a Philips Brilliance 40 CT device (Philips Healthcare, Best, The Netherlands). The data were imported in a commercial image processing software (Mimics Medical, Version 19; Materialise, Leuven, Belgium) and the bone anatomy was segmented from the surrounding soft tissues by applying global intensity-based thresholding and region growing. 3D triangular surface models of femur and pelvis were generated from the segmented images using the Marching Cube algorithm.(22) The models were imported into the in-house developed preoperative planning software CASPA (Computer Assisted Surgical Planning Application, Version 5.29) to simulate the FHRO surgeries [Fig. 3]. The mirrored models of the healthy contralateral sides [Fig. 3, shadow contour] were used to approximate the pre-morbid femoral heads and served as remodelling templates in the simulation. In case of a pathological contralateral side, a geometric sphere was used as a remodeling template. The sphere was manually centered in the mechanical joint center of the hip and resized until it covered the healthy portion of the femoral head.

The definition of the femoral head osteotomy planes is the most important step in the preoperative planning [Fig.3-A, grey planes], because the planes implicitly define the resection of the necrotic part [Fig.3-A, red wedge], the degree of head sphericity, the residual articular step off between the contact surfaces of the fragments [Fig.3-B, red square], and the size of the remaining medial neck pilar [Fig.3. yellow line]. The locations of the osteotomies are constrained by the medial and lateral retinacular blood vessels feeding the femoral head.

The first osteotomy was defined along the lateral end of the necrotic area to create the mobile fragment [Fig. 3, blue]. Afterwards, the reduction of the mobile fragment was simulated by applying 3D rotations and translations such that sphericity, articular step off and medial neck pilar size are optimized. The intersecting volume between the mobile fragment in its reduced position and the stable part was then used to calculate the second osteotomy plane which completes the 3D wedge to be resected. Fine-tuning through iterative refinement of osteotomy planes and reduction was required in each case until the optimal strategy was determined [Fig. 4]. After each FHRO simulation, the congruency and fit of the reshaped head into the acetabulum was assessed in order to reveal necessity and extent of the additional PAO [Fig. 5].

PSI design

PSI are a surgical navigation concept in which cutting, drilling, and reduction instruments are computer-designed and matched to the preoperative simulation of the surgery. The undersurfaces of the instruments are shaped as negatives of the bone anatomy such that the tools can be later placed exactly at the planned position on the bone [Fig. 6]. PSI as navigation tools for corrective osteotomies were first introduced for the treatment of complex malunions of the forearm bones(23–25). We have adopted the PSI approach by designing new instruments tailored to the anatomy of the proximal femur and the FHRO surgery. A main challenge was to design a PSI that can be placed on the proximal femur without compromising the vascular supply at the infero-medial curve of the femur neck [Fig. 7]. The remaining footprint of the anterior bone surface on which the PSI can be placed is small and the surface relief of the bone is insufficiently pronounced to provide sufficient guide stability. For this reason medial and lateral hooks were integrated in the base block of the PSI to improve its stability.For the portion covering the cartilageneous cover of the head an offset of 4 mm was integrated. Two drill sleeves with Ø2.6 mm were designed to allow temporary fixation of the PSI on the bone with surgical pins. The PSI also consisted of two cutting slits into which the blade of the surgical saw will be inserted and precisely aligned according to the planned osteotomy planes. The PSI were additively manufactured as CE-conform medical products by an industrial partner (Medacta International, Castel San Pietro, Switzerland) using biocompatible polyamide (P2200; EOS GmbH, Germany) and a selective laser sintering device (Formiga P395 / P396 / P100, EOS GmbH, Krailling, Germany). Before application in the surgery, autoclave sterilization was performed in the surgical centers.

Surgical technique

The patient was positioned in lateral decubitus position. The pathologic hip was accessed via the surgical hip dislocation approach(26). The fascia lata was split anterior to the gluteus maximus muscle, until the greater trochanter could be visualized and the head could be accessed. The trochanter was then osteotomized and flipped anteriorly together with the attached gluteus medius and minimus muscles on one side and vastus lateralison muscle on the other side. The joint capsule was presented through the gap between piriformis and gluteus minimus and incised in a z-shaped fashion, whereby special attention was paid to protect the retinacular vessels. (27) After sectioning of the ligamentum teres, the hip could be dislocated with traction, adduction and external rotation. (26) The medial femoral circumflex artery was secured in form of a pediculated periosteal flap. (1) For dissection of the retinacular flap, the stable part of the trochanter was piecemeal resected down to the level of the neck and the periosteum was carefully dissected, allowing free access to the lateral and posterior neck bone. For the FHRO the medial retinaculum was left attached to the calcar area (1)

The femoral neck was thereby accessible in its anterior, lateral and posterior circumference and allowed positioning of the PSI. Finding the correct position of the PSI is not straight forward in general and could be only achieved by comparison with a manufactured replica of the patient bone [Fig.8-A]. After fixation of the PSI with two surgical pins of Ø 2.5 mm, the sawing blade (thickness/width/length 1.00/25.00/90.00mm; Ref. Gomina 265.256.100)s was introduced into each of the two cutting slits to perform the medial and lateral head osteotomies under continuous visual control. The level of the subsequent transverse osteotomy at the neck was free hand determined, allowing the necrotic central part and the pedicled lateral fragment to be liberated while the medial part of the head remained stable on the calcar bone.[Fig. 8-B] After resection of the necrotic part, the mobile fragment was reduced in a freehand fashion, but following the position obtained by the preoperative computer simulation. Under continuous control of the retinacular flap, the fragment could be moved in a cephalad or caudad direction, it could be shifted posteriorly or anteriorly and could be rotated to finally obtain an optimal surface congruency. The reduced fragment was stabilized with two Ø3.5 mm cortical screws. Articular step offs between the contact area of the fragments were smoothed out using a scalpel to restore a transition-free joint surface. Retinaculum and capsular flap were loosely adapted before the trochanter was reattached at an advanced position.

