3D Printing in Hip Surgery

Subjects: Orthopedics
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Three-dimensional printing, also known as additive manufacturing, is the process of creating objects from a 3D digital model layer by layer. Its origin dates back to 1984, when Chuck Hall developed his patent “Apparatus for production of three-dimensional objects by stereolithography”. There are many surgical applications of 3D printing in hip surgery, most of them based on CT images.

Keywords: 3D printing ; hip surgery ; PSI

1. Proximal Femoral Osteotomies

1.1. Surgical Planning of Proximal Femoral Osteotomy in Developmental Hip Dysplasia [1]

The 3D-printed model is used to measure the femoral neck anteversion angle. The simulation of the proximal femoral osteotomy is performed with the contralateral side as a reference to restore the correct angles. Once the in vitro osteotomy is completed, the most suitable plate for fixation is chosen. It has been demonstrated that 3D images are more reliable than 2D CT scans when quantifying femoral anteversion in cases of hip dislocation in developmental dysplasia [2].

1.2. Surgical Planning of Triplanar Osteotomy in Slipped Capital Femoral Epiphysis Sequelae [3]

A simulation of the surgical intervention is performed on biomodels by the surgeon. Based on the preoperative CT scan and clinical judgment, the osteotomy is carried out, and a wedge is removed from the trochanteric region to allow for a correction in flexion and valgus. The 3D model enables the surgeon to visualize the head–neck junction and optimize the physis orientation to achieve the desired correction. If the initial wedge is considered inadequate, additional cuts may be made to achieve an acceptable correction. Once the desired reduction is achieved, the fragments are secured with a Kirschner wire.

A similar technique has been employed for combined proximal and diaphyseal osteotomies in cases of sequelae of osteomyelitis. In this scenario, both lower limbs are printed, and the mirror image of the healthy femur is used as a reference to guide the osteotomy [4].

1.3. Patient-Specific Instrumentation in Developmental Hip Dysplasia and Legg–Calvé–Perthes Disease [5][6][7]

Based on preoperative analyses, and in comparison with the contralateral side, varus and rotation angles, as well as the required length to shorten, are calculated. The guide includes two proximal sleeves for K wires which will help position the synthesis plate and guide the achievement of the desired varus. Two distal sleeves will assist in the fulfillment of the rotation. A proximal and distal saw guide permits the shortening. In order to succeed in the exact adaptation of the guide on the bone cortex, the authors suggest a Boolean operation, subtracting the femur from the guide.

Once the osteotomy is performed, the resulting bone fragment and the guide are removed, and the previously inserted wires serve as levers to achieve the correct positioning and orientation. The wires are then removed, and their holes can be used for inserting screws into the planned plate.

1.4. Patient-Specific Instrumentation for Shepherd’s Crook Deformity (Pauwell’s Osteotomy) [8][9]

Preoperative planning is based on the Hilgenreiner epiphyseal angle, which has a normal value of 16 degrees. The difference between the patient’s angle and the standard value will determine the angulation of the fragment (the wedge) to be removed in the osteotomy. After defining this value, the surgical guide is designed.

The boundaries of the wedge are positioned proximally along a horizontal line that extends below the greater trochanter to the inferomedial femoral neck cartilage and distally by an oblique line from the lateral cortex to the first pin.

For the guide design, the lateral femoral surface is used, which is extracted and extruded using processing software for a perfect fit. The guide includes holes for Kirschner wires that secure the guide to the bone and channels for saw insertion.

1.5. Patient-Specific Instrumentation for Acquired Complex Deformities of the Proximal Femur [10]

A better understanding of the deformity and the required correction plates is achieved through a mirror image of the contralateral bone, which is superimposed onto the affected femur. Once the desired correction is determined, a custom surgical guide is designed. This guide incorporates the individual features of the bone to ensure a precise fit in a specific location. Since a subvastus approach is commonly used, the intertrochanteric crest, along with the circumference of the femoral diaphysis, is often used as a reference point. This positioning can be supplemented by integrating stabilizing arms into the guide that can attach to other regions of the femur.

Once the guide is placed on the femur, reference pins are used, which are inserted into the bone through specific sleeves or chimneys. These pins serve as references for placing the remaining surgical guides. To prevent bone weakening, these pins may later be used as holes for plate screws.

In most cases, a cutting guide is designed for an oscillating saw, including references for inclination, direction, and depth. If curved osteotomies are required, a guide with multiple chimneys for drilling holes that can be connected later may be designed.

