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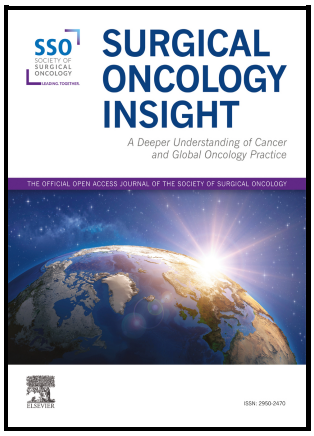

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Outcomes of Pelvis Resections and Reconstructions using 3D Printed Instruments Referencing the Acetabulum

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Abstract

Background: Oncologic resections and reconstructions of the pelvis are among the most challenging procedures in orthopedic surgery due to complex anatomy, tumor variability, and the need for precise margins. Patient-specific instrumentation (PSI) created with 3D printing has emerged as a promising solution, but accurate intraoperative referencing remains difficult. This study evaluates the use of novel acetabular-referencing PSI cutting guides for pelvic tumor resections and reconstructions.

Methods: Five patients (mean age 57.2 years) underwent pelvic resections with acetabular-referencing PSI between 2019 and 2023. Each guide incorporated a hemispherical feature seating within the acetabulum after femoral head removal. Postoperative CT reconstructions were compared with preoperative plans to assess resection accuracy, implant alignment, operative time, and margin status.

Results: All patients achieved negative gross margins; two had microscopically positive margins (one planned). Mean operative time was 8 hours 52 minutes, including two complex procedures. Mean deviations were 8.32 mm for center of rotation (CoR) and 7.37 mm for center of gravity (CoG). Directional CoR deviations averaged 2.62 mm anteroposteriorly, 6.30 mm mediolaterally, and 3.92 mm superoinferiorly. Angular deviations averaged 1.88° in anteversion and –2.54° in inclination. All implants were positioned within or near accepted thresholds for pelvic reconstruction accuracy.

Conclusions: Acetabular-referencing PSI enabled reproducible guide placement and accurate osteotomies in complex pelvic resections without increasing operative time. This technique offers a reliable alternative to surface-contoured guides and may enhance precision in oncologic reconstruction by mitigating challenges of intraoperative interfacing. Larger studies with long-term follow-up are needed to confirm functional outcomes and implant survivorship.

Key words: 3D printing; Additive manufacturing; Patient-specific instrumentation; Orthopedic oncology; Oncologic resection

Introduction

Oncologic resections and reconstructions of the pelvis are highly complex operations that require precise navigation of both critical anatomical structures and the tumor itself [1]. Whether considering the resection or the reconstruction, surgeons must contend with variable disease etiologies, complex patient anatomy, and diverse intervention types—necessitating a surgical approach that is both adaptable and precise. A range of techniques exists, from manual freehand methods relying on direct visualization and measurement to computer-assisted intraoperative navigation. Recent advances in additive manufacturing have introduced promising innovations to pelvic orthopedic surgery in the form of patient-specific instrumentation (PSI) [2,3]. These 3D-printed tools and instruments, including drill and cutting guides, are custom-designed to match the patient's anatomy and help guide surgical instruments such as saws or drill bits along a preplanned trajectory [2,3]. Early results indicate that custom PSI for pelvic resections and reconstructions show promising outcomes [4]. One of the challenges in pelvic referencing involves cutting guides that must conform to relatively subtle bony landmarks. A cutting guide which can be simply and precisely placed would offer a number of advantages. Here the authors describe a novel type of patient specific, pelvic cutting guide which is referenced off of the acetabulum after removal of the femoral head.

Freehand surgery remains common due to its intraoperative flexibility and relatively low resource demands compared to adjunctive technologies like 3D-printed PSI. With freehand surgery, pelvic tumor osteotomies are planned preoperatively using imaging but performed intraoperatively based on direct visualization, anatomical landmarks, and manual measurements. In this approach, the surgeon intraoperatively estimates resection margins and cut trajectories without physical or digital guidance. However, the precision of freehand technique heavily depends upon accurate cognition of the relevant anatomy and complex variability of the pelvic tumor's involvement. Even skilled surgeons may struggle to achieve consistent margins in the pelvis [5]. This variability in accuracy and precision stands in contrast to computer-guided navigation and robotic assistance, which have demonstrated significant improvements in surgical performance [5,6]. Compared specifically to PSI, manual freehand techniques have shown lower precision [2,7,8]. Similarly, intraoperative computer-guided navigation with 3D planning is generally more accurate than freehand methods [6,9,10]. However, these navigation systems can increase operative time, which may raise the risk of contamination, infection, radiation

exposure, financial cost, and blood loss [11,12]. When a custom implant is being utilized to reconstruct the bony pelvis, freehand surgery is rarely practical, as there must be a precise match between the implant and the cuts made.

When comparing PSI to computer navigation, several studies suggest that PSI offers faster execution times without sacrificing precision [12,13, 14]. In fact, PSI may even yield a smaller standard deviation in surgical accuracy compared to computer navigation [7,14].
With comparable precision and improved speed, PSI may help reduce complications associated with prolonged surgical durations [7,14,15]. They are also more cost-effective than navigation-guided surgery [2]. Taken together, custom PSI offers several key advantages for pelvic orthopedic surgery.