Evaluation

The radiological outcome was measured by two independant readers on pre- and postoperative pelvic AP radiographs.(19) For the evaluation of the head shape the femur head diameter in ratio to the healthy contralateral side(10), the sphericity index (ratio of the minor and major axis of the ellipsoid femoral head)(19) and the Stulberg classification(10)were assessed. For the evaluation of the hip containment, the extrusion index (ratio of head extrusion distance and containment)(28), the LCEA (AP), the Tönnis angle(29) and the Shenton line(30) were measured. Additionally, the CCD-angle was obtained to track if the surgery affects varus or valgus alignment and the preoperative Waldenstroem classification(31) for disease state definition. For effort evaluation time and costs associated with the new technique were recorded. Radiologic values were tested for normal distribution using the Shapiro-Wilk test and for statistical relevance using Wilcoxon signed ranks test.

Results

Mean patient age at the time of surgery was 14 years (range, 9–18 years). All patients had a concomitant acetabular reorientation by PAO and relative femoral neck lenghtening(18). The mean follow-up time was 17.5 months (± 2.5).

The results of the pre- and postoperative radiological assessment are given in Table 1. Diameter index, sphericity index and Stulberg grading significantly improved postoperatively. The extrusion index, LCE angle and Tönnis angle significantly changed from dysplastic values preoperativerly to containing values postoperatively. CCD angle was not significantly affected by the procedure and the Shenton line was postoperatively intact in all patients.

On average, the preliminary analysis of the case (review of image data, data processing, pre-discussion with surgeon) took 63 minutes (± 48). The time for the preoperative computer simulation took 156 minutes (± 64) on average and 105 minutes (± 68.5) were spent on PSI design. The time expenses resulted in costs of 2800 USD. The cost of manufacturing the CE-conform PSI and the plastic bone models using additive manufacturing was 600 USD.

Complications have been reported in three cases, however none was directly related to the computer simulation method or navigation technique. In one case, a femoral neck fracture occurred postoperatively due to an insufficient residual neck thickness, which was successfully treated by osteosynthesis in a revision surgery. In a second case, the PSI was incorrectly positioned. It was recognized immediately and the cut direction was corrected. This mistake had no negative influence on the clinical and radiological result. In a third case, the intraoperatively observed necrotic area on the lateral side of the femur was larger than expected, which made the operation no longer feasible.

Radiologic value	Preoperative (avg, ±)	Postoperative (avg, ±)	Difference (avg, ±)	p-value (Wilcoxon signed rank test)
Diameter index (%)	118.2% (11.21%)	98.2% (2.28%)	20% (10.22%)	0.043
Sphericity index (%)	51.49% (10.47%)	72.96% (7.33%)	21.47% (7.21%)	0.028
Stulberg classif.	4.33 (0.81)	1.5 (0.55)	2.83 (0.9)	0.026
Extrusion index (%)	30.77% (11.75%)	-14.02% (7.74%)	44.8% (15.9%)	0.028
LCE angle	22.33° (6.24°)	48.25° (9.65°)	25.92° (7.6°)	0.028
Tönnis angle	14.95° (6.08°)	-2.98° (3.95°)	17.94° (4.59°)	0.028
Shenton line intact	4/6	6/6	2	0.157
CCD angle	134.03° (5.43°)	128.5° (8.05°)	-5.51° (4.08°)	0.028

Table 1. Pre- and postoperative radiologic assessment measured on AP pelvic X-rays.

Discussion

FHRO has been described as an effective surgical treatment for severe deformities of the femoral head.(1, 6, 8, 18–20) Nevertheless, the procedure remains one of the technically most difficult procedures in hip surgery. One reason is that the underlying geometrical problem of restoring the head sphericity is highly three-dimensional, but state-of-the-art planning still relies on 2D measurements when adequate computer methods are not available. Computer simulations have been proven successful in solving 3D planning problems in various extra-(32) (33) and intra-articular(23, 34, 35) corrective osteotomies. One purpose of this study was to investigate the feasbility of using 3D computer simulation for the preoperative planning of FHRO.

Purposes

The postoperative radiological evaluation of our study showed a clear improvement compared to the preoperative situation. The sphericity index improved postoperatively by 20% and the postoperative head diameter difference could be reduced from 18.2% to only 1.8% compared to the healthy contralateral side. The Stulberg classification improved from 4.33 associated with a poor outcome to 1.5 associated with a good outcome in regard of development of coxarthrosis(10). Compared to previous studies in which the FHRO was performed based on conventional preoperative planning and without support by surgical navigation(19), our results indicate a better reconstruction of sphericity up to 8%. The post-operative evaluation remains a limitation of the study, as it was only based on anterior-posterior X-ray projections and 2D measurements. The absurdity of assessing 3D deformities in 2D has already been pointed out by

Siebenrock et al. (19), but the use of post-operative CT only for evaluation purposes cannot be justified ethically for this young patient population. The application of low-dose CT(36) could be a possibility to base future radiological outcome evaluation on post-operative CT. The use of CT-reconstructed 3D models in the post-operative evaluation would allow the application of more precise and powerful measurement methods which have been developed for outcome evaluation of intra-articular osteotomies(23, 35).

