Navigated Pelvic Osteotomy and Tumor Resection
A Study Assessing the Accuracy and Reproducibility of Resection Planes in Sawbones and Cadavers

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**Background:** This Sawbones and cadaver study was performed to assess the accuracy and reproducibility of pelvic bone cuts made with use of a novel navigation system with a navigated osteotome and oscillating saw.

**Methods:** Using a novel navigation system and a three-dimensional planning tool, we navigated pelvic bone cuts that were representative of typical cuts made in pelvic tumor resections. The system includes a prototype mobile C-arm for intraoperative cone-beam computed tomography, real-time optical tracking (Polaris), and three-dimensional visualization software. Three-dimensional virtual radiographs were utilized in addition to triplanar (axial, sagittal, and coronal) navigation. In part one of the study, we navigated twenty-four sacral bone cuts in Sawbones models and validated our results in sixteen similar cuts in cadavers. In part two, we developed three Sawbones models of pelvic tumors based on actual patient scenarios and compared three navigated resections with three non-navigated resections for each tumor model. Part three assessed the accuracy of the system with multiple users.

**Results:** There were ninety navigated cuts in Sawbones that were compared with fifty-four non-navigated cuts. In the navigated Sawbones cuts, the mean entry and exit cuts were 1.4 ± 1 mm and 1.9 ± 1.2 mm from the planned cuts, respectively. In comparison, the entry and exit cuts in Sawbones that were not navigated were 2.8 ± 4.9 mm and 3.5 ± 4.6 mm away from the planned osteotomy site. The navigated cuts were significantly more accurate (p ≤ 0.01). In the cadaver study, navigated entry and exit cuts were 1.5 ± 0.9 mm and 2.1 ± 1.5 mm from the planned cuts. The variation among three different users was 1 mm on both the entry and exit cuts.

**Conclusions:** Navigation to guide pelvic bone cuts is accurate and feasible. Three-dimensional radiographs should be used for improved accuracy. Navigated cuts were significantly more accurate than non-navigated cuts were. A margin of 5 mm between the target tumor volume and the planned cut plane would result in a negative margin resection in more than 95% of the cuts.

**Clinical Relevance:** The accuracy of pelvic bone tumor resections and pelvic osteotomies can be improved with navigation to within 5 mm of the planned cut.

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Pelvic tumors pose a major surgical challenge. They are often large lesions on initial presentation, lying close to major blood vessels, nerves, and urinary and gastrointestinal structures. The three-dimensional structure of the pelvis is difficult to master conceptually in resecting tumors with safe margins. The types of tumors in question are often primary

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bone sarcomas, soft-tissue sarcomas with bone extension, locally recurrent rectal carcinomas adjacent to or invading bone, and occasionally a solitary bone metastasis such as from renal cancer. These are all potentially curable conditions in which wide resection (R0) with negative margins is crucial to avoid local recurrence. The field of orthopaedic oncology continues to challenge itself by attempting to resect larger and more complex tumors with negative margins while sparing adjacent critical structures to conserve postoperative function.

Navigation technology has been available for surgery and interventional radiology over the last decade. The use of navigation to facilitate pelvic bone resections has the potential to improve our ability to achieve negative margin resections by improving accuracy. Long cuts in pelvic bone, unlike in other regions, require the ability to navigate cutting planes with an osteotome or an oscillating saw.

Navigation in surgery often involves the use of special tools—such as a pointer, drill, or burr tip—that can identify a point in space rather than a plane. Freehand navigation of plane cuts is a new field, with unique difficulties. Imaging a plane needs three-dimensional image reconstructions, since any two-dimensional image is limited in its ability to correctly convey a plane that is not perfectly parallel to it. Surgical tools used for performing large pelvic osteotomies are often large osteotomes and oscillating saws. These tools potentially carry a unique set of problems for navigation, including instability due to vibrations and flexibility of the oscillating saw blade, and there is limited experience in the use of these tools with the assistance of navigation.