2. Periacetabular Osteotomy in Developmental Hip Displasia

2.1. Surgical Planning [11][12][13][14]

After the acquisition of images with a CT scan, a 1:1 scale pelvic biomodel is printed on plastics such as ABS or PLA (or salt [13]) in order to perform an in vitro surgery on it. The fragment is rotated to achieve the position with the greatest coverage and stability of the hip, securing it with Kirschner wires. Once the simulation is performed, the model can be taken to the operating room to guide the surgeons in the in vivo procedure. The model can also be used to improve doctor–patient communication.

2.2. Patient-Specific Instrumentation [15][16]

In the first step, the surgeon conducts virtual planning and design of the osteotomy according to the principles described by Ganz [17] or Tönnis. The design of the surgical guide is based on the surface of the resulting independent fragment after the osteotomy at the level of the quadrilateral plate. Two or three holes, 2 mm in diameter, are added for fixation using Kirschner wires. Another surgical guide can be designed to help with the rotation of the fragment. After virtually reducing the osteotomized fragment, it is possible to design a guide that would occupy the empty space between the pelvis and the free fragment, which can be used in surgery to guide the rotation and position the fragment. The available evidence suggests that patient-specific cutting guides have shown an increased precision while reducing surgical times and the need for intraoperative radiation compared to traditional methods [18].

A procedure with PSI has been described in adults for traumatic hip dysplasia, creating supraacetabular osteotomy guides in which the supraacetabular osteotomy is performed with a saw guide, and the retro acetabular osteotomy is carried out with the aid of positioning Kirschner wires [19][20].

3. Femoral Head Reduction Osteotomy in Avascular Necrosis of the Hip

Surgical Planning [21]

During the segmentation process, a 3D reconstruction of the femoral head is obtained. In a first step, a virtual planning of the osteotomy is performed on the computer, adjusting the osteotomy site to create the more spherical shape as possible. After executing the procedure on the processing software, the model is printed in order to assess the roundness of the femoral head and its congruity with the acetabulum.

In vitro planification surgery can also be performed if the femoral head 3D model is printed prior to virtual surgery.

A similar procedure has been described in cases of developmental hip dysplasia [14].

4. Primary Total Hip Arthroplasty

4.1. Surgical Planning in Acetabulum Fracture Sequelae [22]

Once the affected hemipelvis is printed, the next step involves selecting the appropriately sized implant (acetabulum). This is done using the test components included in the set distributed by the commercial company. Additionally, the necessary augmentations are chosen to fill the existing cavities. Once the surgery has been planned in vitro, the biomodel is sterilized to make it suitable for use during the surgical intervention.

4.2. Surgical Planning in Dysplastic Acetabulum [23][24]

The affected hemipelvis is segmented and printed in order to perform an in vitro surgery. In the first step, all the osteophytes around the Harris fossa are removed. Once the acetabular center is assessed, the reaming process is performed until the best fit is observed. Once the acetabular cup is positioned, the remaining defect is filled and measured with bone wax.

4.3. Reaming of the Acetabular Component: The Positioning Ring PSI Method [25]

Originally described for developmental hip dysplasia sequelae, this method is based in the positioning of a ring guided by PSI, facilitating the subsequent reaming process, which is performed thanks to the orientation driven by the ring. For the PSI design, the contralateral (healthy) acetabulum serves as reference to address the true center of rotation. The angulation and anteversion of the cup are chosen according to the contralateral acetabulum, and its size is adjusted to avoid the disruption of the anterior or posterior walls of the true acetabulum. The ring represents the final positioning of the cup and is designed 2 mm wider than the expected cup size. The superior part of the original acetabulum is chosen as the reference landmark to position the PSI, which is fixed with K wires that are also oriented to assist in the reaming. The ring is latterly attached to the PSI. The reamer is kept in the middle of the ring, and the reaming process finishes when a reamer 2 mm below the size of the ring is used.

4.4. Reaming of the Acetabular Component: The K Wire Crown PSI Method [26][27][28]

As in the previous case, a specular image of the healthy acetabulum is used in cases of dysplasia to localize the true center of rotation. The guide fits onto the bony surface of the acetabular rim or within the acetabulum, avoiding contact with the degenerative residual cartilage. The guide is created with multiple holes to place a crown of K wires around the future acetabulum, serving as a guide for the reaming. Once the reaming is finished, these wires also serve as a guide for the positioning of the cup.