Previous surgical navigation approaches around the hip have been reported for extra-articular femur osteomies and PAO(37, 38). In this study we introduced a new PSI approach tailored to the FHRO. The precision of the navigation by PSI is mainly determined by how well the intended position of the PSI on the bone can be found intraoperatively. Jud et al.(39)showed for the proximal tibia that PSI malpositioning can result in severe surgical failures such as screw penetration or tibia plateau fracture. As the footprint on which the PSI can be placed on the proximal femur is very small, we introduced medial and lateral hooks to increase stability. Nevertheless, finding the right position of the PSI on the bone remains challenging. A great support for the surgeon are the patient-specific plastic models of the bone anatomy on which the PSI fits perfectly. Despite these precautions malpositioning occured in one case. Since this case, we integrated slits, representing the planned head osteotomies, in the plastic bone model such that the surgeon can make a better comparison between planning and intraoperative situation.

Another problem is the unease in assessment of the cartilage quality from CT pictures. In one of our cases the cartilage destruction was larger than expected and unfavorably distributed, a condition which not allowed to continue with the FHRO as planned. Cartilage mapping from MRI may become integrated into the simulation process to avoid such mishapes and may help to decide for even better cutting directions.

Our study and the described technique have several limitations. With 324 minutes on average, the effort required for pathology analysis, computer simulation and PSI design is still high. Furthermore, the creation of a preoperative simulation of a FHRO presupposes extensive anatomical and surgical knowledge, requiring stronger support by the surgeon compared to other interventions. However, for a cost-benefit analysis it has to be considered that the only established treatment option for these young patient population of the study would be total hip arthroplasty (THA). Treating adolescents by THA remains a big compromise, because one or probably more revision surgeries would be required during patient lifetime (40). Our approach could contribute to a further standardization of FHRO such that the procedure can become attractive for other highly-specialized centers. Another limitation is the the small study population. It has to be highlighted that patients undergoing FHRO have to be selected very carefully depending on various factors. The short follow-up time allowed us to report only intra-operative expieriences and preliminary radiological results. Another drawback is the retrospective fashion of our study. However it may have created a useful basis for a prospective multicenter project.

A logical next step to be addressed in future work would be the automation of the computer simulation and PSI design to reduce time effort and costs. The work of Carrillo et al. demonstrated for extra-articular forearm osteotomies(41) had generation of clinically acceptable 3D planning solutions is possible through sophistaced computer methods. Another technical improvement would be the integration of patient-specific cartilage models in the computer simulation by using image fusion techniques. The findings of this pilot study should also form the base to justify a multi-centric, prospective clinical trail. However, the implementation of such a study remains very difficult due to the small number of individual cases distributed among different centers worldwide.

Conclusion

In 1999, DiGioia et al. (42) postulated future surgical technologies including tools capable of simulating each step of a surgery with 3D models of the patient anatomy. Through advances in computational power and the development of enabling technologies such as additive manufacturing, their vision has been turned into clinical practice. However, especially in orthopaedics several complex procedures with a small caseload still exist for which - often due to economic reasons - no computer-based solution has been developed. The presented approach introduced such a solution for the treatment of FHRO surgery, providing the surgeon a detailed preoperative plan and an intaoperative tool for precise surgical exeution. The clinical feasibility of our approach has been successfully demonstrated. Our study could serve as an example of how the emerging technologies are increaslingly shaping also orthopedic surgery towards digital and personalized medicine, even in very complex and rare interventions. However, the success of the procedure will always depend on the experience of the surgeon and the aim of these technologies should be to support the surgeon, but not to compensate possibly missing skills. Nevertheless, the complications and challenges reported in our study indicate that FHRO surgery should only be performed by very experienced surgeons in highly specialized centers.

Abbreviations

Legg–Calvé–Perthes: LCP

Femoral head reduction osteotomy: FHRO

Pericatebular osteotomy: PAO

Patient-specific instruments: PSI

Total hip arthroplasty: THA

Declarations

• Ethics approval and consent to participate

Zurich cantonal ethics commitee approval (BASEC-Nr. 2018 – 01555) and patient consent to participate signed by the parents or legal guardian was obtained.

• Consent to publish

All authors provided consent for publication.

• Availability of data and materials

All data generated or analysed during this study are included in this published article [and its supplementary information files].

• Competing interests

Thera are no financial or non-financial competing interests.

• Funding

This work was financially supported by the Deutsche Arthrose Stiftung and the Promedica Stiftung Schweiz.

• Role of funding source:

Coverage of additional treatment costs caused by 3D planning and PSI manufacturing.

References

1. Ganz R, Huff TW, Leunig M. Extended retinacular soft-tissue flap for intra-articular hip surgery: surgical technique, indications, and results of application. Instructional course lectures. 2009;58:241-55.
2. Loder RT, Skopelja EN. The epidemiology and demographics of legg-calve-perthes' disease. ISRN orthopedics. 2011;2011:504393.
3. Ziebarth K, Slongo T, Siebenrock KA. Residual Perthes Deformity and Surgical Reduction of the Size of the Femoral Head. Operative Techniques in Orthopaedics. 2013;23(3):134-9.
4. Wada I, Horiuchi O, Wakabayashi K, Otsuka T. [Bone disease with pain. Legg-Calve-Perthes' disease (LCPD)]. Clin Calcium. 2008;18(2):239-48.
5. Herring JA, Kim HT, Browne R. Legg-Calvé-Perthes Disease: Part II: Prospective Multicenter Study of the Effect of Treatment on Outcome. JBJS. 2004;86(10):2121-34.
6. Ganz R, Horowitz K, Leunig M. Algorithm for femoral and periacetabular osteotomies in complex hip deformities. Clin Orthop Relat Res. 2010;468(12):3168-80.
7. Paley D. The treatment of femoral head deformity and coxa magna by the Ganz femoral head reduction osteotomy. Orthop Clin North Am. 2011;42(3):389-99, viii.

