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REVIEW

New options and techniques in reconstructing the sacrum

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Abstract

Purpose Sacral tumours, both benign and malignant, often necessitate surgical removal (sacrectomy) to achieve optimal outcomes. However, this procedure disrupts the pelvic ring's stability, potentially leading to pain and limited mobility.

Methods This article explores innovative approaches to reconstruct the sacrum and restore function in primary and secondary sacral tumours.

Results Beyond traditional bone graft-based spino-pelvic fixation, the paper delves into minimally invasive alternatives like robotic-assisted surgery which may be used especially as a palliative procedure in destructive lumbosacral junction metastases. This technique offers enhanced precision for implant placement and often a reduced surgical exposure, potentially improving patient recovery. Additionally, the article discusses the application of 3D-printed custom implants, precisely matched the patient's anatomy to provide immediate structural support. It also explores the use of vascularised long bone flaps for pelvic reconstruction to achieve both stability and ambulation after sacrectomy. Additionally, it is necessary to mention the crucial role of soft tissue reconstruction using local flaps or free flaps from other body regions.

Conclusion By presenting these advancements in sacral reconstruction techniques, this article empowers surgeons to select an individualised approach for their patient. This personalised approach can optimise post-operative outcomes, allowing patients to regain function and improve their quality of life.

Keywords Sacrectomy · Sacral tumour · Spino-pelvic fixation · Robotic surgery · 3D print

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Introduction

The most common tumours affecting the sacrum are metastases from solid organ malignancies, such as breast or prostate cancer, or haematologic tumours, such as multiple myeloma [1, 2]. Primary malignant tumours are extremely rare by comparison. They are most represented by chordoma, with osteosarcoma, chondrosarcoma, malignant peripheral nerve sheath tumour, and Ewing's sarcoma being less commonly encountered, while benign sacral tumours primarily comprise giant cell tumours and benign neurogenic tumours [3]. They manifest by local pain due to the periosteal stretching or mechanically as a result of instability. Moreover, radicular pain or neurological deficit occurs due to nerve root compression or even tumour infiltration [4].

Partial or total sacrectomy, the surgical removal of the sacrum, is often necessary for treating primary tumours to achieve en bloc resection with a negative margin, which can minimise local recurrence and enhance overall prognosis [5]. These procedures present significant challenges due to the sacrum's critical role in pelvic stability and its proximity to essential neurovascular structures. Post-sacrectomy reconstruction must restore the biomechanical integrity of the pelvic ring to allow weight-bearing and mobility. It is also crucial to consider oncological margins to ensure the complete removal of the tumour while preserving as much nerve function as possible [6, 7]. The removal of all sacral nerve roots results in the total loss of urinary bladder, rectum, and sexual functions. In most cases, a bilateral lesion of the S2 or S3 roots leads to a similar clinical outcome. However, unilateral resection of these roots typically does not cause significant functional impairment [8].

The mechanical reconstruction of the pelvic ring involves a spino-pelvic construct supported by a structural autograft (usually fibula, free or vascularised) or allograft (fresh frozen or irradiated, commonly used are fibula and femur) [9]. More recently some surgeons have used custom 3D sacral implants to restore the spino-pelvic anatomy [6]. Finally, the posterior soft tissue reconstruction is typically achieved via the use of a myocutaneous flap [10].

The aim of the article is to present alternative options in reconstructing the lumbo-pelvic junction and discuss the latest advancements in techniques and materials used in sacral reconstruction, evaluating their benefits, limitations, and clinical outcomes.

Case 1: robotic-assisted lumbo-pelvic stabilization

53 years old female with inoperable cholangiocarcinoma with lung and liver metastases presented with progressive lower back pain and severe right sided S1 radiculopathy limiting her mobility. She had been treated with chemotherapy and radiotherapy. No further oncological treatment was possible, the life expectancy was below 6 months. MRI showed a soft tissue mass associated with the S1 lesion causing severe sacral canal stenosis, and bilateral foraminal stenosis more marked on the right where the exiting S1 nerve root was encased by tumour (Fig. 1).

Due to very limited prognosis and a risk of wound healing problems after previous radiotherapy it was decided to perform a palliative procedure to address both mechanical lower back pain by minimally invasive L4-S2AI (Alar-Iliac) stabilisation and S1 radiculopathy by targeted mini-open decompression.

After placing the patient prone on a Jackson table, surveillance jigs and markers were placed on both posterior superior iliac spines, and 3D X-ray was performed. The L4, L5 and sacral ala to illiac (S2AI) instrumentation was planned on ExcelsiusGPS® Robotic Navigation Platform (Fig. 2). Screws were placed via stab incisions using the robotic arm. The right S2AI incision was extended to midline to expose the S1 lamina (level check using navigation) which was then together with the S1 pedicle resected by a bone scalpel. The tumour mass was debulked to decompress the dura and right sided S1 nerve root. The rods were placed percutaneously.