Nonetheless, challenges remain in translating virtual planning into accurate intraoperative PSI cutting guide placement, even with custom contouring based on preoperative imaging [16,17]. Historically, PSI cutting guides for the pelvis have been referenced off of specific bony surface contours. Intraoperative issues such as soft tissue interference or mismatches between the PSI and bony surface—due to limitations in design or manufacturing—can impair proper fit [18]. One proposed solution is to enlarge the PSI to increase the mating surface area, though this may lead to higher costs and greater invasiveness due to the need for additional dissection and bone exposure [12]. Moreover, without distinct anatomical landmarks, PSIs risk being misaligned, potentially compromising surgical outcomes [4, 13,17]. Therefore, consistent and reliable anatomical landmarks are essential for accurate PSI cutting guide placement. The authors have recently developed a technique of utilizing PSI cutting guides referencing the acetabulum – rather than surface bony landmarks - as a means of making bony cuts during pelvic resections. This provides a simple and obvious means of "seating" the cutting guide against the pelvis. This study aims to evaluate the efficacy, potential benefits, and limitations of using patient-specific instruments that reference the acetabulum as a landmark in pelvic orthopedic surgery.

Methods

Study Design

This retrospective study included five patients who underwent radical resections of pelvic malignancies guided by custom 3D-printed surgical guides that referenced the acetabulum as the critical anatomical landmark for seating the cutting guide. Each patient underwent both a preoperative and a postoperative CT scan. All patients provided informed consent after comprehensive discussions of the procedure and alternative treatment options. The primary clinical indications for surgery included large, invasive pelvic malignancies associated with significant bony deformities, functional deficits, and the failure of previous reconstructions and/or treatments. Each patient was determined to be an appropriate candidate for the use of patient-specific 3D-printed instruments and implants.

Patient Demographics

A total of five patients who underwent tumor resections between 2019 and 2023 were included. The cohort consisted of four females (aged 43, 64, 66, and 62 years) and one male (aged 51 years), with a mean age of 57.2 years. Body mass index (BMI) ranged from 23.58 to 41.09 kg/m², with an average of 30.59 kg/m². Relevant preoperative comorbidities included obesity, diabetes, hypothyroidism, and hyperthyroidism.

Patient	Case 1	Case 2	Case 3	Case 4	Case 5	Mean
Age (years)	43	64	51	66	62	57.2
BMI (kg/m^2)	34.16	41.09	23.83	23.58	30.28	58 kg/m^2

Diabetes	Prediabetes	Yes	No	No	No	

Table 1: Case series demographics and certain comorbidities.

Design and Manufacturing of Patient-Specific Instrumentation

To design the 3D-printed PSI, thin-slice computed tomography (CT) scans were first obtained and digitally reconstructed using Materialise Mimics (Leuven, Belgium). These scans were used to generate accurate 3D models of each patient's pelvic anatomy. Once the anatomical models were created, resection margins were planned in close collaboration with the orthopedic oncologist, referencing corresponding magnetic resonance imaging (MRI) scans to ensure adequate resection. A standard 10 mm resection margin was applied to all planned cuts to ensure sufficient clearance from the tumor. Due to the variable complexity of the pelvic malignancies and their surrounding anatomy, different resection approaches were employed. Some resections were planned for use with a straight oscillating saw blade**,** while others required curved resections**,** necessitating the use of a router bit. This flexibility allowed for tailored resections that accommodated patient-specific anatomical challenges and surgical goals.

Following resection planning, the anatomical surface models and proposed resection planes were exported to Materialise 3-matic (Leuven, Belgium), a mesh-based design software used for detailed modeling and PSI creation. Within 3-matic, PSI guides were designed. Each PSI guide was designed to achieve direct anatomical registration by contouring precisely to the patient's bony anatomy, with added tolerance for provisional fixation using 1.6 mm Kirschner wires (K-wires). Importantly, no fixation points were placed in areas scheduled for resection, preserving the integrity of the surgical margin and preventing contamination of oncologic boundaries.

To address the difficulty of achieving accurate registration in areas with complex or irregular anatomy, each guide was designed with a novel spherical registration feature that referenced the acetabulum. Specifically, the guides included a hemispherical structure designed to seat into the acetabular cup at the location corresponding to the femoral head. This acetabular reference sphere provided a clear and reproducible registration point, offering the surgeon a reliable anatomical landmark to ensure correct placement of the guide intraoperatively. After the guide body, acetabular registration feature, and K-wire holes were finalized, cutting slots were incorporated to complete the guide design. These slots were tailored to the specific dimensions of the surgical saw blade planned for use, allowing for precise trajectory control. A 0.2 mm clearance was included in the cutting slot design to accommodate saw blade thickness and ensure ease of use without compromising accuracy.

All PSI guides were manufactured using Formlabs Durable Resin (Restor3d, Durham, NC), infused with barium sulfate to enable intraoperative visualization under fluoroscopy (Figure 2a, 2b). This material was selected for its biocompatibility, mechanical strength, and stability under intraoperative conditions. In addition to the PSI guides, physical models of the patient's anatomy were also printed using Stratasys MED610 (Restor3d, Durham, NC) (Figure 2c, 2d). These anatomical models reproduced the surface contours corresponding to the PSI fit and were used intraoperatively to visually confirm correct guide placement before osteotomies were performed (Figure 2e, 2f). Figure 1 shows the overall workflow for the creation of custom implants and instrumentation, with Figure 3 demonstrating the option of surgical rehearsal for iterative design.