The purpose of this study was to assess the accuracy and reproducibility of pelvic bone cuts with the use of a novel navigation system with a navigated osteotome and oscillating saw. Our hypothesis was that the accuracy of our cutting planes would be within 5 mm of the plan in 90% of cuts, both in Sawbones (Pacific Research Laboratories, Vashon, Washington) and cadaver models. In addition, we assessed the clinical applicability by building models based on real-life clinical scenarios and navigating complete resections on a Sawbones model while assessing our ability to stay within 5 mm of our planned bone cuts. The clinical importance of this study is in defining the distance between the planned and actual cuts. This distance is the minimum safe distance from the tumor that navigated cuts should be planned in patients.

**Materials and Methods**

**Navigation System**

The navigation system includes a prototype mobile C-arm for intraoperative cone-beam computed tomography (CT), real-time optical tracking (Polaris; NDI, Waterloo, Ontario, Canada), and custom three-dimensional visualization software (Fig. 1). Clinical applications under investigation with use of this image-guidance system include otolaryngology procedures, spinal procedures, and orthopaedic surgery. The cone-beam CT imaging system demonstrates three-dimensional image quality with submillimeter spatial resolution and soft-tissue visibility at doses sufficiently low (approximately 0.1 to 0.35 milliSievret [mSv]) to allow repeat intraoperative imaging. For this study, three-dimensional images (256 × 256 × 192 voxels) were reconstructed with use of 0.8-mm3 voxels.

Registration of cone-beam CT imaging with the navigation system was performed with use of four to six anatomical landmarks on the pelvis and paired-point registration methods. The anatomical landmarks differed in the three resection models and included the anterior superior and anterior inferior iliac spines, the acetabular rim, the posterior iliac spine, the iliac crest, the posterior sacral foramina, the S1 spinous process, and the superior and inferior tip of the sacroiliac joint. Navigation of the surgical cutting tools (osteotome and oscillating saw) was performed with use of infrared reflective tracker tools and custom fixtures fabricated by a three-dimensional rapid prototype printer. Calibration of the cutting tools was achieved with use of a calibration jig containing optical reflective markers. A static reference marker was rigidly affixed to the iliac crest to allow movement without loss of registration during cutting.

The in-house navigation software (GTx Eyes), based on the open-source Image-Guided Surgery Toolkit (IGSTK; Insight Software Consortium), provides a variety of three-dimensional visualization options, including standard triplanar views (axial, sagittal, and coronal), bone-surface renderings, dynamic clipping planes, and oblique reslicing. Anatomic contours of tumors and critical structures (e.g., nerves) were manually delineated with use of ITK-SNAP software (Insight Toolkit-SNake Automatic Partitioning; University of Pennsylvania, Philadelphia, Pennsylvania). Each resection plane was defined by the placement of points on the images. These points were used to construct a best-fit plane with use of RANSAC (RANdom SAmple Consensus; SRI International, Menlo Park, California).

**Surgical Experiments**

The clinical problem was defined by searching our clinical database for all partial pelvic resections performed in the last five years. Tumor recurrences often occurred in the sacrum, where the osteotomy had been performed in proximity to the tumor while an attempt was made to simultaneously preserve a nerve root running through a nearby foramen. The difficulty in achieving a negative margin resection in these cases was related to either our ability to be precise in a complex region or our ability to accurately assess the intraosseous extent of the tumor.
The study compared the accuracy of the cuts with and without navigated guidance and comprised three parts. Part one included basic navigated sacral bone cuts in Sawbones and cadavers. Part two included resection of three typical pelvic tumors in Sawbones based on clinical scenarios. Part three compared variability among three different users.

In the first part of the study, we made four typical sacral bone cuts and repeated each cut six times in simulated pelvic bones made from solid rigid polyurethane closed foam (Sawbones). We assessed our accuracy and the reproducibility on the basis of those twenty-four cuts. The cuts included a midline longitudinal osteotome cut, a transverse osteotome cut between the S1 and S2 levels, an oscillating saw cut lateral to the sacral foramina, and a diagonal saw cut. We then validated our results by repeating those same four sacral cuts in four cadavers (a total of sixteen cuts in cadavers). The cadaver study was initiated after ethics review board approval. The goal was to simulate a situation similar to one in an operating room with a real patient and validate imaging accuracy, image-to-tracker and image-to-image registration errors, ease of navigation, and cut accuracy.