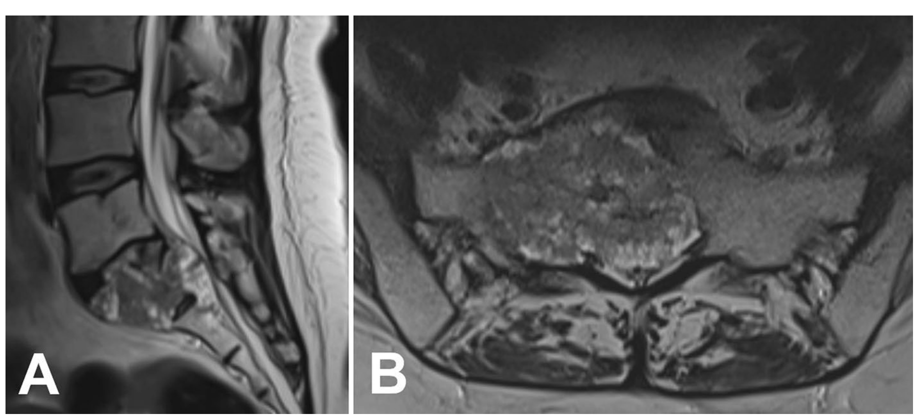

Fig. 1 MRI showing S1 metastasis of cholangiocarcinoma. **A** sagittal and **B** axial T2 weighted image

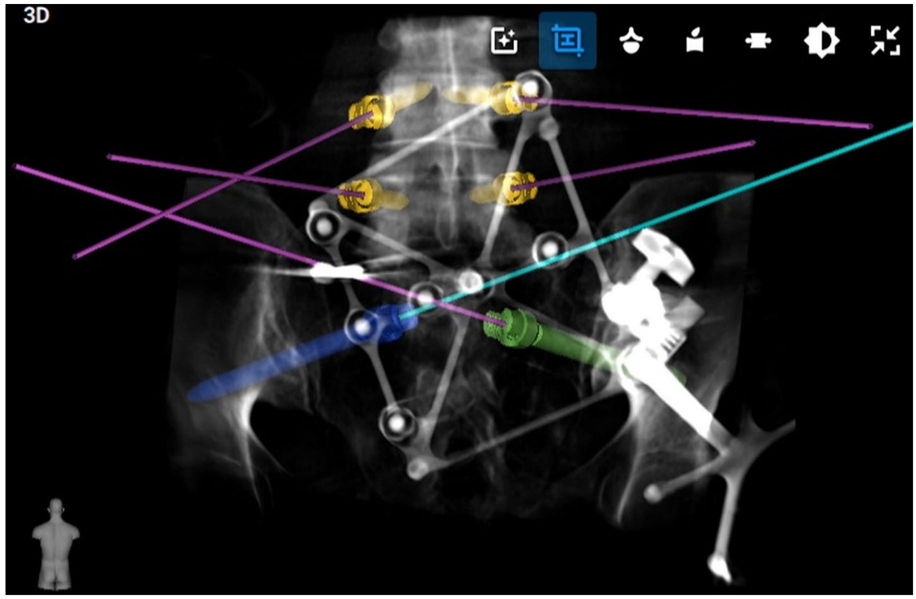

Fig. 2 Intra-operative L4-S2AI instrumentation planning on a Robotic Navigation Platform

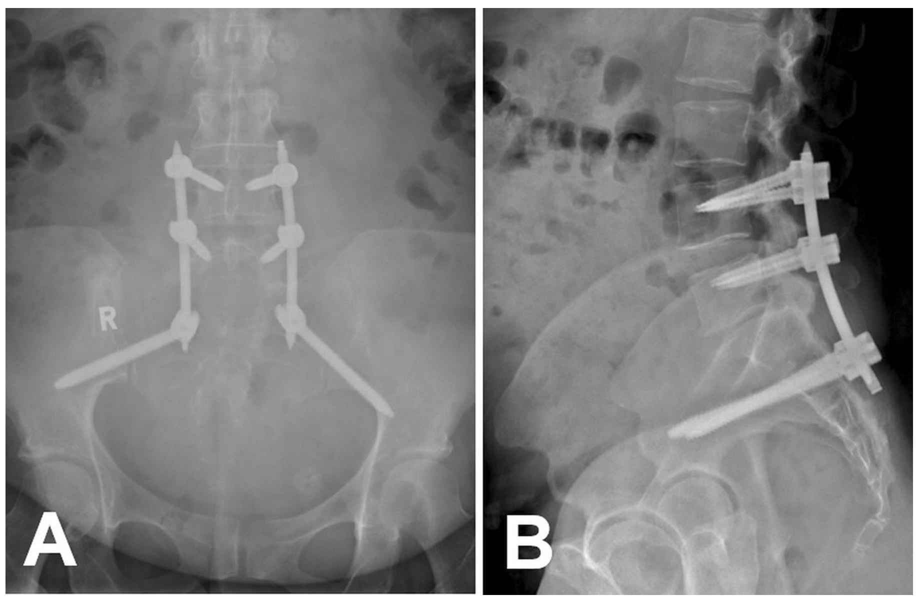

Fig. 3 Post-operative X-ray showing L4-S2AI fusion

The surgery was uneventful, the patient felt immediate pain relief and was able to walk again two days after the operation. She was discharged to home care four days after surgery. At one month follow-up, she was pain free and X-ray showed good position of the instrumentation (Fig. 3).