8. Clohisy JC, Pascual-Garrido C, Duncan S, Pashos G, Schoenecker PL. Concurrent femoral head reduction and periacetabular osteotomies for the treatment of severe femoral head deformities. The bone & joint journal. 2018;100-b(12):1551-8.
9. Clohisy JC, Ross JR, North JD, Nepple JJ, Schoenecker PL. What are the factors associated with acetabular correction in Perthes-like hip deformities? Clin Orthop Relat Res. 2012;470(12):3439-45.
10. Stulberg SD CD, Wallensten R. The natural history of Legg-Calvé-Perthes disease. The Journal of bone and joint surgery American volume. 1981;63(7):1095–108.
11. Quain S, Catterall A. Hinge abduction of the hip. Diagnosis and treatment. The Journal of bone and joint surgery British volume. 1986;68(1):61-4.
12. Rowe SM, Jung ST, Cheon SY, Choi J, Kang KD, Kim KH. Outcome of Cheilectomy in Legg-Calve-Perthes Disease: Minimum 25-Year Follow-Up of Five Patients. Journal of Pediatric Orthopaedics. 2006;26(2):204-10.
13. Moya-Angeler J, Abril JC, Rodriguez IV. Legg-Calve-Perthes disease: role of isolated adductor tenotomy? European journal of orthopaedic surgery & traumatology : orthopedie traumatologie. 2013;23(8):921-5.
14. Novais EN, Clohisy J, Siebenrock K, Podeszwa D, Sucato D, Kim Y-J. Treatment of the Symptomatic Healed Perthes Hip. Orthopedic Clinics of North America. 2011;42(3):401-17.
15. Aprato A, Pellegrino P, Kain MS, Masse A. Do osteotomies of the proximal femur still have a role? Curr Rev Musculoskelet Med. 2014;7(4):323-9.
16. Clohisy JC, Nunley RM, Curry MC, Schoenecker PL. Periacetabular osteotomy for the treatment of acetabular dysplasia associated with major aspherical femoral head deformities. The Journal of bone and joint surgery American volume. 2007;89(7):1417-23.
17. Rosello O, Solla F, Oborocianu I, Chau E, ElHayek T, Clement JL, et al. Advanced containment methods for Legg-Calve-Perthes disease: triple pelvic osteotomy versus Chiari osteotomy. Hip Int. 2018;28(3):297-301.
18. Leunig M, Ganz R. Relative neck lengthening and intracapital osteotomy for severe Perthes and Perthes-like deformities. Bulletin of the NYU hospital for joint diseases. 2011;69 Suppl 1:S62-7.
19. Siebenrock KA, Anwander H, Zurmuhle CA, Tannast M, Slongo T, Steppacher SD. Head reduction osteotomy with additional containment surgery improves sphericity and containment and reduces pain in Legg-Calve-Perthes disease. Clin Orthop Relat Res. 2015;473(4):1274-83.
20. Paley D, Feldman D. Femoral Head Reduction Osteotomy: A Case-Based Approach. Pediatric Pelvic and Proximal Femoral Osteotomies. 2018:379-420.
21. Ganz R, Klaue K, Vinh TS, Mast JW. A new periacetabular osteotomy for the treatment of hip dysplasias. Technique and preliminary results. Clin Orthop Relat Res. 1988(232):26-36.
22. Lorensen W, E. Cline H. Marching Cubes: A High Resolution 3D Surface Construction Algorithm1987. 163 p.

