Background: Despite advances in medical, surgical, and radiation oncology, deep-seated bone sarcomas that require large osseous resections continue to present resection and reconstructive challenges to musculoskeletal surgeons.

Methods: We describe our experience with computer navigation techniques combined with complex pelvic resections and limb-preserving surgeries.

Results: Computer-assisted navigation has shown promise in aiding in optimal preoperative planning and in providing more accurate and precise feedback during surgery.

Conclusions: Computer-assisted navigation offers precise instrumentation, technology-oriented imaging systems, and powerful information processing, all of which can assist in decision making, preoperative planning, and surgical accuracy.

Introduction
Sarcomas are diverse and rare malignant tumors that develop in soft tissue and bone. These tumors represent less than 1% of all newly diagnosed cancers each year in the United States. In 2010, approximately 2,650 new cases of cancer of the bones and joints were diagnosed and 1,460 patients died of this disease. Sarcomas arise from mesenchymal cell lines that include bone and soft tissue locations and often involve the extremities, pelvis, and retroperitoneum.

Advances in sarcoma treatment have laid the groundwork for continued progress. A multidisciplinary team approach that includes medical, surgical, and radiation oncologists is vital in maximizing successful outcomes. Combined progress in all of these fields of oncology has improved chemotherapeutic strategies, imaging techniques, and limb-preserving procedures. Despite these advances, however, surgeons still struggle with the challenges of large, deep-seated bone sarcomas that require large osseous resections. Studies that focused specifically on surgeries for sarcomas located in and around the pelvis have reported a lower than average negative margin status at the time of resection and a higher than average local recurrence rate. Surgical challenges also include locations in the lower extremities due to massive bone loss during resections, difficulties with anatomic implant positioning, and limb length discrepancies (Fig 1). Although advanced imaging techniques such as magnetic resonance imaging (MRI) and computed tomography (CT) scans can provide anatomic detail about the surgical bed, the successful transfer of that information from a view screen to the intraoperative field can be difficult.

Computer-assisted surgery allows surgical teams to merge computer technology, newly developed software,
modern imaging techniques, and surgical instrumentation in a more precise and coordinated fashion. The introduction of computer-assisted navigation techniques to aid in musculoskeletal sarcoma surgery helps to address the challenges described above by adding a level of accuracy and precision to the surgical procedures and also by applying the advanced imaging technologies that are now available.² ⁴ ⁷

Preoperative Planning

In 2008, we implemented a computer navigation software and hardware system for image-guided musculoskeletal oncologic resections and reconstructions. Early experience with the technique involved adapting software designed for total joint arthroplasty and applying this software to oncologic surgeries. A commercially available system (OrthoMap 3D, Stryker Orthopaedics,}

Fig 1. — Intraoperative photograph of the traditional method for measuring resection level, based on preoperative scans for an osteosarcoma of the distal femur. Measurements made with a ruler are subject to user error and perspective.

Fig 2. — Intraoperative photograph illustrating use of a navigated osteotome, an instrument used to cut through the underlying bone.

Fig 3. — Screen image of a planned resection and reconstruction of an osteosarcoma of the distal femur. Note MRI incorporation and notation of anatomic rotation for later reconstruction.
Mahwah, NJ) is now being used to accommodate a wide variety of oncologic surgical scenarios. The software package allows the surgeon to utilize patient data collected from both preoperative and intraoperative sources. Such advanced imaging techniques (eg, MRI, CT scans) were routinely obtained within a few days of the surgery and then loaded into the computer system to facilitate surgical planning. Additionally, intraoperative data were collected and used in some cases, taking advantage of a 360° fluoroscopic image intensifier. These intraoperative scans were combined with MRI/CT data to improve verification and accuracy. Intraoperative data were also collected, and surgeon-defined landmarks were used to create a virtual map of the operative field, thereby aiding the computer program in defining optimal implant positioning and resection levels.

Hardware and accessories have an important role in computer-assisted surgery by allowing communication between the surgeon, patient, and software. A tracker device used to follow the motion of surgical tools during surgery is integral to a navigation system, showing real-time motion of the tools relative to the patient anatomy on a computer display. With the ability to “see” the operating field, the computer device relays information to the computer and allows for careful calibration and incorporation of common surgical tools. In conjunction with the software, tools such as osteotomes, cutting saws, electrocautery devices, and even screwdrivers communicate such information as location, direction, and projection (Figs 2 and 3).

Once the information is entered into the computer, it can be accessed to aid in surgical planning. The software centralizes the data from the various sources (eg, MRI, CT scans, intraoperative imaging) and allows for a reconstructed virtual patient. Using this specialized software, the gathered dataset can be developed into a 3-dimensional representation of the patient. This virtual model can be viewed from multiple angles and provides an accurate depiction of the surgical field to aid

Fig 4. — Using preoperative CT imaging, surgical planning can program resection planes for the pelvic resection, accommodating the vital structures of the pelvis, tumor margin, and bone preservation.
the surgeon in preoperatively planning resection levels, resection planes, and the notation of pertinent anatomic points such as rotation of the distal femur or the soft tissue mass of a pelvic sarcoma. These points and planes can be projected onto the virtual patient and tested (Fig 4). In addition, different scenarios can be stored and recalled as needed, leaving a map for alternative plans and recording the final results of positioning and reconstruction (Fig 5).