Case 2: sacral reconstruction with a 3D printed implant

A 45-year-old female treated with multiple excision surgeries, chemotherapy and radiotherapy over the last 17 years for an uncommon ovarian neoplasm (Brenner tumour) presented with a new local recurrence of the disease involving the L5-S1 vertebrae on the right side (Fig. 4).

Following on a multidisciplinary team decision it was planned to perform an en bloc resection with subsequent reconstruction using a custom-made trabecular titanium prosthesis. The osteotomy lines extending from L5 to the sacrum were planned according to the preoperative MRI, and cutting guides were printed using a 3D printer to guide the osteotomes during the resection.

The operation was performed in two stages. The first surgical stage was performed in supine decubitus through a xipho-pubic incision. The aorta, inferior vena cava and common iliac veins were isolated. Once the bone surface had been reached, the L5 and S1 roots on the right side

Fig. 4 MRI showing right sided L5-S3 metastasis of Brenner tumour

were identified and resected. The cutting guides were then positioned, and the osteotomy was performed at the level of L5 and the anterior side of the sacrum. The right sacroiliac joint was dislocated. An omental flap was then prepared and positioned next to the anterior surface of the sacrum.

The second surgical stage was performed with the patient in a prone position, with spread legs, through a curved incision extending from L2 to the right posteroinferior iliac spine. Pedicle screws were inserted bilaterally in L3 and L4 and in the left pedicle of S1 vertebra. After performing laminectomies at L4-S3 levels, the right L5-S3 roots were ligated. Using the cutting guides, the osteotomies were performed, completing the resection of the L5 and S1 on the right side. The reconstruction of the anterior column was then performed by positioning the custom-made trabecular titanium prosthesis. Subsequently, it was connected to the posterior instrumentation using a pre-shaped titanium rod and to the right iliac bone through screws inserted in previously planned holes already present on the prosthesis (Figs. 5, 6, 7). Eventually, the omental flap previously prepared during the first surgical stage was used to cover and protect the dural sac.

The diagnosis of Brenner tumour metastasis was confirmed on the specimen. The patient underwent debridement of the wound for infection with retention of the prosthesis on the thirtieth postoperative day. The patient was discharged eleven days later when she was able to walk with two crutches and the use of a knee brace and an orthosis for the right foot. She stayed on antibiotic treatment for another 5 months until the inflammation markers returned to normal.

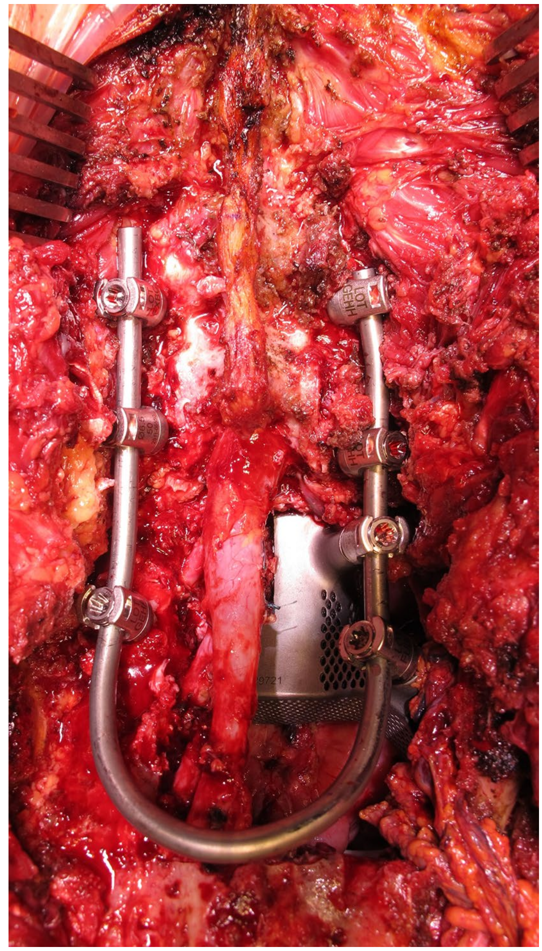

Fig. 5 Intraoperative photograph showing the reconstruction of right hemi-sacrum by a 3D printed implant and lumbo-pelvic fixation. Sacral part of the dural sac is fully exposed and L2-S3 roots are ligated on the right side