23. Schweizer A, Furnstahl P, Nagy L. Three-dimensional correction of distal radius intra-articular malunions using patient-specific drill guides. J Hand Surg Am. 2013;38(12):2339-47.
24. Murase T, Oka K, Moritomo H, Goto A, Yoshikawa H, Sugamoto K. Three-dimensional corrective osteotomy of malunited fractures of the upper extremity with use of a computer simulation system. The Journal of bone and joint surgery American volume. 2008;90(11):2375-89.
25. Ma L, Zhou Y, Zhu Y, Lin Z, Wang Y, Zhang Y, et al. 3D-printed guiding templates for improved osteosarcoma resection. Sci Rep. 2016;6:23335-.
26. Ganz R, Gill TJ, Gautier E, Ganz K, Krügel N, Berlemann U. Surgical dislocation of the adult hip. A technique with full access to the femoral head and acetabulum without the risk of avascular necrosis. Journal of bone and joint surgery. 2001;83:1119-24.
27. Kalhor M, Horowitz K, Gharehdaghi J, Beck M, Ganz R. Anatomic variations in femoral head circulation. Hip Int. 2012;22(3):307-12.
28. Heyman CH, Herndon CH. Legg-Perthes disease; a method for the measurement of the roentgenographic result. The Journal of bone and joint surgery American volume. 1950;32 a(4):767-78.
29. Tönnis D. Congenital Dysplasia and Dislocation of the Hip. New York, NY: Springer-Verlag; 1987.
30. Jones DH. Shenton's line. The Journal of bone and joint surgery British volume. 2010;92(9):1312-5.
31. Waldenström H. The definite form of coxa plana. Acta Radiologica. 1922(1):384.
32. Vlachopoulos L, Schweizer A, Meyer DC, Gerber C, Furnstahl P. Three-dimensional corrective osteotomies of complex malunited humeral fractures using patient-specific guides. J Shoulder Elbow Surg. 2016;25(12):2040-7.
33. Fürnstahl P, Schweizer A, Graf M, Vlachopoulos L, Fucentese S, Wirth S, et al. Surgical Treatment of Long-Bone Deformities: 3D Preoperative Planning and Patient-Specific Instrumentation. In: Zheng G, Li S, editors. Computational Radiology for Orthopaedic Interventions. Cham: Springer International Publishing; 2016. p. 123-49.
34. Pillukat T, Osorio M, Prommersberger KJ. [Correction of Intraarticular Malunion of the Distal Radius Based on a Computer-Assisted Virtual Planning]. Handchirurgie, Mikrochirurgie, plastische Chirurgie : Organ der Deutschsprachigen Arbeitsgemeinschaft fur Handchirurgie : Organ der Deutschsprachigen Arbeitsgemeinschaft fur Mikrochirurgie der Peripheren Nerven und Gefasse 2018;50(5):310-8.
35. Fürnstahl P, Vlachopoulos L, Schweizer A, Fucentese SF, Koch PP. Complex Osteotomies of Tibial Plateau Malunions Using Computer-Assisted Planning and Patient-Specific Surgical Guides. J Orthop Trauma. 2015;29(8):e270-6.
36. Alagic Z, Bujila R, Enocson A, Srivastava S, Koskinen SK. Ultra-low-dose CT for extremities in an acute setting: initial experience with 203 subjects. Skeletal radiology. 2019.
37. Mihalič R, Trebse R. Modern approach to periacetabular osteotomy performed with osteotomy guiding jigs and navigation2014.

38. Liu L, Siebenrock K, Nolte L-P, Zheng G. Computer-Assisted Planning, Simulation, and Navigation System for Periacetabular Osteotomy. In: Zheng G, Tian W, Zhuang X, editors. Intelligent Orthopaedics: Artificial Intelligence and Smart Image-guided Technology for Orthopaedics. Singapore: Springer Singapore; 2018. p. 143-55.
39. Jud L, Furnstahl P, Vlachopoulos L, Gotschi T, Leoty LC, Fucentese SF. Malpositioning of patient-specific instruments within the possible degrees of freedom in high-tibial osteotomy has no considerable influence on mechanical leg axis correction. Knee Surg Sports Traumatol Arthrosc. 2019.
40. Prokopetz JJ, Losina E, Bliss RL, Wright J, Baron JA, Katz JN. Risk factors for revision of primary total hip arthroplasty: a systematic review. BMC musculoskeletal disorders. 2012;13:251-.
41. Carrillo F, Roner S, von Atzigen M, Schweizer A, Nagy L, Vlachopoulos L, et al. An automatic genetic algorithm framework for the optimization of three-dimensional surgical plans of forearm corrective osteotomies. Medical Image Analysis. 2020;60:101598.
42. Anthony M DiGioia III BJ. Computer-assisted tools and interventional technologies The Lancet 354.

Figures

Figure 1

Radiographs (A) and volumetric rendering (B) of a LCP disease affected hip. The new contour of the head resembles a mushroom with a short neck and a high-riding trochanter.

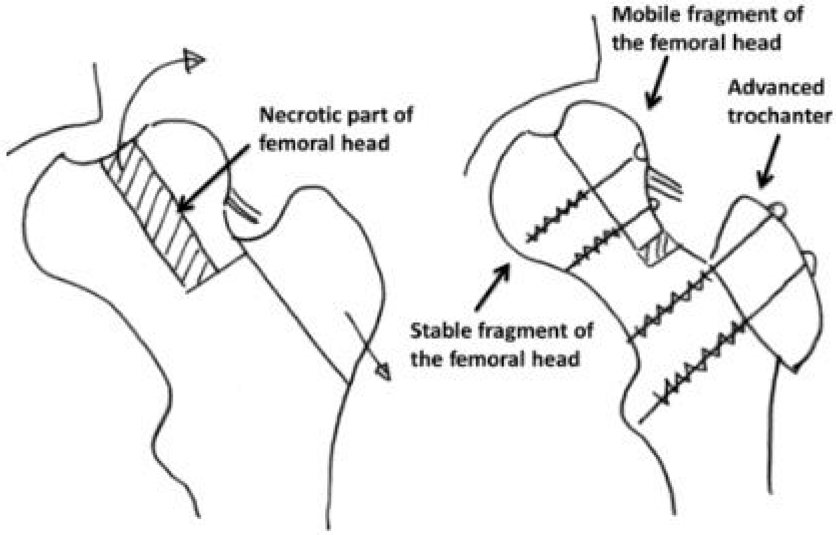

Figure 2

Modified from Fig. 9 Ganz et al. 2009(1)