In the second part, we designed three typical clinical scenarios involving pelvic bone tumors and navigated a complete resection of each of these lesions. Each clinical scenario was based on the case of an actual patient managed for a sarcoma. The first case was a partial sacral resection between the S1 and S2 nerve-root level with a transverse osteotomy as well as two oblique cuts, sparing the S1 nerve roots for a sacral chordoma (Fig. 2). The second case was a sarcoma spanning the sacroiliac joint and involving the posterior aspect of the ilium and

| TABLE I Comparison of Basic Navigated Sacral Bone Cuts in Sawbones and Cadavers |
|---------------------------------|--------|--------|-------------|-------------|
| No. of Cuts | Entry Cut (mm) | Exit Cut (mm) | Absolute Pitch (deg) | Absolute Roll (deg) |
| Sawbones 24 | 1.6 ± 1.1 | 2.3 ± 1.1 | 6.7 ± 3.7 | 2.7 ± 1.5 |
| Cadaver 16 | 1.5 ± 0.9 | 2.1 ± 1.5 | 3.6 ± 2.7 | 2.6 ± 1.7 |
| P value* | 0.78 | 0.21 | 0.23 | 0.99 |

*Statistical evaluation was performed with use of the Wilcoxon rank-sum (Mann-Whitney) test. A p value of < 0.05 was considered significant.

Fig. 2 A T1-weighted axial magnetic resonance image (MRI) of a sacral chordoma. The patient underwent a partial sacrectomy at the S1 and S2 levels, sparing the S1 nerve roots. Fig. 2-B A Sawbones model of a sacral-based tumor was designed. Fig. 2-C The Sawbones pelvis was scanned with a flat-panel C-arm mobile computed-tomography scanner with high resolution, 0.8-mm fine cuts. The images were reconstructed into a three-dimensional model. The model tumor (brown) and S1 nerve roots (yellow) running in the S1 foramen were contoured and defined. Fig. 2-D The bone cuts were planned to achieve negative margin resection of the tumor and spare the S1 nerve roots. The resection plan is shown as a red line on the bone surface. The cuts are defined as planes, and therefore three resection planes are shown. Cuts were navigated freehand with an oscillating saw. The Sawbones were then rescanned, the three-dimensional image was reconstructed, and the precut and postcut images were registered to each other. The actual cuts overlap with the planned cuts (Fig. 2-D). The resection included a transverse cut between S1 and S2 and two diagonal cuts. CBCT = cone-beam computed tomography.
the lateral aspect of the sacral ala. The osteotomies included a longitudinal sacral cut just lateral to the S1 and S2 foramina, thus sparing those nerve roots. The third case was a tumor involving the acetabulum that required a periacetabular pelvic resection. Four cuts were made through the lateral part of the superior pubic ramus, the proximal part of the ischium, the ilium just proximal to the acetabulum, and down the posterior column midway between the ischial spine and the posterior wall of the acetabulum so as not to disrupt the integrity of the pelvic ring (Fig. 3). We compared the results of three navigated resections with a control group of three non-navigated resections. For the control group, the planned outer bone cuts were marked, and the distance to nearby anatomical landmarks was measured to simulate our current intraoperative routines.

In the third part of the study, we assessed the variability among multiple users by comparing outcomes for three different surgeons who were using the same system and completing the same task. Each surgeon completed three navigated and three non-navigated periacetabular resections in Sawbones. The surgeons had only limited experience with navigation and a short practice session with the system before the study.

With the use of navigation, the plane of the planned bone cut is shown as a red line on the bone surface of the three-dimensional reconstructed view.

**TABLE II Comparison of Navigated Cuts with Non-Navigated Cuts in Three Different Tumor Models***

<table>
<thead>
<tr>
<th></th>
<th>Entry Cut (mm)</th>
<th>Exit Cut (mm)</th>
<th>Absolute Pitch (deg)</th>
<th>Absolute Roll (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Navigated cut</td>
<td>1.4 ± 1</td>
<td>1.9 ± 1.2</td>
<td>4.4 ± 3.3</td>
<td>2.6 ± 2.1</td>
</tr>
<tr>
<td>Non-navigated cut</td>
<td>2.8 ± 4.9</td>
<td>3.5 ± 4.6</td>
<td>7.9 ± 7.7</td>
<td>6.0 ± 4.7</td>
</tr>
<tr>
<td>P value†</td>
<td>≤0.01</td>
<td>≤0.01</td>
<td>≤0.01</td>
<td>≤0.01</td>
</tr>
</tbody>
</table>

*For each of the three models (periacetabular tumor, sacral resection, and sacroiliac joint resections), three resections were repeated with navigation and without navigation. †Statistical evaluation was performed with use of the Wilcoxon rank-sum (Mann-Whitney) test. A p value of < 0.05 was considered significant.