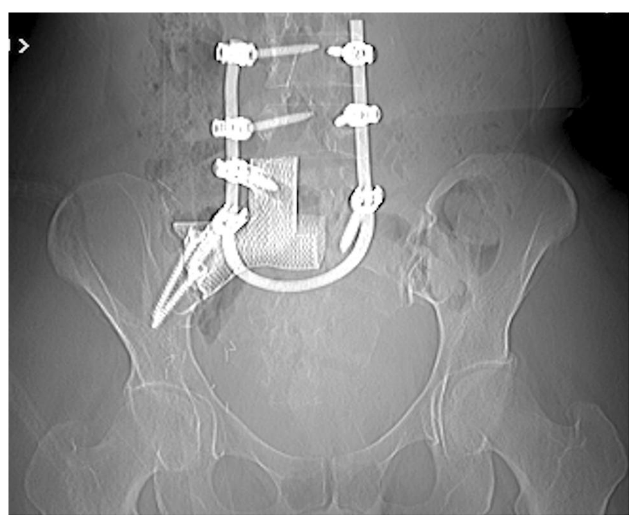

Fig. 6 Post-operative X-ray showing L3-pelvis fusion and reconstruction of the right hemi-sacrum

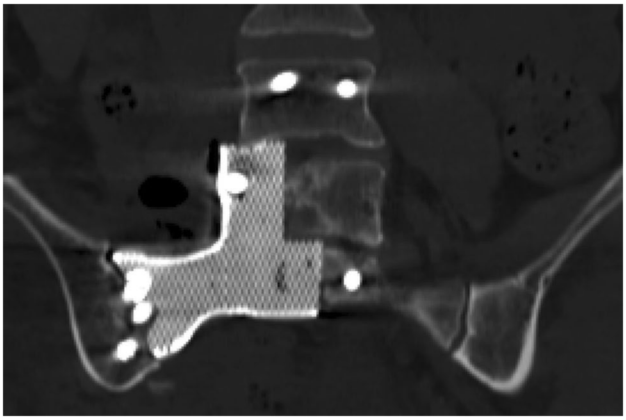

Fig. 7 Post-operative CT showing reconstruction of the right hemisacrum

One year after the operation the patient patient reported a return back to normal activities of daily living., always with the use of orthoses for the right lower limb and the pain flare-ups were well controlled with painkillers. Eighteen months after surgery she developed a fistula at the distal part of the surgical wound and for this reason, she underwent a new debridement surgery and resumed antibiotic therapy. Unfortunately, she died 2.5 years later due to the disease progression.

Case 3: complex lumbo-pelvic reconstruction with a vascularized femur and leg flap

45 years old female presented with progressive chronic low back pain and right sided sciatica. MRI showed lytic destructive lesion involving the right hemisacrum including the spinal canal from S2 below and right ilium with an intrapelvic component and extension into the right gluteal muscles (Fig. 8). PET confirmed the solitary necrotic right sacral and iliac mass. CT guided biopsy showed inconclusive finding of pleomorphic/high grade sarcoma. She underwent radiotherapy to the right hemipelvis and a left sided colostomy, six months later, in the absence of metastatic disease and with ongoing intractable pain, we undertook a two-stage radical resection of the tumour and reconstruction of the right hemipelvis.

The first stage was performed in a prone position. After a midline incision, the muscles were detached from the L2 vertebra to sacrum. Pedicle screws were inserted into the L2-L4 on the right side and L2-L5 together with two iliac screws on the left side. After L5 and S1 laminectomy, the dural sac was ligated obliquely above the right L5 and below the left S1 roots.

The second stage was performed in a floppy lateral position with the pelvis elevated on the right side. After an iliac crest curvilinear incision with a very elongated anterior medial thigh flap to below the knee which preserved the obturator nerve sensation and femoral nerve sensation, a right hemipelvectomy was performed. Firstly, the pubis and the ischium were cut on their lateral border and separated from the ilium and acetabulum. Secondly, the extended right sided hemi-sacrectomy was performed after partial L5/S1 discectomy on the right followed by oblique incision through S1-2 vertebrae medially from the S1 foramen to preserve the left S1 root and sacroiliac joint (Fig. 9).

The internal iliac vessels were ligated, and the external iliac vessels were dissected distally preserving the profunda femoris vessels supplying the femur and vastus lateralis, and the superficial femoral artery supplying the medial skin, the soleus and gastrocnemius. The femur was divided at the mid-point and the proximal half discarded with the specimen including the previously released hemi-sacrum, ilium and acetabulum. The distal half of