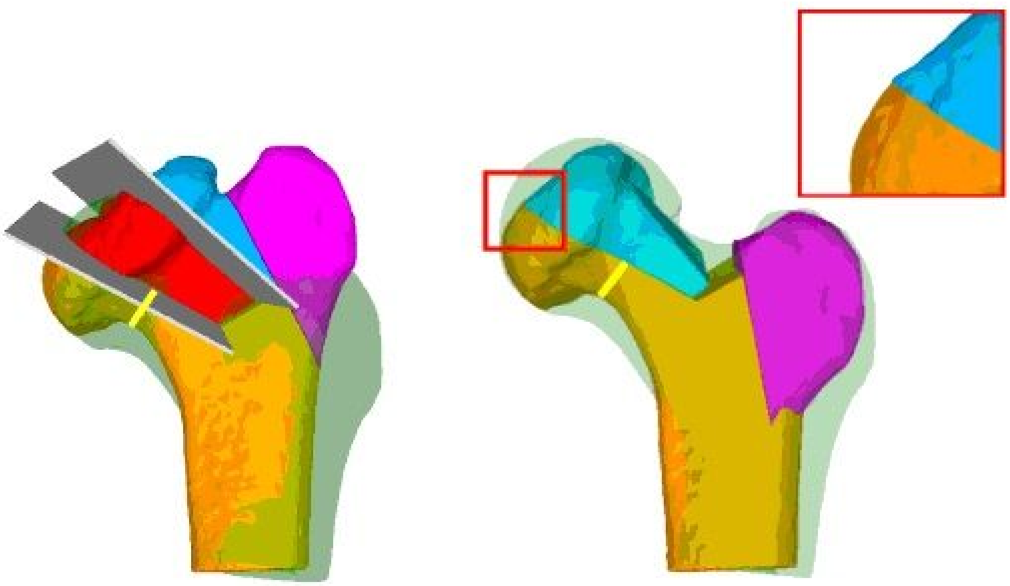

Figure 3

Preoperative computer simulation of the FHRO surgery. The greater trochanter shown in purple, the mobile fragment in blue, the necrotic part in red and the stable fragment in orange. The yellow line representes the remaining femoral neck thickness and the shadow contour the template. A)Preoperative pathological femur. B)Postoperative femur. The red square visualizes the contact zone between the fragments.

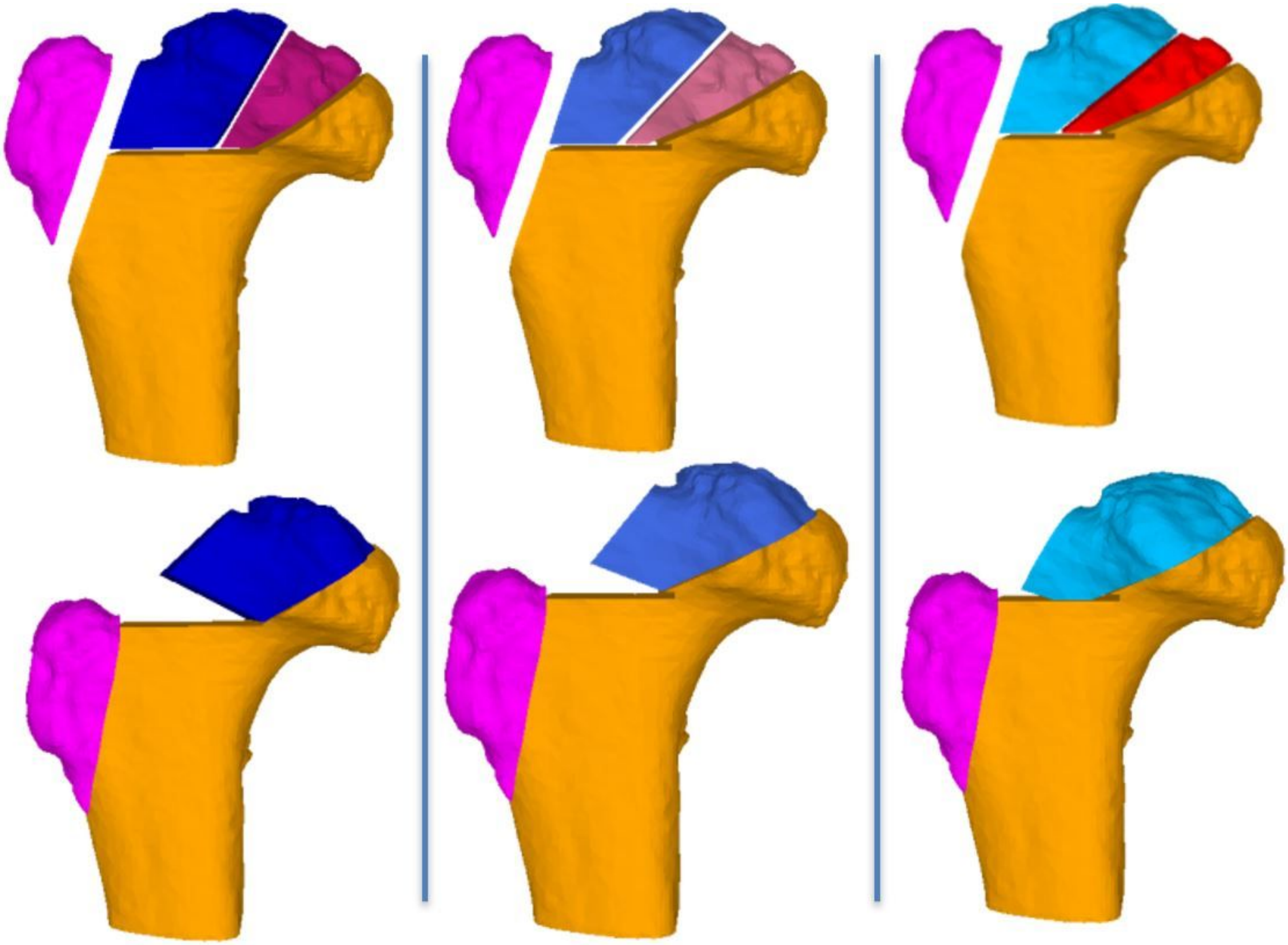

Figure 4

Iterative fine-tuning of the osteotomy planes (top row) and reductions (bottom row) is required until the optimal solution for the FHRO can be found. Each column represents one simulated planning solution. The right most solution was implemented in the surgery.