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Fig. 3

**Fig. 3-A** A T2-weighted axial magnetic resonance image (MRI) of a periacetabular lesion in a patient who underwent a type-II (periacetabular) pelvic resection. **Fig. 3-B** A Sawbones pelvic model was designed with the tumor shown in purple and the sciatic nerve shown in yellow. The model was scanned, and a three-dimensional image was reconstructed. The tumor and sciatic nerve were defined, and a resection plan was drawn to achieve a negative margin resection and spare the sciatic nerve. **Fig. 3-C** Four planes of resection were defined: a supra-acetabular cut, a cut down the posterior column, a cut through the ischium, and a superior pubic ramus cut. Results of a navigated resection are shown in comparison with the planned cuts (red lines). **Fig. 3-D** Results of a non-navigated cut are shown compared with the planned resection (red lines). Substantially better accuracy and reproducibility of cuts was achieved with the navigated cuts compared with the non-navigated cuts.
The plane is defined by four points: two lying along the entry cut and two lying along the exit cut. The osteotome and oscillating saw are shown as a rectangle on the three-dimensional views, and a dotted line shows the trajectory of the tool (Fig. 4). We navigated the bone cuts by using the three-dimensional view to place the tool on the red line on the outer cortex, from a bird’s eye perspective (above). This was termed the entry cut. Pitch and roll were visualized with use of the clipping plane three-dimensional view. The entry cut, pitch, and roll measurements best define the plane of the osteotomy.

A battery-powered oscillating saw (Battery Power Line II; Synthes, Solothurn, Switzerland) equipped with a 100-mm-long, 19-mm-wide, and 1.25-mm-thick blade (Synthes) was used to make all cuts without jigs or slotted guides.

**Cut-Plane Analysis**

Postoperative cone-beam CT scans of each Sawbones and cadaver pelvis were made to assess the accuracy of the cut plane. Preoperative and postoperative images were registered with use of paired-point registration. As with the cut planning, the plane of the actual cuts was defined by two entry and two exit points. The pairs of planned and actual cuts were compared by measuring the difference in entry and exit positions and the relative pitch and roll with use of MATLAB (R2012a; MathWorks, Natick, Massachusetts). The distance between the planned and actual cuts was calculated for both entry and exit points by calculating the perpendicular distance of the actual cut points to the planned plane. The pitch for each cut was calculated by measuring the angle about the axis defined by the two entry points. The roll was calculated by measuring the angle between the plane formed by the cutting tool and that formed by the planned plane (Fig. 4). Differences in pitch and roll were calculated for each pair of planned and actual cuts.

Statistical analysis comparing planned and actual bone cuts, looking at entry into bone and exit from bone (in millimeters) and pitch and roll angle of the cuts (in degrees), for both navigated cuts and non-navigated cuts did not follow a normal distribution based on quantile-quantile (Q-Q) plot analysis. As such, the two-sample Wilcoxon signed-rank-sum (Mann-Whitney) test was applied to allow for nonparametric comparisons. Pitch and roll were also assessed separately for positive, negative, and absolute values. Since these were not significantly different, they are presented only as absolute values. A p value was deemed significant at <0.05.

**Source of Funding**

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**Results**

In the first part of the study, we assessed similar navigated sacral cuts in Sawbones (twenty-four cuts) and cadavers (sixteen cuts) (Table I). The entry and exit points in Sawbones were a mean (and standard deviation [SD]) of 1.6 ± 1.1 mm and 2.3 ± 1.1 mm from the planned resection plane. In cadavers, entry and exit cuts were a mean of 1.5 ± 0.9 mm and 2.1 ± 1.5 mm from the planned cuts. With regard to these cuts, the accuracy that we achieved in cadavers was similar to our accuracy in Sawbones.