4.5. Reaming of the Acetabular Component: The Single K Wire in the Center of the Acetabulum PSI Method [28][29]

To establish the center of rotation of the acetabulum, it is visualized as part of a sphere. Spheres of different diameters are positioned in the acetabulum. The one with the maximum contact surface is chosen. Reference values of 40 degrees of inclination and 15 degrees of anteversion are used to draw a line from the center of the sphere to the acetabulum. The point where it intersects the acetabulum becomes our reaming center in which a guide will position a K wire. The positioning guide consists of the following components: a central hole for the wire and two or three branches that attach to the acetabular rim. After positioning the guide, a Kirschner needle is inserted through the guide. Reamers with a cannulated handle are required to allow the use of the guiding Kirschner wire.

4.6. Patient-Specific Instrumentation for Femoral Neck Osteotomy [28][30]

Following the hip segmentation, the guide for the femoral neck osteotomy (above the tip of the lesser trochanter and at an angle of 45 degrees to the femoral shaft) is determined based on preoperative three-dimensional planning, including coronal (XZ) and sagittal (YZ) alignment of the femoral component.

Two different designs have been reported. One of the designs features a slot for performing femoral neck osteotomy using a saw, whereas the other design defines a blunt cutting surface at the edge of the guide. Both guides include a fixation area on the proximal part of the femoral neck.

It should be noted that these guides direct the osteotomy but cannot adjust the anteversion of the femoral stem.

4.7. Patient-Specific Instrumentation for Femoral Diaphyseal Osteotomy in Crowe IV Developmental Hip Dysplasia [31]

This technique is useful when there is a greater length in the affected femur than in the contralateral side. A measurement is performed on both femurs to assess the length to shorten. The design of the surgical guide uses the surface of the posterior femur, distal to the lesser trochanter, ensuring adaptation to this anatomical region. The guide locks to the femur with K wires and limits the surfaces in which the two Z-shaped osteotomies should be performed in order to shorten the femur.

5. Revision Total Hip Arthroplasty

5.1. Surgical Planning [32][33][34][35][36][37]

The pelvic bones, prosthesis and femur should be segmented and printed independently. These models can be reamed, and acetabular components can be placed in situ to assess the need for augmentations. In cases with significant defects (pelvic discontinuities), the placement of union supports using processing software may be necessary to prevent their movement during maneuvers. This technology enhances both sensitivity and precision in defect evaluation, providing better localization and increased efficiency compared to plain radiographs and CT scans [38].

5.2. Training of Orthopedic Surgery Residents [24][39]

Anatomical biomodels are prepared for patients with or without acetabular deformities and from whom the femur has been removed. This process is undertaken for the assessment of the clinical case and the practical training of surgical interventions in resident training courses. In those cases with big defects, such as revision surgeries, models are printed in two colors to facilitate a better assessment of the defects.

6. Femoroacetabular Impingement

6.1. Surgical Planning of Osteoplasty in Femoroacetabular Impingement [40]

The acetabulum the femoral head and neck models are printed separately. It has been demonstrated that the use of models contributes to modify the surgical approach regarding the location and amount of resection in 90% of femoral resection cases and 100% of acetabular resection cases.

6.2. Patient-Specific Instrumentation for CAM Osteoplasty [41]

After acquisition and segmentation, two guides are created during processing. For the “Femoral Head Guide”, a sphere is designed on the healthy side, adapting its dimensions to those of the femoral head. Once this sphere is obtained, another sphere is created with a diameter 5 mm larger. Using a Boolean subtraction operation, the “custom sphere” is subtracted from the larger one, resulting in a hollow sphere with a wall thickness of 5 mm, which is cut to obtain a quadrant corresponding to a quarter of the total surface. A cylinder is added to be used as a handle for the guide during surgery. Another small cylinder is added to the front of the guide as a reference for the anterior and posterior parts.

A “Cervicocephalic Junction Guide” is created as a contoured plate, 6 mm in width and 3 mm in thickness, designed to fit the contour of the femur at the cervicocephalic junction. A cylinder is added as a handle. This guide will be used as a limit, marking the end of the femoral head.

6.3. Self-Manufacturing of an Arthroscopy Simulator [42]

All unnecessary bone structures are removed during segmentation, retaining only the anterior superior iliac spine, the acetabulum, and the proximal femur. Since CT scans are performed in the supine position, the femur is repositioned to simulate traction conditions. This allows access to the central compartment for the simulated operations.