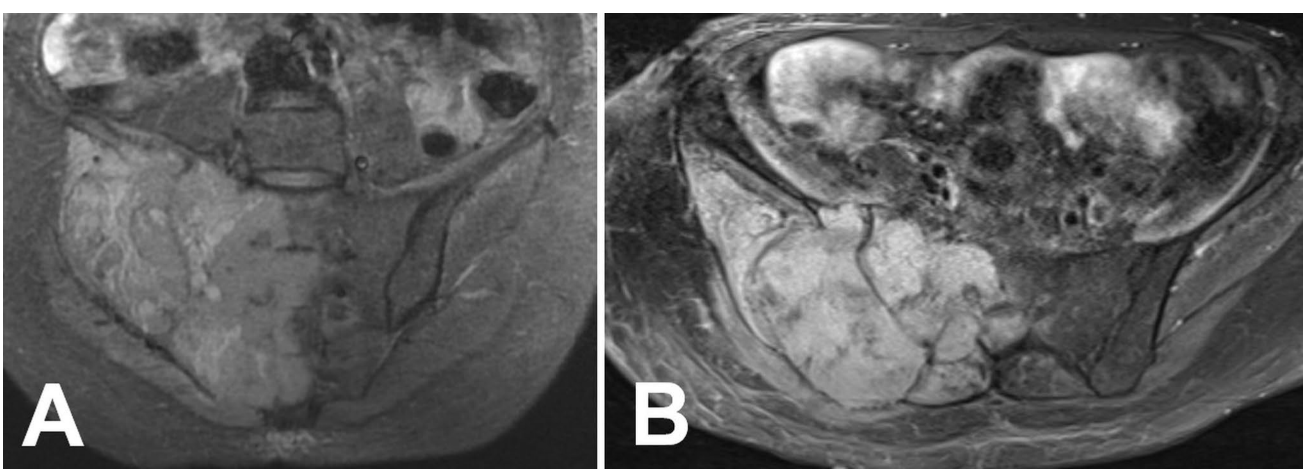

Fig. 8 MRI showing an osteosarcoma of the right hemisacrum and right ilium. **A** coronal STIR (Short Tau Inversion Recovery) sequence, **B** axial TSE (turbo-spin echo) sequence

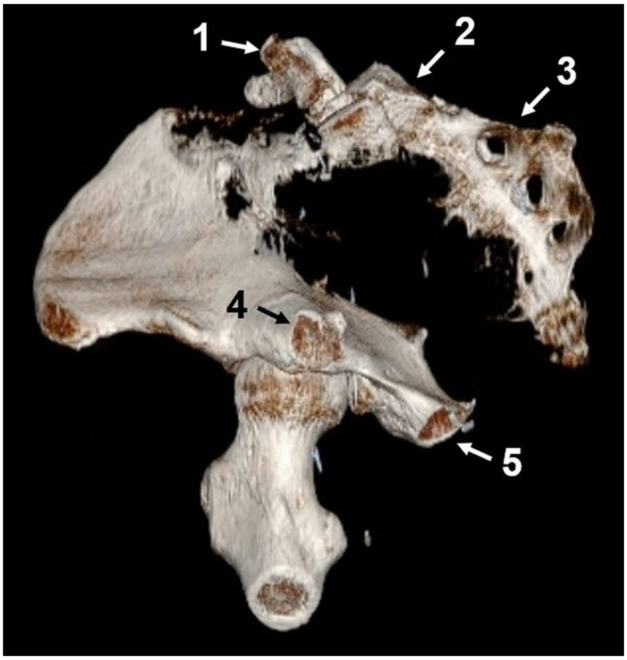

Fig. 9 3D CT reconstruction of the specimen removed during the en bloc tumour resection. 1—the right sided part of the L5 vertebral body, right pedicle and facet joint. 2—the right half of the S1 vertebra. 3—the left hemi-sacrum cut obliquely below the S1 foramen. 4—the lateral part of the right pubis and 5—ischium

the femur was dislocated from tibia and patella remaining in-continuity with the musculature of the thigh and vessels. The distal femur was transposed into the pelvis by advancing the diaphysis and internally rotating it through 90 degrees. The proximal diaphyseal end was fashioned with a step cut and wedged under the right half of the L5 vertebra. The femur was secured by a lag screw inserted through the bone and L5 vertebral body. The femoral condyles were secured to the remnant of the superior and inferior pubic rami. The hamstring origin and small remnant of the ischium was secured to what had previously been the medial femoral condyle now lying posteriorly. The femur was also connected by two T connectors with a rod inserted between the right L2 and distal iliac screws. The left sided rod was put between L2 and proximal iliac screws. In addition, the rods were connected by two side connectors between L2-3 and L3-4 screws. The rectus femoris and vastus lateralis were used to obliterate the dead space anteriorly and medially and close the abdominal cavity. The soleus and gastrocnemius muscles were used to fill the dead space posteriorly. The elongated anteromedial thigh and leg flap was flipped over to close the skin with the knee skin sitting cranially (Figs. 10, 11). The only complication was wound revision for infection. She was discharged to home care after 25 days.