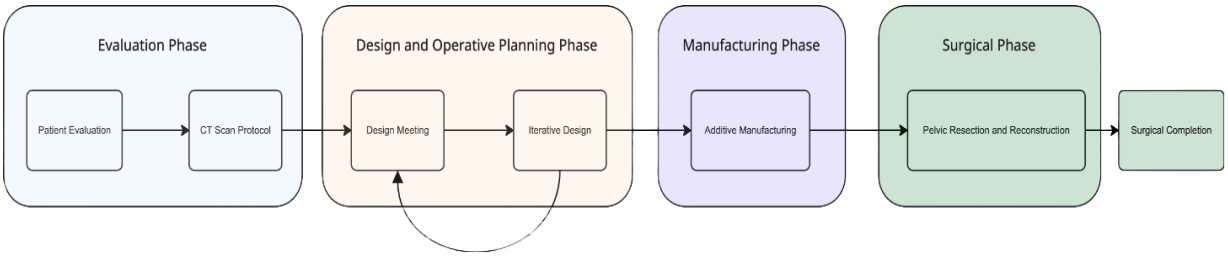

Figure 1. Flowchart illustrating the process of designing custom prostheses and instruments, manufacturing, and surgical implementation

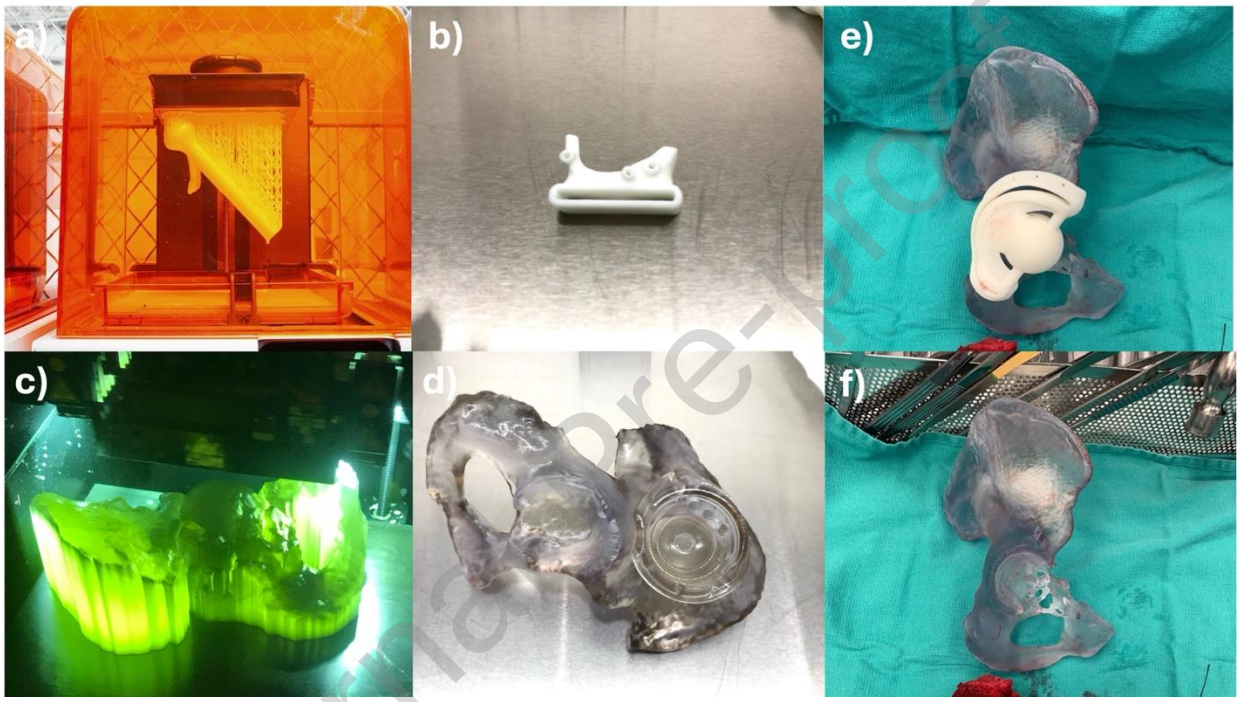

Figure 2. Example manufacturing of cutting guide PSI (b) on a Formlabs Form 2 (a) and patient specific anatomy (d) on Stratasys Objet 500 Connex 3 (c). Intraoperative use of Stratasys Med610 model of patient anatomy with and without the PSI (e, f)