The simulator consists of two main parts: a soft component to simulate soft tissues and a hard component to simulate bone structures. As the acetabular labrum cannot be clearly defined in the CT scan, it is manually designed with a thickness of 3–4 mm and a width of approximately 8 mm. Nine fixed markers are incorporated on the surface of the acetabulum from the 8 o’clock to the 4 o’clock positions to facilitate the intra-articular identification of anatomical structures.

7. Osteosynthesis of Intracapsular Neck of Femur Fractures (Garden I or II)

Patient-Specific Instrumentation [43]

The virtual planning of the desired screw positions is performed during image processing. The design of a percutaneous surgical guide that sits perfectly on the bone cortex, taking into consideration the skin surface, is carried out. The guide includes three chimneys to position the Kirschner wires for the cannulated screws. To aid in the positioning of the guide, an extra chimney for a Kirschner wire that slides along the anterior surface of the femoral neck is included. This wire will help the surgeon maintain the guide in the desired position during the procedure.

8. Osteosynthesis of Extracapsular Neck of Femur Fractures

8.1. Surgical Planning [44][45]

Care should be taken during segmentation in order to separate individual bone fragments. Using software, a virtual reduction of the fracture is performed, and the most suitable implant and positioning are selected. Printing is carried out twice for each fracture: as the unreduced, monoblock fracture, and subsequently, each of the individualized bone fragments is printed for manual reduction in a physical manner. The advantages highlighted by the authors for this surgical planning approach include reduced surgical time, decreased blood loss, and a shorter time until ambulation.

8.2. Self-Manufacturing of Surgical Tools: A Device to Prevent Excessive Drill Penetration during Cortical Drilling of Distal Screws [46]

The design involves a screw nut with a side opening. This design allows the device to be inserted above the drill bit without requiring its removal from the drill. As the drill bit is introduced, the screw rotates around the nut. This has a dual purpose—on the one hand, it provides a secure grip for the surgeon to handle the system effectively, and on the other, it adjusts the length of the device to suit the specific requirements of each patient. This device has been shown to improve the precision of surgeons' drilling, especially among those who are less experienced.

8.3. Surgical Planning and Nail/Plate Pre-Bending in Atypical Femur Fractures with Bone Deformity [47][48]

For the selection of the most suitable nail, two orthogonal X rays of the femur are printed on paper. Various options for femoral nails and plates are placed on these paper prints to assess which one provides the best fit. Once the most suitable hardware is chosen, the complete femur is printed. An anatomical reduction of the fracture is manually performed if required, and the nail or plate is bent as needed. The standard antegrade nailing or MIPO technique is applied in vitro to assess the correct fit. In this simulation, all techniques that may be anticipated in real surgery, such as the use of Poller screws, can be employed.

8.4. Surgical Planning and Plate Pre-Bending in a Peri-Implant Proximal Femur Fracture on an Arthrodesed Hip [49]

The model is printed including the pelvis and the entire femur. All artifacts caused by the DHS system used for the original arthrodesis are removed with a gouge during post-processing. Once these are removed, the desired implant is adapted. Various implants can be bent in order to choose the one with the best fit to the patient's anatomy. The author's preferred plate was a contralateral LISS plate in an anterograde direction. Temporary fixation is performed on the 3D biomodel using Kirschner wires to ensure that the screw trajectory will not penetrate the greater sciatic notch or the ilium. The definitive surgery is then carried out in a minimally invasive manner.

9. Trephination of Specific Trabeculae from Femoral Heads

Patient-Specific Instrumentation [50]

A CT scan with 0.625 mm slices is recommended for this purpose due to the size of the object of interest. According to the needs of the study, principal compressive trabeculae (PCT), principal tensile trabeculae (PTT) or bone tumors are localized using multiplanar reconstructions (MPR) with the segmentation software. Once the best corridor for the graft/biopsy extraction is selected, the design of the surgical guide is performed. Two cylinders (7.15 and 8.15 mm radii) are digitally positioned inside the main trabecular bundle, defining the channel for the trephine. This channel is created through a Boolean subtraction operation, creating a chimney. In the next step, a hemispherical dome is generated over the head. The head is then extracted with a Boolean subtraction operation, achieving a perfectly fit mold of the femoral head. Both the chimney and the dome are connected by a Boolean addition operation. The trabeculae are extracted with a trephine.