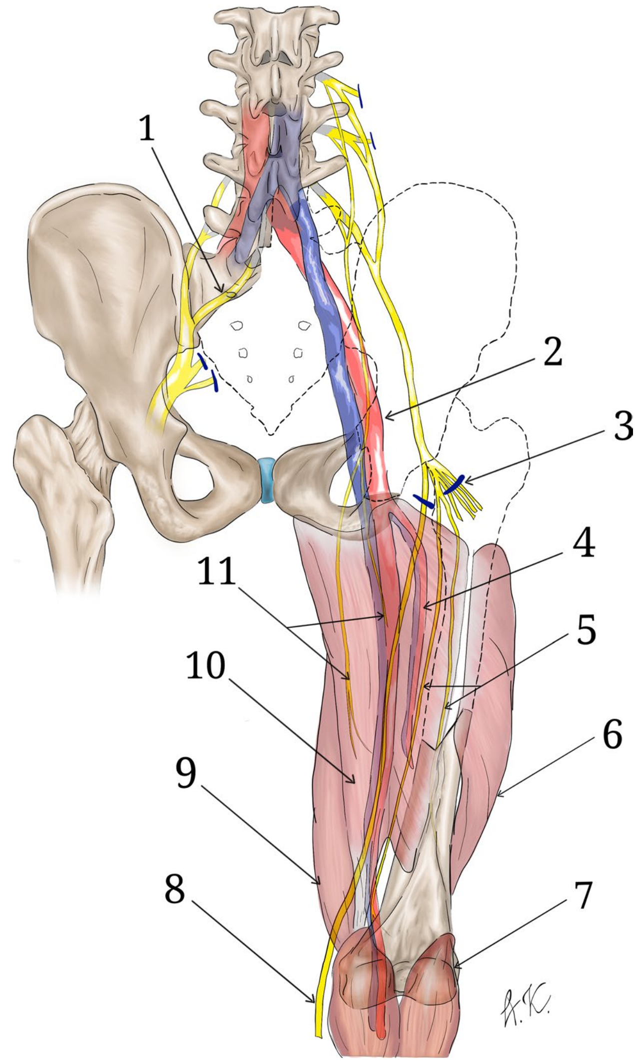

Fig. 10 Schematic drawing of the right sided hemipelvectomy with removal of the proximal part of the femur and muscles used for the reconstruction of the defect. 1—first sacral root, 2—femoral artery, 3—transected muscular branches of the femoral nerve, 4—deep femoral artery, 5—cutaneous branches of the femoral nerve, 6—vastus lateralis muscle, 7 triceps femoris muscle, 8—saphenous nerve, 9—vastus medialis muscle, 10 adductor magnus muscle, 11—obturator nerve

Final histology confirmed a giant cell-rich osteosarcoma. Adjuvant chemotherapy (methotrexate, doxorubicin, cisplatin) was completed three months later. She underwent thoracotomy and resection of a left upper lobe metastasis 15 months and right sided lung metastasis 20 months after the initial surgery. At the 10 years follow up, X-ray showed good position of the femoral graft and spino-pelvic instrumentation (Fig. 12). The patient is fully mobile when using a prosthesis, has an indwelling urinary catheter and a colostomy. The ongoing phantom pain is treated by a pain specialist and a psychologist.

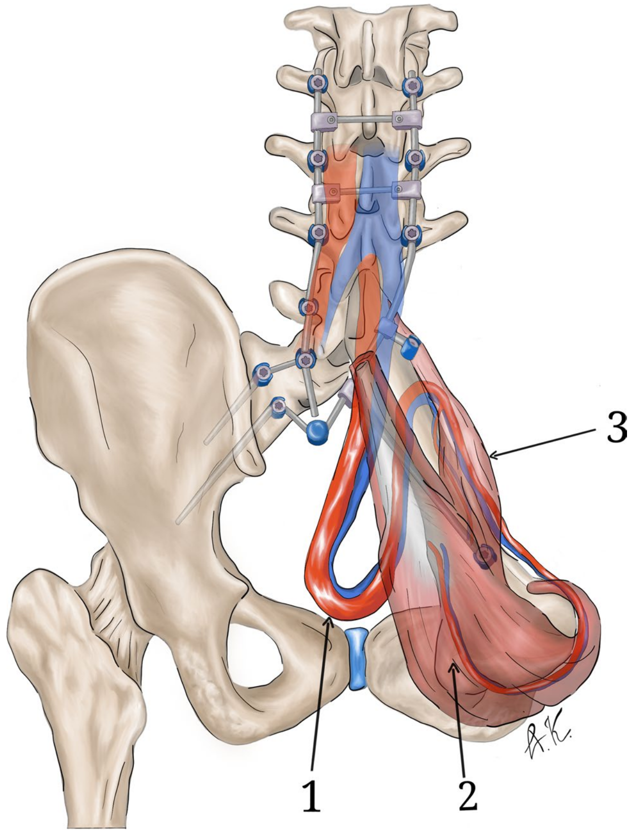

Fig. 11 Schematic drawing of the spinopelvic reconstruction after the right sided hemipelvectomy. Femoral graft was inserted between the L5 vertebra and obturator foramen and the bony structures were fixed together by bilateral L2-illiac ala/femur instrumentation. 1—common femoral artery and vein, 2—triceps femoris muscle, 3—rectus femoris muscle

Fig. 12 Post-operative X-ray showing L2-pelvis fusion and reconstruction of the right hemipelvis by a femoral graft

Discussion

Spino-pelvic fixation by spinal instrumentation anchored to the lumbar spine and iliac bones provides immediate mechanical stability and structural support after sacrectomy or as a palliative procedure in destructive metastatic lumbosacral lesions [4]. It should be undertaken after total sacrectomy when there is no preservation of ilio-lumbar ligamentous stability to prevent increased length of stay, pain, and inability to ambulate. The recommendation for spino-pelvic reconstruction in cases with some preserved ilio-lumbar ligamentous stability is weak. In cases where there are concerns regarding the feasibility of prolonged surgery or in whom bone quality precludes sound instrumentation, there is adequate evidence to consider resection without stabilization [7].