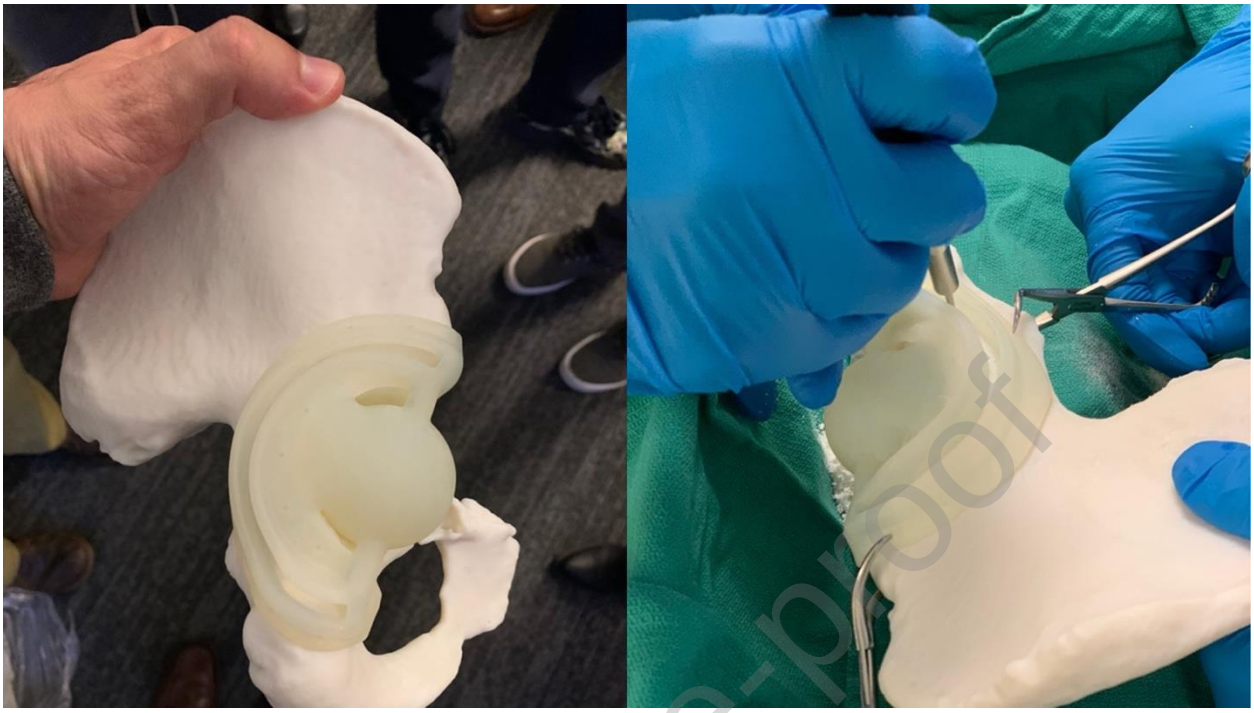

Figure 3. Use of 3D-printed PSIs allow operative rehearsal and fast, low-cost iterative improvements to the design through surgeon feedback and testing

Operative Procedure

All surgical operations in the study were primarily led and performed by the same orthopaedic oncologist, with varying members of the surgical team specific to each case. The typical workflow included, exposure, surgical hip dislocation, femoral neck osteotomy with subsequent removal of the femoral head, placement of the cutting guide within the acetabulum, performance of osteotomies using the acetabulum-based PSI, then removal of the tumor, followed by reconstruction and wound closure. Fixation is achieved with standard titanium screws planned with patient-specific screw trajectories. Figure 5 shows the post-operative reconstructions, with each patient having a patient specific titanium custom prosthesis that can be designed to match any standard femoral component.

Postoperative Analysis

A postoperative CT scan was obtained for each patient and segmented to generate three-dimensional digital reconstructions of the actual postoperative anatomy and implant positioning. These segmented postoperative models were then digitally aligned with the preoperative planning models, which included the intended instrument trajectories and implant locations. Alignment was done based on a geometrical best fit with the individual patient's pelvic anatomy. Rigid registration techniques were employed to ensure accurate alignment between the preoperative and postoperative datasets, allowing for a direct comparison of planned versus actual outcomes. To evaluate the accuracy of the patient-specific instrumentation (PSI), several quantitative measurements were taken. These included translational deviations (in millimeters) and rotational deviations (in degrees) of the implant from the planned position across multiple planes. Coordinate system for anatomical measurements was defined using the ISB pelvis coordinate system. Implant positioning accuracy was evaluated using several key parameters comparing the planned versus actual outcomes. These included differences in the center of rotation (CoR) and center

of gravity (CoG) of the implant, radius of curvature, anteversion, and inclination. To further assess surgical precision, deviations from the planned resection planes were measured in both linear (millimeters) and angular (degrees) dimensions.

In addition to postoperative alignment metrics, intraoperative variables were recorded, including total operative time and margin status, defined as the presence or absence of tumor at the resection margins based on final pathology. These combined measurements provided a comprehensive evaluation of both the technical accuracy and clinical utility of the PSI system in facilitating complex pelvic oncologic resections and reconstructions.

Results

Case 1

This patient was a 43-year-old female with a BMI of 34.16 and prediabetes who presented with hip pain and found to have a right acetabular mass as well as a 17 cm uterine mass on imaging, with biopsy of the osseous lesion showing intermediate-grade chondrosarcoma and biopsy of the uterine mass showing a benign smooth muscle neoplasm. After the initial dissection to the pelvis was performed, two patient specific 3D-printed cutting guides were placed. The first guide was clamped onto the pubis/ischium and its placement was determined by centering a spherical portion of the guide into the acetabulum. The ease of placement of this guide was the genesis for making subsequent referencing based off of the acetabulum. The second guide was placed on the ilium. Both guides facilitated the pelvic resection through complex geometric osteotomies to remove the right acetabulum and ileum anteriorly to the pubic symphysis (Figure 4a). The gynecologic oncology team then performed a total abdominal hysterectomy, removal of broad ligament fibroids, and bilateral salpingectomy. Afterwards, the custom 3D-printed prosthesis was carefully placed in the desired location which was deemed to have a 5mm x 4 mm gap between superior aspect of prosthesis and remaining superior iliac bone" which was subsequently filled with cement after appropriate fixation of the implant with screws and confirmation of prosthesis stability. The proximal femur was then prepared in standard fashion with a press fit stem placed. The acetabular component then cemented into the cup with good stability. A dual mobility trial was placed, and the selected components were confirmed to have acceptable stability and leg length after placement and reduction. A drain was placed, and closure of the wound was performed. Intraoperative findings reported grossly negative margins though final histopathological analysis later reveal microscopically positive tumor margin at the pubic ramus. The total operative time was 10 hours and 12 minutes.

Subsequently, the patient's prosthesis was dislocated while mobilizing 6 days after initial pelvic resection and reconstruction. Dissection and exploration revealed dissociation of the dual mobility head from the trunnion of the femoral component. The head was removed, the intact metal liner replaced with an appropriately sized constrained liner, and then the head was impacted onto the trunnion. The femoral component of the hip was reduced, taken through full range of motion and noted to be secure at all extreme ranges. Figure 5a shows the final implant construct.

Postoperative analysis demonstrated a center of rotation (CoR) deviation of 2.85 mm and a center of gravity (CoG) deviation of 5.36 mm between the planned and actual implant positions. Five osteotomies were performed in this particular patient in order to shape the pelvis for reconstruction using a custom 3D-printed implantable prosthesis. Each osteotomy was executed using flat cut planes guided by patient-specific 3D-printed surgical cutting guides.