In the second part of the study, we assessed the ability to completely resect three types of simulated bone tumors. Each of the three tumor models was resected three times with the aid of navigation and then three times without the aid of navigation. In the periacetabular tumor model (Fig. 3), navigated entry and exit cuts were a mean (and SD) of 1.2 ± 0.6 mm and 1.3 ± 0.9 mm from the planned cut planes. The mean pitch and roll were 2.4° ± 1.2° and 3.1° ± 1.9°, respectively. In the sacral resection model (Fig. 2), the navigated entry and exit cuts were a mean of 0.8 ± 0.7 mm and 0.9 ± 0.5 mm from the planned cuts. The mean pitch and roll were 2.4° ± 3° and 3.1° ± 1.9°, respectively. In the sacraliliac joint resection model, the navigated entry and exit cuts were a mean of 2.1 ± 1.4 mm and 1.7 ± 1.1 mm from the planned cuts. The mean pitch and roll were 4.4° ± 3.5° and 1.8° ± 1.4°, respectively. In all three tumor models, the navigated cuts were significantly more accurate than the non-navigated cuts were with regard to the entry-cut distance and exit-cut distance as well as the pitch angle and roll angle (p ≤ 0.01 for all) (Table II).

In the third part of the study, we assessed user variability. Differences in the entry and exit cuts among the three users were less than 1 mm (See Appendix). There was similarity in the navigated-cut results of all three surgeons with regard to the entry cut (p = 0.66) and the absolute roll (p = 0.86) but significant differences with the exit cut (p = 0.09) and the pitch (p = 0.01). For all three surgeons, the navigated-cut results were significantly better than the non-navigated cut results for entry, exit, absolute pitch, and absolute roll (p ≤ 0.01 for all).
Overall, there were ninety navigated cuts in Sawbones that were compared with fifty-four non-navigated cuts. In the navigated Sawbone scenarios, the mean entry and exit cuts were $1.4 \pm 1\ mm$ and $1.9 \pm 1.2\ mm$, respectively, from the planned cuts. More than 95% of the cuts were accurate to within 5 mm. The mean pitch and roll were $4.4^\circ \pm 3.3^\circ$ and $2.6^\circ \pm 2.1^\circ$, respectively. In comparison, the mean entry and exit cuts in Sawbones that were not navigated were $2.8 \pm 4.9\ mm$ and $3.5 \pm 4.6\ mm$, respectively. The mean absolute pitch and roll were $7.9^\circ \pm 7.7^\circ$ and $6.0^\circ \pm 4.7^\circ$, respectively.

The mean image-to-tracker point-to-point registration error was $1 \pm 0.3\ mm$ in Sawbones and $0.9 \pm 0.3\ mm$ in cadavers. The mean image-to-image registration error was $0.9 \pm 0.2\ mm$ in Sawbones and $0.9 \pm 0.3\ mm$ in cadavers. With use of a saw blade with a width of 1.25 mm, the mean cut width for the oscillating saw was $2 \pm 0.7\ mm$ and $0.6 \pm 0.2\ mm$ for the osteotome.

**Discussion**

The goal of this study was to assess the accuracy and reproducibility of freehand-navigated pelvic bone cuts in a Sawbones model and in cadavers. The results are relevant to other pelvic scenarios such as periacetabular osteotomies. Surgeons find performing accurate periacetabular osteotomies difficult. The use of navigation may be beneficial in this situation, as demonstrated in the periacetabular tumor model, with osteotomies similar to those used in periacetabular osteotomies. The mean distance between the actual cut plane and the planned cut was $1.4 \pm 1\ mm$ for the entry cut and $1.9 \pm 1.2\ mm$ for the exit cut for the ninety navigated cuts. More than 95% of the cuts were within 5 mm of the planned cut plane, with a maximum distance of 5.45 mm. Roll, representing the clinician’s ability to line up the tool correctly on the entry line, was accurate to within $2^\circ$ to $3^\circ$. Pitch, representing the clinician’s ability to target the slope of the plane correctly, was accurate to within $4^\circ$ to $5^\circ$. The mean image-to-tracker registration (for tracking) and image-to-image registration (for analysis) were each $<1\ mm$, which is comparable with the image voxel size (0.8 mm$^3$), as expected. Cuts were made by experienced orthopaedic surgeons under ideal conditions, with no soft-tissue obstruction overlying the Sawbones and the full pelvis in clear view. Even under these ideal conditions, the navigated cuts were significantly better than the non-navigated cuts. The clinical relevance of this difference between the navigated and non-navigated cuts is unknown; however, we would expect more significant differences in patients undergoing surgery, when exposure is more limited.

