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Image Stereotactic Navigation for Primary Spine and Pelvis Tumor Resection and Reconstruction: A Narrative Review

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Abstract

Primary tumors of the mobile spine, sacrum, and pelvis are rare but biologically aggressive lesions for which en bloc resection with tumor-free margins remains the single most important determinant of local control and long-term survival. The complex three-dimensional anatomy of these regions — dense neurovascular structures, visceral organs, and irregular bony corridors — has historically made it difficult to translate meticulous preoperative planning into an equally precise intraoperative cut. Stereotactic (image-guided) navigation, long established for pedicle screw placement in degenerative spine surgery, has increasingly been repurposed as an oncologic tool to guide osteotomies and reproduce preoperative resection plans in real time. This review synthesizes the current evidence base — anchored by a 2026 systematic review of 21 studies and 240 patients — describing how navigation is used in spine and pelvic tumor surgery, what outcomes have been reported, and where the technology is heading.

Keywords: Stereotactic navigation; Image-guided surgery; Spine tumor; Pelvic tumor; Sacral chordoma; Chondrosarcoma; En bloc resection; Surgical margins; Tumor reconstruction; Virtual cutting guides.

1. Introduction

Primary bone and soft-tissue tumors of the spine and pelvis — chordoma, chondrosarcoma, osteosarcoma, Ewing sarcoma, and giant cell tumor among them — are uncommon relative to metastatic spinal disease, but they carry disproportionately high morbidity because of their location. Unlike appendicular sarcomas, where a wide margin of normal tissue can often be sacrificed without functional consequence, spinal and pelvic tumors sit adjacent to the spinal cord, cauda equina, major vessels, and pelvic viscera. Surgeons must thread a resection plane that is oncologically adequate yet anatomically survivable.

The Enneking classification has long guided musculoskeletal oncologic surgery: wide or marginal ("adequate") resections are associated with substantially lower local recurrence than intralesional ("inadequate") resections, particularly for chordoma and spinal sarcomas. Achieving an Enneking-appropriate margin freehand, however, is difficult when the surgeon cannot directly visualize the dorsal or deep extent of a tumor relative to bone. This visualization gap is precisely the problem stereotactic navigation was designed to solve.

2. What Stereotactic Navigation Adds to Tumor Surgery

Stereotactic navigation systems register a patient's real-time anatomy to a preoperative or intraoperative imaging dataset (CT, or CT fused with MRI), then track a surgical instrument in space relative to that registered anatomy — displaying the instrument's position on the imaging in real time, analogous to a GPS system. In degenerative and deformity spine surgery this technology is well established for guiding pedicle screw trajectories. Its oncologic application is conceptually different: rather than guiding an implant into bone, navigation is used to guide an osteotomy plane around a tumor.

Several technical approaches have emerged:

- CT-based intraoperative navigation: a preoperative plan is registered to an intraoperative CT (often obtained with an O-arm or similar mobile scanner), allowing the surgeon to trace the planned resection margin directly on a tracked probe, saw, or drill.
- MRI-CT fusion navigation: overlays preoperative MRI (superior for soft-tissue and tumor margin definition) onto intraoperative CT (superior for bony anatomy), giving the surgeon a composite three-dimensional model of the tumor relative to bone in the operating room.
- Virtual cutting guides: preoperative computer-assisted design (CAD) software is used, often with biomedical engineering support, to plan osteotomy lines that are then projected onto the intraoperative navigation display as a real-time cutting template — effectively a digital patient-specific instrument without a physical guide.
- Navigated power instruments: including ultrasonic bone scalpels and precision cutting tools that are themselves registered to the tracking system, allowing the cutting instrument's tip — not just a separate pointer — to be tracked during the osteotomy itself.