Translational deviations from the planned cut planes were measured at 3.60 mm, 1.20 mm, 3.42 mm, 1.36 mm, and 0.65 mm. Corresponding angular deviations were 24.17°, 3.66°, 3.45°, 1.22°, and 1.91°,

respectively, indicating generally high accuracy with one notable outlier. The acetabular cup was preoperatively planned for 20° of anteversion and 50° of inclination. Postoperative analysis revealed an actual anteversion of 22.1°, resulting in a deviation of -2.1°, and an actual inclination of 54.2°, resulting in a deviation of -4.2°.

Case 2

This patient was a 64-year-old female with BMI of 41.09, hypothyroidism, and Type 2 diabetes mellitus who presented with left hip pain and lytic periacetabular grade 2 chondrosarcoma. Dissection to pelvis was performed and a decision was made to perform a chevron osteotomy of the greater trochanter for better visualization of the acetabulum. The left hip was dislocated posteriorly, and the femoral head was removed. The custom cutting guide was seated into the acetabulum and the cutting slots were flush with the bony surfaces of the posterior iliac wing and inferior acetabulum, which facilitated two curved osteotomies for the removal of the oncologic lesion en bloc and for the preparation of the pelvic reconstruction (Figure 4b). The custom 3D-printed implantable prosthesis was placed, and two screws were placed retrograde through the posterior ilium. Another two screws were then placed in a percutaneous, antegrade fashion through the anterior ilium. No inferior fixation was placed due to the inferior bony margin being unable to be reduced to the implant in a manner that seemed conducive to stability. The acetabular cup was cemented into place and the femur was prepared using a cemented system with a modular dual mobility bearing. Intraoperative assessment indicated excellent alignment and stability. The greater trochanter osteotomy was reduced with GT osteotomy was reduced with point of reduction clamps, staples, and final placement of bone graft. The surgical site was closed without complications. Intraoperative findings reported grossly negative margins and pathology report notes all margins were negative for tumor. Total operative time was 9 hours and 35 minutes. Figure 5b shows the final implant construct.

Postoperative analysis revealed a center of rotation (CoR) deviation of 9.7 mm and a center of gravity (CoG) deviation of 9.81 mm from the planned implant position. Two curved osteotomies, each with a planned radius of curvature (RoC) of 113.7°, were performed using patient-specific 3D-printed surgical cutting guides. The actual RoC achieved was 105.6°, corresponding to an angular deviation of -8.1° from the intended curvature. Linear deviations for the two osteotomies were measured at 2.32 mm and 4.37 mm, respectively. The acetabular cup was planned with an anteversion of 17.83° and an inclination of 41.68°. Postoperative measurements showed an actual anteversion of 14.79°, resulting in a deviation of 3.04°, and an actual inclination of 48.32°, resulting in a deviation of -6.64°.

Case 3

This patient was 51-year-old man with a BMI of 23.83 who presented with dedifferentiated chondrosarcoma of the pelvis. Definitive resection and reconstruction were planned while the patient was undergoing neoadjuvant chemotherapy. After initial dissection, the hip was dislocated, and the femoral head was removed. A custom 3D-printed cutting guide was placed securely into the acetabulum and several flat plane cuts to the pelvic bone were made through the cutting guide as to mobilize the tumor (Figure 4c). The pubic symphysis was cut with a Gigli saw. After bony resection and removal of malignant mass, the cutting guide in the acetabulum was removed and a custom 3D-printed prosthesis was placed and secured with 15 screws. Intraoperative assessment indicated the implant was secure and durable despite extremely poor bone quality noted in this patient. The femur was then prepared with a broach only system and a stem was impacted into place. After a successful trial, a cup and constrained liner were assembled and cemented into the implant and the head was placed the femoral component. Intraoperative findings reported grossly negative margins and the final histopathological assessment

found all margins to be microscopically negative as well. The total operative time was 11 hours and 27 minutes. Figure 5c shows the final implant construct.

Postoperative analysis revealed a center of rotation (CoR) deviation of 17.05 mm and a center of gravity (CoG) deviation of 8.28 mm relative to the planned implant position. Three flat-plane osteotomies were performed using patient-specific 3D-printed surgical cutting guides. Linear deviations from the planned cut planes were 2.44 mm, 8.71 mm, and 4.84 mm, while corresponding angular deviations were 1.11°, 8.28°, and 6.66°, respectively. The acetabular cup was planned with 27.2° of anteversion and 50.4° of inclination. Postoperative measurements showed an actual anteversion of 23.16°, resulting in a deviation of 4.04°, and an actual inclination of 59.96°, corresponding to a deviation of -9.56°.

Case 4

This patient was a 66-year-old female with a BMI of 23.58 and hypothyroidism who presented with metastatic carcinoma involving the left hemipelvis resulting in pain and loss of mobility. The patient had already undergone several rounds of chemotherapy, radiation, and a previous excision of her left ilium/sacrum lesion with a Harrington type reconstruction of the left acetabulum and ilium one year prior. After initial dissection, hip dislocation, and cutting of the femoral neck, two custom 3D-printed cutting guides were placed sequentially into the acetabulum and secured. The first guide was utilized to facilitate two curved osteotomies through the ilium and the second guide was placed on the pubis to cut the pubis, allowing the acetabulum containing the tumor to be removed *en bloc* (Figure 4d). After the resection, a custom 3D-printed prosthesis was secured in place with several screws and the femur was prepared, trialed, and reduced without complications. Intraoperative findings reported grossly negative margins, but pathology report notes the sacral bone margin was microscopically positive for tumor (in this case, there was not a goal to obtain negative margins). Total operative time was 6 hours and 51 minutes. Figure 5d shows the final implant construct.