Bedermann et al. described in their systematic review three types of constructs used to stabilize the pelvic ring [11]. (1) 'Spino-pelvic fixation' (SPF) is referred to a construct connecting the lumbar spine to the ilium such as intrapelvic Galveston rods [12] and hook–rod constructs connected to transiliac bars [13] and new constructs like pedicle screw–rod constructs connected to iliac screws, transiliac rods, or custom plates [14]). (2) 'Posterior pelvic ring fixation' (PPRF) connects only the ilia together without fixation to the lumbar spine—transiliac rod or plate fixation [15], structural allografts [16], or prosthetic cages [17]. (3) 'Anterior spinal column fixation' (ASCF) aims to strengthen the anterior spinal column—iliolumbar screws [18], fibular grafts [19], titanium mesh and expandable cages [20] or a vertical rod through the lumbar vertebral bodies [21]. All patients received SPF in association with either one or two other techniques. Ambulation was preserved in 90% of the patients. A trend toward a lower rate of hardware failure emerged in the group utilizing anterior spinal column support when compared to the patients without it (12.5 vs. 17.4%) [11].

Robotic-assisted surgery

Robotic systems enhance precision in implant placement through improved visualisation and instrument control. Park et al. published early experience with percutaneous iliac screw fixation for destructive lumbosacral metastatic lesions in two patients in which placing S2AI screws was not feasible. The patients did not experience immediate postoperative complications and had stable hardware at one-month follow-up [22]. In cases with intact S2 level, the S2AI screws may be used. They have increased biomechanical stability compared to traditional methods of iliac fixation and due to their entry point and trajectories, these screws align well with proximal instrumentation and do not require extensive dissection or offset connectors. Robotic technique brings a slightly higher accuracy compared to freehand S2AI screws [23]. Hardigan et al. published a series of seven sacral fractures treated with robotic assisted percutaneous S2AI screws. Such procedure reduces tissue damage, speeds up recovery and decreases the risk of wound healing problems and infection [24]. This is especially important in oncological patients after previous radiotherapy [25] undergoing palliative procedure like in *Case 1* when the initially bed bound patient with severe mechanical low back pain was able to walk again and be discharged four days after surgery. The main limitations are a significant initial investment and operational costs and learning curve requiring extensive training and experience [26].

3D print

Advanced 3D printing techniques unlock the creation of custom-made implants for patients. Using detailed scans, these implants perfectly match the patient's unique anatomy, eliminating size discrepancies. Tailored for each individual, they offer immediate and robust mechanical support after surgery without associated morbidity from harvesting a bone autograft like in *Case 2*. However, this innovative approach comes with challenges. Production and planning can be expensive, and the surgeries themselves require meticulous preoperative planning and precise execution during the operation. Studies have shown that 3D-printed implants offer excellent osseointegration, durability and stability in sacrectomies for malignant [27] and benign tumours [28].

Wei et al. found that the use of 3D-printed endoprostheses for sacral reconstruction provides significantly better spinopelvic stability and implant survival with no greater intraoperative haemorrhage or perioperative complications compared to cases treated by SPF or non-endoprosthetic combined reconstruction, including anterior spinal column fixation [29]. Gong et al. described satisfactory short-term (median 26.5 months) outcomes in ten patients undergoing total sacral reconstruction with 3D-printed self-stabilizing endoprosthesis without supplemental lumbar fixation. The median operation time was almost 400 min, and the median intraoperative blood loss was and 3200 ml (2400–7800 ml). There were no mechanical complications related to the endoprosthesis at the last follow-up [6].

Fibula grafts

Free vascularised fibula graft has demonstrated successful integration and long-term stability in several case series, making it a viable option for biological reconstruction. It has a very high union rate (around 90%, median time to union, 5.0 months in long bones reconstructions). The risk of non-union is twice as low compared to an allograft [19].

Welling et al. found that SPFs augmented with free vascularized fibular flap were superior to allograft fibular strut and were associated with a shorter time to union and a trend towards a reduced risk of hardware failure secondary to nonunion [30]. Autologous vascularized fibula grafts involve transplanting a section of the fibula with its blood supply to the sacral defect. The vascularized grafts promote natural bone integration and healing. Moreover, the enhanced vascularity reduces infection risks. However, the procedure requires microsurgical expertise and is associated with potential complications at the bone harvest site. Based on experts' opinion it has been suggested that vascularized bone reconstruction should be undertaken if the patient is medically stable enough to undergo such a procedure [7].