Based on these results, we now have the ability to perform freehand complex three-dimensional pelvic cuts with an accuracy of $\leq 5\ mm$ of the planned cut when aided by navigation. The surgical plan should provide for a minimum distance of 1 cm between the tumor and the critical structures, and the critical structures are assumed to remain at a safe distance from the tumor and the critical structures when relying solely on the navigation system. We compared the direction of the error between the planned and the final bone cuts. The results showed that the error occurred in both directions compared with the original plan, and that the direction was random. Therefore, up to $5\ mm$ of error in either direction from the actual surgical plan has to be accounted for when relying solely on navigation.

Unique to this study, we believe, is the focus on three-dimensional imaging. Two-dimensional imaging has limitations in guiding surgery, since most osteotomies are not completely parallel to one of the standard imaging views (axial, coronal, and sagittal). Alignment of the surgical tools to the osteotomy plane is difficult to visualize on standard two-dimensional imaging. A surface-rendered three-dimensional reconstruction improves the clinician’s ability to align and place the saw blade on the entry line and provides visualization of the cut trajectory and the exit plane. It was noted that a two-dimensional view, which includes trajectory, may give a false sense of accuracy when used without three-dimensional view confirmation, because the two-dimensional views show only a projection of the tool. Another difficulty relates to the ability to assess the roll of the cut correctly when performing long bone cuts. This can be improved with the use of a view that shows the whole length of the plane of the cut and not just the tool. This view enables the surgeon to more accurately align the roll of the tool and the planned cut. We recommend relying on three-dimensional view navigation and the use of two-dimensional views as a validating tool only. This was our practice in the study, and the accuracy of our results support this practice.

The average width of the cut differed substantially between the osteotomy, which splits the bone, and the oscillating saw, which removes bone. With the osteotome, the width was approximately 0.6 mm; with the oscillating saw, it was approximately 2 mm, and the saw blade thickness was 1.25 mm. The cut width increased when the surface of the entry cut was not flat and when the planned cut was not perpendicular to the entry surface. In addition, when a long cut is made by connecting several cuts, minor differences in the entry location, pitch, and roll of the cuts cause an increased width at the point of overlap of the cuts. In cadavers, there was a tendency for the bone to gradually change the direction of the osteotome. This was not true for the oscillating saw. The osteotome is technically easier to control for initiating the cut compared with the saw, since the saw has to be started away from the bone before it can be placed directly onto the bone. This means that the start location, the pitch, and the roll of the saw all need to be managed simultaneously. In addition, the vibration of the saw adds another degree of complexity. In practical terms, we still prefer to make the majority of the cuts with the saw and to use the osteotome for the final fine-tuning of the cuts, such as connecting the corners and finishing the exit cuts on the inner table of the pelvis or sacrum.

While this study demonstrates the advantage of the use of navigation, several limitations in its current implementation were identified. Line of sight between the tool, the static fiducial point, and the navigation camera is challenging for some of the tool positions. Real-time intraoperative manipulation and modification of the plan would also be beneficial. Research into improving image contrast in cone-beam CT for pelvic imaging is ongoing (e.g., scatter and truncation artifact management). Additional navigational features can be added to make the system even more intuitive and user friendly, such as system guidance to...
help the user achieve accurate pitch and roll. The navigation system is still in beta-testing and is still unavailable to surgeons. However, it will be used to manage patients in the near future.

Appendix

Charts showing user variance with regard to absolute pitch, entry cut, absolute roll, and exit cut are available with the online version of this article as a data supplement at jbjs.org.

References