Postoperative analysis revealed a center of rotation (CoR) deviation of 5.87 mm and a center of gravity (CoG) deviation of 9.03 mm compared to the planned implant position. A single osteotomy was performed using a patient-specific 3D-printed surgical cutting guide. The planned osteotomy was curved, with a target radius of curvature (RoC) of 49.81°. The actual RoC achieved was 52.69°, resulting in a deviation of -2.88°. The angular deviation of the osteotomy from the planned trajectory was 10.79°. The acetabular cup was planned with 20.72° of anteversion and 50.34° of inclination. Postoperative measurements showed an actual anteversion of 21.83°, corresponding to a deviation of 1.11°, and an actual inclination of 54.94°, resulting in a deviation of 4.6°.

Case 5

This patient was a 62-year-old female with a BMI of 30.28 kg/m2, and hyperthyroidism who presented with dedifferentiated chondrosarcoma of the right acetabulum, requiring a radical resection of tumor and pelvic structures, total arthroplasty, and reconstruction. After initial dissection, femoral neck osteotomy, and exposure of the acetabulum, a custom 3D-printed cutting guide was placed into the acetabulum. The patient specific guide was used to perform two curved osteotomies to cut the ilium and ischium. A separate pubic osteotomy was also performed, which freed the tumor bearing portion of the pelvis (Figure 4e). The custom 3D-printed prosthesis was implanted with integrated fins and planned screws. Femoral preparation, assembly, and hip reduction were performed without difficulty and dual mobility trials were assessed as stable. Final impants were placed and intraoperative assessment indicated proper implant position, stability and leg length. Intraoperative findings reported grossly negative margins and the final histopathological assessment found all margins to be microscopically negative as well. Figure 5e shows

the final implant construct. The total operative time was 6 hours and 17 minutes. Subsequently, patient had a spontaneous dislocation of her prosthetic hip three weeks post-operatively. The dislocation was treated with a closed reduction without complications.

Postoperative analysis revealed a center of rotation (CoR) deviation of 6.12 mm and a center of gravity (CoG) deviation of 4.35 mm relative to the planned implant position. Two curved osteotomies were performed using patient-specific 3D-printed surgical cutting guides. The planned cut planes had a target radius of curvature (RoC) of 79.35°, while the actual RoC achieved was 80.25°, resulting in a deviation of -0.9°. Linear deviations from the planned cuts were measured at 4.52 mm and 5.52 mm. The acetabular cup was preoperatively planned with 30.58° of anteversion and 56.01° of inclination. Postoperative measurements showed an actual anteversion of 33.89°, corresponding to a deviation of 3.31°, and an actual inclination of 59.11°, resulting in a deviation of 3.1°.

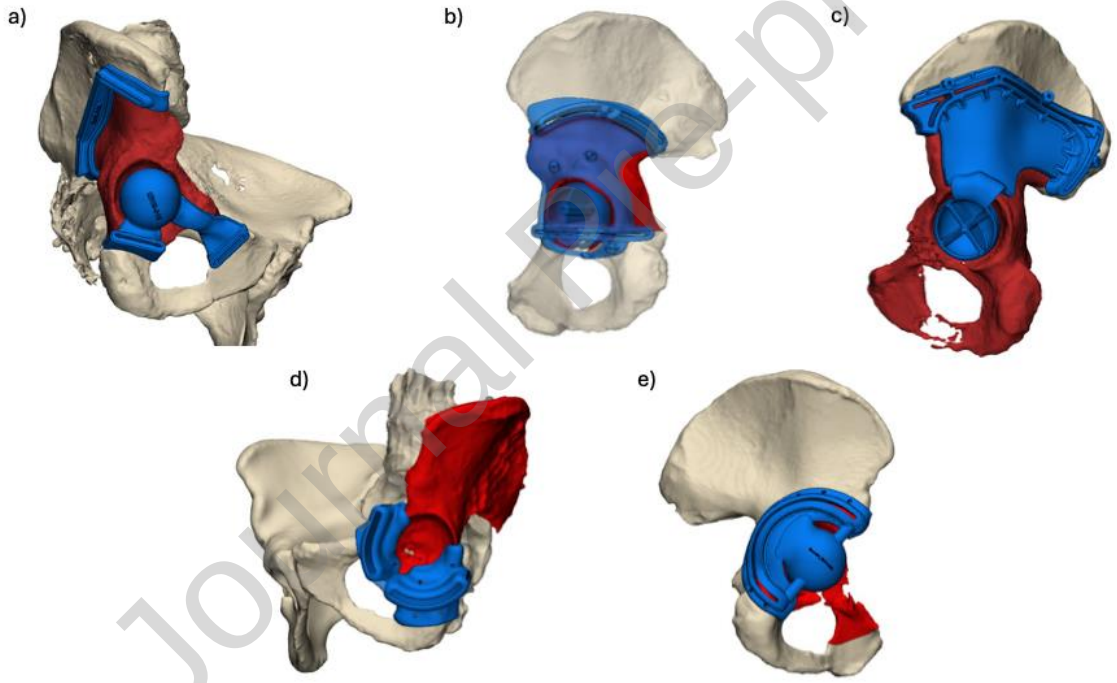

Figure 4. Digital reconstruction of Case 1 (a), Case 2 (b), Case 3 (c), Case 4 (d), and Case 5 (e) with the planned resection represented in red and the PSI is represented in blue.