3. Summary of the Current Evidence Base

The most comprehensive synthesis to date is a 2026 systematic review (HSS Journal) that followed PRISMA methodology to identify studies using stereotactic navigation specifically for primary spine and pelvic tumor resection, rather than for instrumentation alone. The review pooled 21 studies comprising 240 patients, with a mean age of 46 years and mean follow-up of 33.4 months — a reasonable interval for assessing local recurrence in slow-growing tumors such as chordoma.

Key descriptive findings

- Tumor location: the sacrum/pelvis accounted for the large majority of cases (81.3%), followed by the thoracic spine (8.3%), cervical spine (5.8%), and lumbar spine (4.6%) — reflecting both the disproportionate representation of sacral chordoma in this literature and the particular anatomic difficulty of sacral/pelvic osteotomies that makes navigation especially attractive there.
- Histology: chordoma (31.7%) and chondrosarcoma (27.1%) were the two most common diagnoses, consistent with the broader literature on primary spinal malignancy.

Pooled outcomes

- Margin status: negative (tumor-free) surgical margins were achieved in 88.3% of cases, a rate that compares favorably with historical freehand series.
- Local recurrence: recurrence was reported in 16% of patients overall, but this varied substantially by histology — chondrosarcoma had the highest recurrence rate at 32.4%, reflecting both its relative chemo- and radio-resistance and, likely, the technical difficulty of achieving clean margins in cartilaginous tumors that can have subtle, infiltrative extensions.
- Complications: complications of any kind occurred in 30.3% of patients — a reminder that these remain major operations regardless of navigation — but only 1% of cases (two patients total) had a complication specifically attributed to the navigation technology itself, suggesting the added technical layer does not meaningfully increase risk.

- Comparative data: two studies directly compared navigated to non-navigated cohorts. Both suggested improved bony margin accuracy and lower recurrence risk associated with navigation use, though the authors of the systematic review were appropriately cautious about the strength of this comparison given the small number of studies.

4. Illustrative Applications from the Broader Literature

Beyond the pooled systematic review, several single- and multi-institution series illustrate how navigation is being deployed in practice:

- Sacral chordoma. A case series using preoperative MRI fused with intraoperative CT to build three-dimensional tumor reconstructions for sacral chordoma resection achieved negative margins in five of five planned en bloc cases, with stable or improved neurologic function postoperatively. This MRI–CT fusion approach directly addresses the core limitation of CT-alone navigation — CT delineates bone well but is poor at showing the soft-tissue extent of a tumor, which MRI captures far better.
- Virtual cutting guides for sacropelvic resections. A series from a major cancer center used CAD-based virtual cutting guides integrated with an ultrasound-powered cutting tool to perform navigated osteotomies in six patients undergoing en bloc sacral/pelvic tumor resection, achieving negative margins in all patients at short-term follow-up. This approach essentially digitizes the "cutting guide" concept familiar from 3D-printed patient-specific instrumentation, without requiring a physical device to be manufactured and sterilized in advance.
- Navigated ultrasonic bone scalpel. Technical reports describe registering an ultrasonic bone scalpel directly to the navigation platform so that the cutting instrument itself — rather than a separate tracked pointer — is displayed relative to the tumor margin in real time, allowing the surgeon to maintain a defined safety margin (e.g., ≥ 5 mm) throughout the osteotomy.
- CT-based navigation for reconstruction as well as resection. Korean case-series data using CT-based navigation for both spinal tumor resection and subsequent reconstruction found negative margins in six of seven patients (85.7%), with no navigation-related intraoperative complications, reinforcing that the value of navigation extends beyond the resection step into accurate hardware placement during reconstruction of the resulting bony defect.
- Pelvic bone malignancy more broadly. A review focused specifically on computer-assisted navigation and robotics for primary and metastatic pelvic bone malignancy reached a similar conclusion from a parallel literature: navigation has been associated with a higher rate of negative-margin resection, although long-term oncologic outcomes with navigation remain to be firmly established, and its role in percutaneous stabilization of pelvic metastases is still in early stages.

5. Interpreting the Evidence: Strengths and Limitations

Several themes emerge when this literature is read as a whole.