Aside from the time and procedures necessary to attach the trackers and manipulate the software, surgical resections and reconstructions of the patients in all cases were done using our usual approaches and implants. Muscle-sparing approaches to the femur and tibia as well as adequate open exposures for the pelvic tumors were routinely performed. Trackers were attached with either custom bone clamps or, when necessary, outside of the main operative incision using percutaneously placed pins. Reconstruction of the skeletal defects was performed with a segmental oncologic prosthesis system (Global Modular Replacement System [GMRS], Stryker Orthopaedics).

**Institutional Experience**

A retrospective review of the surgeries performed in the last 2 years at our institution revealed that computer navigation was used in 20 patients undergoing orthopaedic oncologic surgery. Anatomic surgical sites were varied, occurring in the pelvis, proximal femur, distal femur, and proximal tibia. Surgeries included resection and reconstruction in the majority of the cases, and an external hemipelvectomy with the use of navigation was required in 1 patient. Diagnoses included osteosarcoma, Ewing sarcoma, chondrosarcoma, pleomorphic high-grade sarcoma, angiosarcoma, lymphoma, and metastatic disease.

All procedures were performed with negative surgical margins as confirmed by pathology (Fig 6). No preoperative plans for limb preservation were changed during...
surgery. No vascular events occurred as a result of the navigation technique, instrumentation, or intraoperative measurements. A deep infection occurred in 1 patient who had undergone a proximal tibia resection and reconstruction for a dedifferentiated chondrosarcoma. Local recurrence developed in a second patient who initially had an internal hemipelvectomy for a chondrosarcoma of the pelvis. Surgical procedures involving navigation took slightly longer to perform than surgeries that did not use navigation. Patients who underwent limb-preserving surgeries were assessed by both radiographic and clinical examination, and limb length discrepancies were no greater than 1.5 cm (Fig 7).

Discussion
Initially used in applications related to total joint reconstructive surgery, spine surgery, and orthopaedic trauma, computer-assisted navigation in the field of musculoskeletal oncology is in its infancy.8-11 Positive feedback regarding experience with variations of the software, hardware, and technology has been encouraging. From a reconstructive perspective, both improved accuracy and superior precision have been beneficial for patients, particularly with regard to implant positioning and function.8,11 We have been able to minimize leg length discrepancies, improve restoration of the joint line, and address rotational concerns of implant alignment. Again, results are preliminary yet promising. The goals of these efforts in musculoskeletal sarcoma surgery are improved tumor resections and superior implant positioning, resulting in not only better patient outcomes and satisfaction, but also longer implant survival.

A current limitation of computer-assisted navigation is the need for increased surgical time. Critics and even early proponents of the technology noted that adding more time to already lengthy surgeries increases the risk of infection and adverse events. However, a learning curve is an essential part in any new and evolving technique or technology. Anecdotally, we have found that with repetition and familiarity, the technique has become less obtrusive and, as expected, requires less time. Furthermore, with such a variety of different clinical scenarios, patience to adapt is needed. Cost has also been noted as a negative consequence of the technology. Initially, costs are relayed to the hospital system in terms of monetary value and to the surgeon and staff in terms of time and training. However, these systems are often multifunctional and can be utilized by more than one specialty or service such as neurosurgery and oral/maxillofacial surgery. Cost comparisons are needed as to the short- and long-term benefits as they relate to improvements in patient outcomes, durability, and function.

As previously noted, one local recurrence and one deep infection occurred in our series. The deep infection was located in a proximal tibial reconstruction and eventually required an amputation. Known for being a difficult reconstructive region, proximal tibia replacements can be problematic and present a higher risk for wound complications. The local recurrence developed following an internal hemipelvectomy and reconstruction. Despite negative margins and adjuvant treatment, the local recurrence rate in the pelvis has been reported to be as high as 70% to 90%, again underscoring the need for improvement with this difficult locale.12,13

Conclusions
Computer-assisted navigation offers several potential benefits in the surgical management of patients with musculoskeletal conditions, which is a challenging location for resection and reconstruction. Preoperatively, this technology offers improved visualization of the operative field and facilitates surgical planning. Intraoperatively, data from real-time imaging can be merged with MRI and CT scans to create a virtual map of the operative field.

Fig 6. — Gross specimen of the resected tumor. Note the acetabulum as well as soft tissues involved with tumor invading the underlying bone.

Fig 7. — CT scan illustrating the postsurgical results. Note the custom prosthetic reconstruction of the acetabulum and hip joint as well as lack of any perceptible leg length discrepancy.

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As the use of computer-assisted surgery becomes more extensive, it is hoped that the costs and time of the procedures will decrease and clinical outcomes will improve for patients with musculoskeletal sarcoma.

References