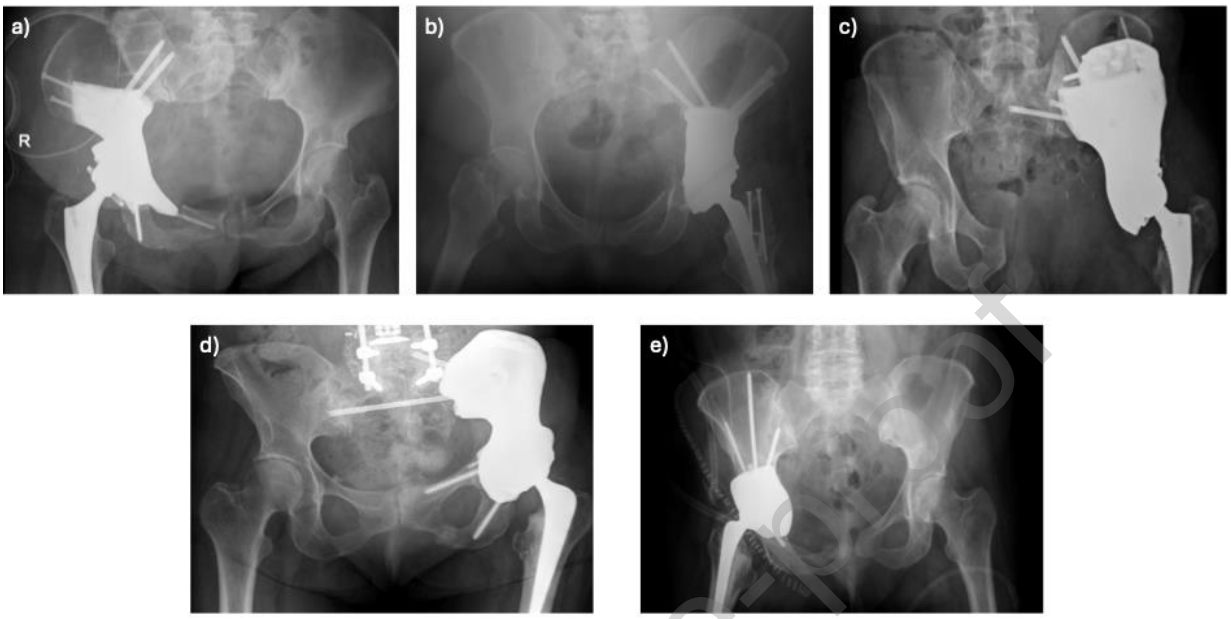

Figure 5. Post-operative X-Ray of Case 1 (a), Case 2 (b), Case 3 (c), Case 4 (d) and Case 5 (e) showing successful implantation of custom prosthesis after resection using a PSI that references the acetabulum.

Summary Data

Data across all 5 cases is shown in Tables 2. Mean operative time across the cohort was 8 hours and 52 minutes, though this included two prolonged procedures with additional complexity (concurrent gynecologic oncology procedures in Case 1 and significant bone removal in Case 3). Gross resection margins were negative in all five patients, while microscopic margins were positive in two patients, one of which was a planned positive margin due to metastatic disease. Postoperative analysis demonstrated a mean center of rotation (CoR) deviation of 8.32 mm and a mean center of gravity (CoG) deviation of 7.37 mm. When decomposed directionally, mean deviations in the CoR were 2.62 mm anteroposteriorly (AP), 6.30 mm mediolaterally (ML), and 3.92 mm superoinferiorly (SI). Angular deviations of the acetabular cup averaged 1.88° in anteversion and –2.54° in inclination. Case 3 demonstrated the highest CoR and CoG deviation from the preoperative plan which could potentially be related to the volume of bone removed.

Patient	Case 1	Case 2	Case 3	Case 4	Case 5	Mean
Intraoperative time	10 hrs, 12 mins	9 hrs, 35 mins	11 hrs, 27 mins	6 hr, 51 mins	6hr, 17 mins	8 hrs, 52 mins ± 2 hours, 12 mins
Gross Margins	Negative	Negative	Negative	Negative	Negative	N/A
Microscopic Margins	Positive	Negative	Negative	Positive (planned)	Negative	N/A

CoR Deviation (mm)	2.85	9.7	17.05	5.87	6.12	8.318 ± 5.31 mm
AP Deviation (mm)	2.15	0.1	5.54	2.2	3.14	2.62 ± 1.97
ML Deviation (mm)	0.66	9.3	14.6	3.32	3.64	6.30 ± 5.47
SI Deviation (mm)	1.74	3.0	6.80	4.31	3.80	3.92 ± 1.86
CoG Deviation (mm)	5.36	9.81	8.28	9.03	4.35	7.37 ± 2.38 mm
Anteversion Deviation (degrees)	-2.1	3.04	4.04	1.11	3.31	1.88 ± 2.47
Inclination Deviation (degrees)	-4.2	-6.64	-9.56	4.6	3.1	-2.54 ± 6.25

Table 2. Case intraoperative time, gross margins, microscopic margins, Post operative implant deviations between planned and actual positioning

Discussion

As advances in additive manufacturing continue to support the integration of patient-specific instrumentation (PSI) and implants in orthopedic surgery, the design paradigms guiding these technologies remain an area of active investigation and rapid refinement. Custom cutting guides for performing geometrically complex pelvic osteotomies are not novel. However, surgeons have noted the difficulty of affixing cutting guides to the specifically selected areas of the bony pelvis. This occurs for a variety of reasons, including the subtlety of selected bony prominences, changes to the shape of the surface of the pelvis due to tumor progression, and the presence of soft tissues that were not detected on CT images used to generate the custom guides. These challenges led to the development of an acetabulum-based system of cutting guide placement. This study suggests that, for complex orthopedic procedures involving the pelvis, the use of PSI specifically designed to sit within – and reference - the acetabulum as an anatomical landmark can facilitate precise osteotomies necessary for pelvic resections.