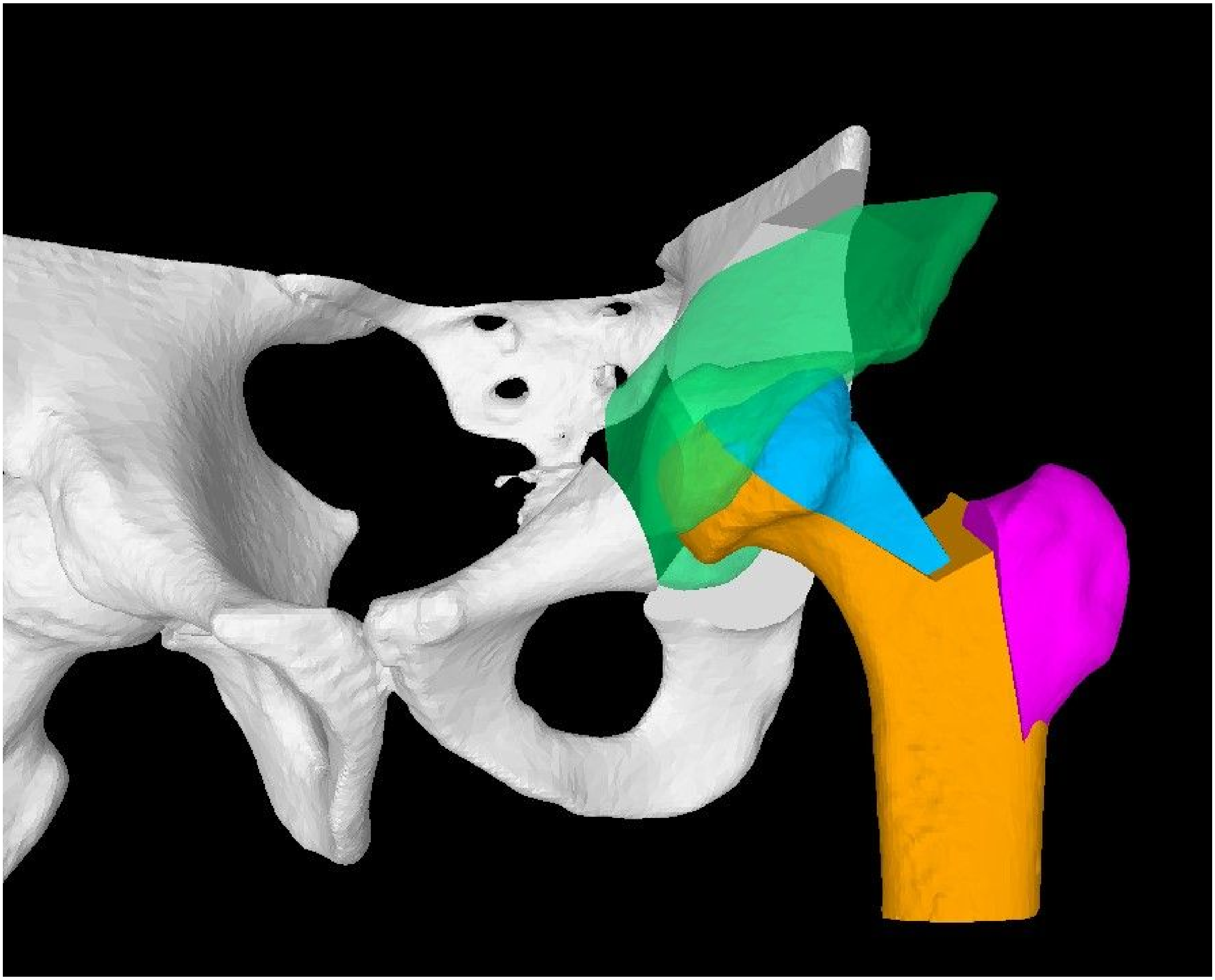

Figure 5

Simulation of a combined FHRO and PAO. The reduced fragments of the femur and acetabulum are shown in blue and green, respectively.

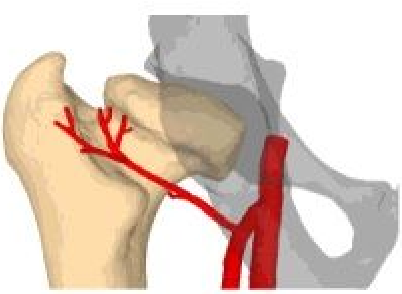

Figure 6

The proposed PSI design for the navigation of FHRO. (A) The PSI contains two cutting slits for guiding the blade of the surgical saw and two drill sleeves for temporary fixation of the PSI with surgical pins. (B) The undersurface of the PSI is shaped as a negative of the patient's bone surface.