10. Soft Tissue Sarcomas of the Thigh

Surgical Planning and Teaching [51]

The segmentation is carried out by removing the muscles of the thigh and adjusting the transparency of the tumor. Bone, arteries, veins and nerves must be segmented separately applying masks of different colors.

Table 1. Current applications of in-house 3D printing in hip orthopedic surgery.

Category	Application	Type of Study	N*	Country
Preoperative planning	Proximal femoral osteotomy in DDH [1]	Retr. comparative	40 (20)	China
	Triplanar osteotomy in slipped capital femoral epiphysis sequelae [3]	Prosp. comparative	15 (5)	USA
	Periacetabular osteotomy in DDH [11][12][13][14]	Case report [11]	1 (1)	USA
		Case series [12]	42 (42)	USA
		Case report [13]	1 (1)	Japan
		Case series [14]	4 (4)	Italy
	Femoral head reduction osteotomy in AVN of the hip [21]	Case series	2 (2)	Turkey
	Primary THA in acetabulum fractures sequelae [22]	Case report	1 (1)	Spain
	Primary THA in dysplastic acetabulum [23][24]	Case series [23]	17 (17)	China
		Case series [24]	14 (14)	China
	rTHA [32][33][34][35][36][37]	Case series [32]	3 (3)	Ireland
		Case series [33]	17 (17)	Russia
		Case report [34]	1 (1)	Bulgaria
		Case report [35]	1 (1)	USA
		Retr. comparative [36]	45 (21)	Spain
		Retr. comparative [37]	72 (20)	Italy
	Osteoplasty in femoroacetabular impingement [40]	Case series	10 (10)	USA
	Osteosynthesis of extracapsular neck of femur fractures [44][45]	Prosp. comparative [44]	39 (19)	China
		Meta-analysis [45]	346 (172)	China
	Atypical femur fractures with bone deformity [47][48]	Case report [47]	1 (1)	South Korea
		Case series [48]	2 (2)	South Korea
	Peri-implant proximal femur fracture on an arthrodesed hip [49]	Case report	1 (1)	China
	Soft tissue sarcomas of the thigh [51]	Case series	2 (2)	China

Category	Application	Type of Study	N*	Country
Patient-Specific Instrumentation	Proximal femoral osteotomies in DDH and Perthes disease [5][6][7]	Prosp. comparative [5]	25 (12)	China
		Case series [6]	11 (11)	China
		Retr. comparative [7]	36 (16)	China
	Proximal femoral osteotomies in Shepherd's Crook deformity [8][9]	Device presentation [8]		Italy
		Case series [9]	10 (10)	China
	Osteotomies for complex deformities of the proximal femur [10]	Device presentation [10]		Switzerland
	Periacetabular osteotomy in DDH [15][16]	Prosp. R. trial [15]	20 (8)	China
		Retr. comparative [16]	38 (20)	China
	Reaming of the acetabular component in THA [25][26][27][28][29]	Prosp. R. trial [25]	25 (12)	China
		Prosp. R. trial [26]	36 (18)	USA
		Case series [27]	24 (24)	Japan
		Review [28]		Japan
		Retr. comparative [29]	72 (40)	China
	Femoral neck osteotomy in THA [28][29][30]	Review [28]		Japan
		Retr. comparative [29]	72 (40)	China
		Case series [30]	30 (30)	Switzerland
	Femoral diaphyseal osteotomy in Crowe IV DDH [31]	Case series	12 (12)	China
	CAM osteoplasty [41]	Case report	1 (1)	India
	Osteosynthesis of intracapsular neck of femur fractures [43]	Prosp. comparative	40 (20)	China
	Trephination of specific trabeculae from femoral heads [50]	Prosp. R. trial	20 (10)	China
Training	Training of orthopedic residents in rTHA [39]	Case series	2 (2)	Brazil
	Hip arthroscopy simulator [42]	Cross sectional	19	China
	Soft tissue sarcomas of the thigh [51]	Case series	2 (2)	China
Surgical tools	A device to prevent excessive drill penetration during cortical drilling of distal screws	Prosp. R. trial	40	Spain

DDH (developmental dysplasia of the hip), AVN (avascular necrosis), THA (total hip arthroplasty, rTHA (revision total hip arthroplasty), N*: sample of patients. In brackets, patients in which 3D printing was used, Retr. (Retrospective), Prosp. (Prospective), R. (Randomized).

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