A 10 mm acceptable margin of error was established by consensus among experienced orthopedic oncologists for this study. The patient-specific cutting guides that utilized acetabular referencing demonstrated a mean linear deviation of 3.54 mm—well within the predefined threshold—indicating high resection accuracy. Implant positioning accuracy was also evaluated using parameters including the center of rotation (CoR), inclination, and anteversion. It is difficult to define what should be the acceptable limits for implant positioning in the context of pelvic resections. In the field of revision total hip arthroplasty, Baauw *et al*. define malposition as more than 10° deviation in inclination or anteversion, or more than 5 mm of deviation in any single anatomical direction (anteroposterior, superoinferior, or mediolateral), rather than total vector deviation [19]. Although the definition of malposition in the context

of pelvic resection must certainly be more liberal that than used in the setting of hip arthroplasty, we still considered this as at least a related baseline. While our reported mean CoR deviation was 8.32 mm using a 3D vector calculation, when we decomposed the deviations into their directional components and applied Baauw's criteria, two implants were just outside of Baauw's criteria while three were within it. No cases were malpositioned based on inclination or anteversion. This analysis suggests that overall implant accuracy in this cohort was acceptable, even when using stricter, direction-specific criteria. Interestingly the deviation was primarily seen in the ML plane when the components were analyzed individually. It is intuitive why this would be the case, given that the medial wall of the acetabulum is being resected in its entirety in these cases.

The relevance of CoR as a metric remains debated. Romagnoli et al. argue that the correlation between CoR deviation and clinical outcomes—such as implant survival or function—is not well established [20]. In this context, the center of gravity (CoG) may serve as a more holistic and clinically meaningful measure. Unlike CoR, which captures joint center alignment, CoG represents the global placement of the implant relative to the preoperative plan. In large, complex oncologic resections where multiple components and planes are involved, CoG may better reflect whether the overall implant was positioned appropriately. In this study, the relatively low CoG deviations observed—even in cases with notable CoR deviations—indicate that implants were generally well aligned with the intended construct, reinforcing the effectiveness of acetabular-referencing PSI.

Some literature has associated CoR deviation with increased risk of aseptic loosening or revision [21,22], but these thresholds vary by study, and others have suggested that cup inclination, rather than CoR, may be more predictive of clinical outcomes [23]. Further research is needed to clarify which implant alignment parameters are most clinically significant, if any, when applied to the context of large pelvic reconstructions. When comparing our outcomes to intraoperative computer navigation, it's notable that only one study achieved sub-5 mm accuracy using a novel imaging system—but that study focused on soft tissue malignancies rather than the bony pelvis [24]. Thus, direct comparisons may be limited. Nevertheless, our findings suggest that PSI with acetabular referencing can achieve comparable, if not superior, precision without the logistical complexity and time demands of full navigation systems.

Operative time analysis revealed a mean surgical duration of 8 hours and 52 minutes. However, this included two complex outlier cases: Case 1 involved a concurrent gynecologic oncology procedure, and Case 3 required hardware removal from a previous reconstruction. When excluding these cases, the adjusted mean operative time was 7 hours and 34 minutes—comparable to the 7 hours and 25 minutes reported in another series using PSI for complex pelvic reconstruction [1]. This suggests that the use of acetabular-referencing PSI does not add substantial operative time compared to other forms of PSI, despite the technical demands of these procedures. However, every pelvic resection is unique and the amount of time any given resection/reconstruction will take is highly variable. Because there was not a goal for negative margins for the patient with metastatic bone disease, there was only one patient in this series (Patient 1) with an unexpected positive margin. For this patient, the error was due to an inability to detect the full extent of disease within the pubic bone, rather than a failure of the cutting guide itself (either in planning or in placement). This patient is now 5.5 years postoperative and remains disease free.

This study does not seek to demonstrate superiority of acetabular-referencing PSI over other PSI designs. Rather, it confirms that these guides provide high accuracy within established thresholds, and it demonstrates a novel means of referencing that avoids the frustrations and limitations of cutting guides that must be affixed to a specific area of the bony pelvis. In patients with extremely large tumors, it may be impossible or undesirable to use fixation pins within the pelvis to affix a cutting guide. Existing studies have shown that even junior surgeons can achieve resection precision comparable to senior surgeons when using PSI on synthetic models [13], indicating potential benefits in both training and practice. Cutting guides referenced off the acetabulum following removal of the femoral head represent an even

easier means of utilizing PSI by creating a more standardized and more accessible reference point for PSI seating. Compared to surface-contoured guides which may require more extensive exposure or iterative repositioning or ambiguous positioning, the acetabular socket served as a self-centering landmark that enabled rapid confirmation of correct guide placement. Future research should include longer-term follow-up to assess implant survivorship and patient outcomes, as well as expansion of the study cohort to validate findings in a larger population. Furthermore, comparison of planned margins to actual margins during the resection process would be valuable to the further elucidating the accuracy of these PSIs. Finally, there is promising potential in combining acetabular-referencing PSI with intraoperative navigation systems. Emerging evidence suggests this hybrid approach may be complementary, offering the tactile and visual advantages of PSI with the real-time feedback of navigation [17,25,26].

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Ethics approval and consent to participate

This study involved a retrospective review of fully anonymized data and did not require institutional review board approval, in accordance with the policies of the Duke University Health System.

Consent for publication

Because all data and images were anonymized, the requirement for individual patient consent was waived.

Availability of data and materials

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request

Author Contributions

T.L.: Conceptualization, Methodology, Data Curation, Formal Analysis, Validation, Investigation, Writing—original draft, Writing—review & editing, Visualization

B.R.W.: Conceptualization, Methodology, Data Curation, Formal Analysis, Validation, Investigation, Writing—original draft, Writing—review & editing, Visualization

W.C.E.: Conceptualization, Methodology, Resources, Writing—review & editing, Supervision, Project Administration

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