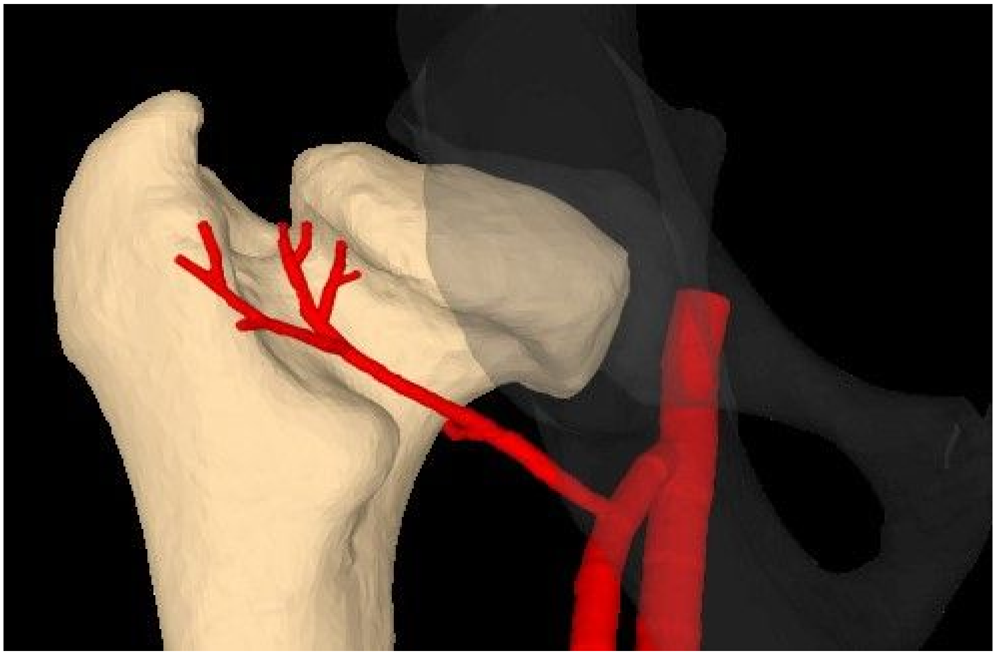

Figure 7

Posterior view of a LCP hip with a schematic 3D model of the medial curciumflex femoral artery (red)

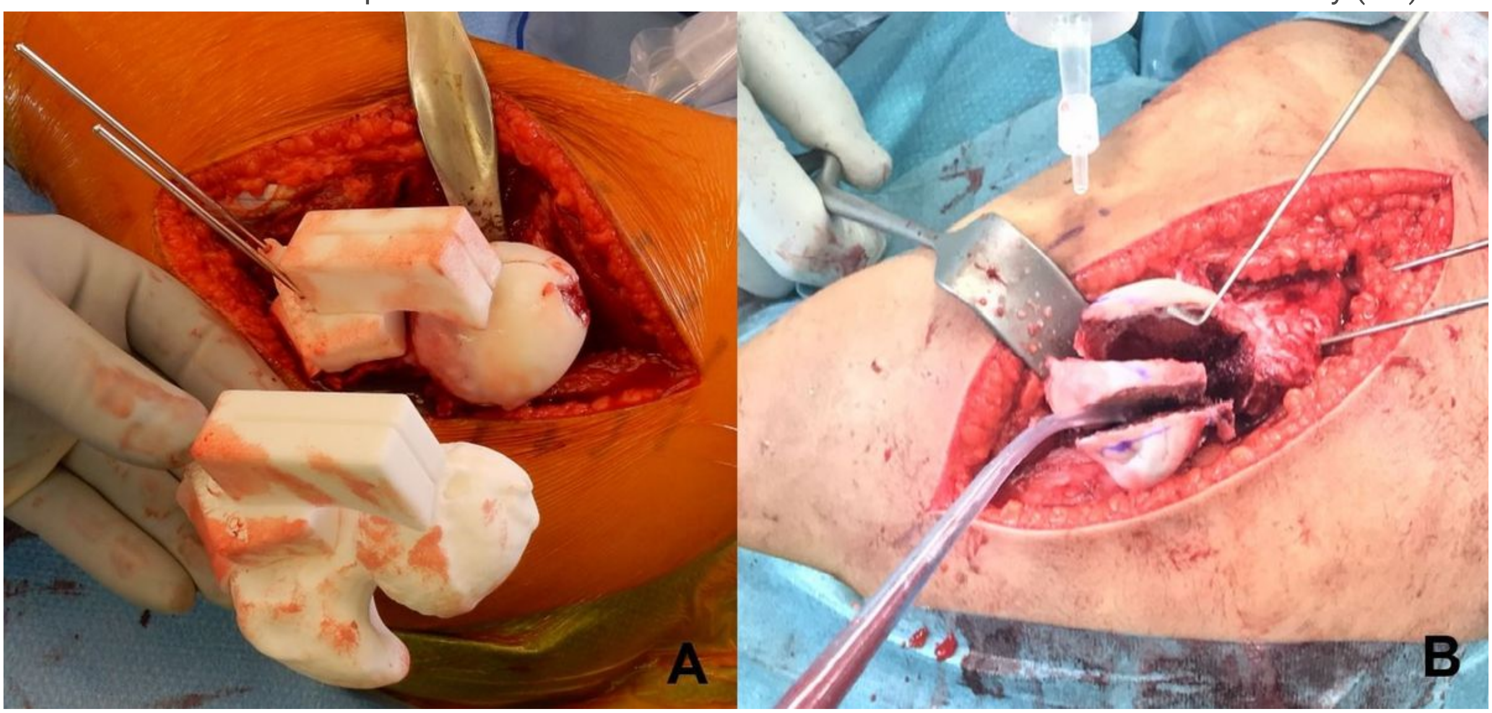

Figure 8

Application of the PSI in the surgery. (A) A patient-specific model of the patient bone was used to verify the correct position of the PSI in the surgery. (B) Resection of the centrally located nectrotic fragment.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- rawdata.xlsx