Erol et al. reviewed 16 children with pelvic Ewing's sarcoma who had undergone pelvic ring reconstruction using double-barrelled free vascularised fibula graft after sacroiliac resection. The fibula graft was placed between the supraacetabular region distally and the remaining ilium or sacrum proximally. The mean time for bone union was 9 months. Graft hypertrophy was found in all patients at 12 months [31]. Garvey et al. published a case series of patients with vascularized bone reconstruction in the form of a free fibula flap which was vascularized via the deep inferior epigastric artery of a pedicled VRAM flap. This has the advantage of eliminating dead space through the muscle flap, skin closure with the VRAM skin flap, and import of vascularized tissue from out of the zone of injury, thus allowing improved overall tissue (bone and soft tissue) healing and clearance of infection [32].

Soft tissue reconstruction

Soft tissue reconstruction preferably by a regional flap should be performed after total sacrectomy to allow a tension-free closure, and dead space elimination, thus reducing wound dehiscence and return to theatre rates [7]. A gluteal-based flap is most commonly used for reconstruction because of its proximity to the defect site and robust blood supply. It also offers advantage of a one-stage procedure from one approach without a need of repositioning to harvest another flap if the sacrectomy is performed through an exclusive posterior approach. Although there is a risk of flap tension due to its poor extensibility and decreased muscle strength and functional drawbacks, the majority of patients (91%) are independently ambulatory after the procedure. Other viable option is a vertical rectus abdominis muscle (VRAM) flap. This flap is based on the inferior epigastric vessels, while the gluteal flaps are based on the superior and inferior gluteal arteries. Injury to these arteries as a result of radiation, sacrificing of the internal iliac artery during extensive resections or previous abdominal surgery is a potential concern for using these flaps.

In cases in which local flaps are not available, free flaps like latissimus dorsi, omental or anterolateral thigh flap can be used. Preoperative radiation and also high sacrectomy leads to a higher complication rate after soft tissue reconstruction which can be explained by larger defect size, more extensive dissection, spinopelvic instability, requirement of a combined anterior and posterior exposure, and the additional morbidity resulting from sacral roots resection [10].

Long bone flaps

A pedicled vascularized femur flap for restoration of the pelvic ring was firstly described by Yamamoto et al. in 1997 [33]. However, in situations where a pedicled flap has inadequate reach and arc of rotation, a free flap reconstruction might be necessary. McKnight et al. described a case of a 22-year-old female with a recurrent high-grade osteosarcoma of the left iliac bone. They performed a femur-fibula-fillet of leg (3F) chimeric free flap to reconstruct the pelvic ring, stabilize the spine, and provide soft tissue coverage of the wound, respectively. A 22 cm-long segment of femur was rigidly fixed posteriorly, by interdigitation into the L4 vertebral body and through and through lag screw fixation, and anteriorly to the pubic symphysis, again with lag screws, to restore continuity of the pelvic ring. The fibula was fixed to the posterior lumbar vertebral bodies and spinous processes to support the spine. The flap arterial anastomosis was performed between the common femoral artery and common iliac artery [34].

Mendel et al. described a patient with an iliosacral chondrosarcoma treated with an external hemipelvectomy with sagittal sacrectomy. The composite lower extremity flap consisted of the shaft of the femur, based on the profunda femoris artery and veins, the entire anterior thigh skin and subcutaneous tissues, and the shaft of the fibula, based on the continuation of the superficial femoral, popliteal, and peroneal vessels. The vascularized femoral graft was fixed to the inferior left hemi-endplate of L5 and pubic symphysis with cancellous screws. The posterior instrumentation was augmented with a double-rod construct on the right, the side of the only lower extremity. On the left side, pedicle screws (L3–5) with a rod construct were also attached to the right iliac crest to increase rotational stability. The vascularized fibula graft was placed posteriorly over the left L3–5 transverse processes, secured to the left side rod construct with titanium cables, and connected inferiorly to the femur graft using a screw to further augment the construct. At the 18-month follow-up, the patient was pain free, used intermittent catheterisation to void urine, he was able to ambulate with the assistance of his custom-made smart technology prosthesis [35]. Utilizing the flaps from the amputated extremity, which would otherwise have been discarded, drastically reduces the morbidity of such procedure since no flap donor sites are needed from the rest of the patient's body for wound reconstruction [36] similarly to *Case 3*.

Conclusion

Advancements in sacral reconstruction techniques offer a range of options to address the challenges posed by sacrectomy. Custom 3D-printed implants, biodegradable scaffolds, vascularized long bones grafts, composite allografts, and robotic-assisted surgery each provide unique benefits tailored to specific patient needs. Continued innovation and research are essential to further improve these techniques, enhance patient outcomes, and reduce complications. Future directions include the integration of advanced biomaterials, enhanced imaging technologies, and artificial intelligence in surgical planning and execution.

Author contribution RK: Methodology, Investigation, Data Curation, Visualization, Writing—Original Draft. AG: Data Curation, Validation, Writing—Review & Editing. SP: Data Curation, Validation, Writing—Review & Editing. AK: Visualization, Writing—Review & Editing. GM: Methodology, Writing—Review & Editing. HG: Methodology, Data Curation, Writing—Review & Editing JS Visualization, Writing—Review & Editing JR: Supervision, Validation, Resources, Visualization, Writing—Review & Editing.

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interests The authors declare no competing interests.

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