- The rationale is anatomically sound. The sacrum and pelvis — where the majority of navigated tumor cases originate — are the regions where freehand orientation is hardest and where the consequence of a misjudged margin (violation of the tumor capsule, or unnecessary sacrifice of nerve roots) is highest. It is logical that navigation clusters here.
- The margin and recurrence data are encouraging but not yet definitive. An 88.3% negative-margin rate and a 16% overall recurrence rate are respectable figures, but the systematic review authors classified the evidence as Level IV — a systematic review of predominantly Level III and IV studies. Almost all included studies were retrospective case series without contemporaneous non-navigated controls, and the two comparative studies that did exist, while favorable to navigation, are too few to support a strong causal claim.
- Histology matters more than many people expect. The stark difference in recurrence between chordoma-type and chondrosarcoma-type tumors (32.4% for chondrosarcoma versus the overall pooled 16%) is a reminder that navigation is a tool that improves the precision of a plan — it cannot fully compensate for tumors with inherently infiltrative or satellite-lesion behavior, which chondrosarcoma is known to exhibit.
- Safety appears favorable. The very low rate of navigation-attributed complications (1%) against a substantial overall complication rate (30.3%) suggests that most morbidity in these operations comes from the scale and location of the surgery itself — extensive blood loss, prolonged operative time, and proximity to neurovascular structures — rather than from the navigation technology. Other reported series of complex en bloc resections in the mobile spine describe similarly high complication rates (as high as 90% in some small cohorts) and very long operative times, underscoring that these remain among the most demanding procedures in musculoskeletal surgery regardless of navigation.
- Registration accuracy is a practical rate-limiting step. Across the broader navigation literature, fiducial registration error is typically reported in the range of a few millimeters. In tumors where the intended margin is itself only a few millimeters beyond grossly normal tissue, registration accuracy is not a trivial technical detail — it directly determines whether the "navigated" margin matches the "achieved" margin.

6. Future Directions

Several trends are likely to shape the next generation of evidence in this space:

- Larger, prospective, and multi-institutional comparative studies are needed to move beyond retrospective single-arm series and better isolate the independent contribution of navigation to margin status and recurrence, controlling for surgeon experience and tumor histology.
- Integration of navigation with robotics and navigated power instruments (as already piloted with ultrasonic bone scalpels and CAD-based virtual cutting guides) may further reduce the gap between the planned and executed osteotomy, particularly in anatomically constrained corridors such as the high sacrum or pelvic ring.
- Standardized outcome reporting — consistent definitions of margin status, recurrence, and navigation-specific complications — would materially improve the ability to pool future data, an explicit limitation noted by the 2026 systematic review given the heterogeneity in methodology, tumor type, and follow-up across the included studies.
- Cost-effectiveness and learning-curve data remain sparse; as with any capital-intensive technology, adoption outside high-volume tertiary sarcoma centers will likely depend on evidence that outcomes benefits persist even as the technology is used by a broader range of surgical teams.

7. Conclusion

Stereotactic navigation has moved from a tool for spinal instrumentation into a genuine oncologic adjunct for the resection and reconstruction of primary spine and pelvic tumors. The best current evidence — pooled from 21 studies and 240 patients — shows negative margins achieved in nearly 9 of 10 navigated cases, an overall local recurrence rate of 16% (concentrated in chondrosarcoma), and a navigation-attributable complication rate of only about 1%, against a substantial background complication rate inherent to these operations. Comparative data, while still limited to two studies, favor navigation over freehand technique for bony margin accuracy and recurrence risk. The evidence is not yet Level I, and the field would benefit from larger prospective comparative trials, standardized outcome definitions, and continued integration with complementary technologies such as virtual cutting guides and navigated power instruments. For now, stereotactic navigation should be regarded as a promising, safe, and increasingly well-supported adjunct — not yet a proven standard of care, but a technology with a clear anatomic rationale and a growing evidence base in favor of its adoption at experienced sarcoma centers.

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