Interactive Technology and the New Paradigm for Healthcare
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A Stereotactic/Robotic System for Pedicle Screw Placement

Julio J. Santos-Munné
Michael A Peshkin
Dept. of Mechanical Engineering
Northwestern University
Evanston, IL 60208

Srdjan Mirkovic
S. David Stulberg
Thomas C. Kienzle III
Dept. of Orthopaedic Surgery
Northwestern U. Medical School
Chicago, IL 60611

Abstract. We are developing a robotic system to assist a surgeon in placing spinal pedicle screws. While several groups have undertaken such systems, our approach differs in that it endeavors to remain as close to current clinical technique as possible, yet achieve stereotactic accuracy.

This paper describes the conventional surgical methodology, justifies the need for stereotactic/robotic assistance, and discusses the various approaches to system design. In describing our system design, we emphasize key issues that arise with regard to robot accuracy, image linearity, and system registration.

1. Pedicle Screw Placement Surgery

1.1 Conventional Methodology

Currently about 60,000 lumbosacral fusions are performed a year in the United States using a variety of different surgical techniques and instrumentation. These various surgical techniques, though different, follow a similar methodology. The patient is in a prone position and the surgical approach is posterior. The vertebral grooves have to be well cleaned on each side in order to locate the pedicle [1]. Also common among the various surgical techniques is the is the use of two-dimensional images for preoperative planning.

During the planning stage, the surgeon becomes familiar with the specific anatomy of the patient's pedicle by using two-dimensional roentgenograms taken in the anterior-posterior (A/P - back-to-front), and sagittal (from the side) and CT slice showing the transverse (head-to-toe) views. From these images the surgeon can determine any deviations from normal anatomy, and obtain a feel for pedicle dimensions and relationships to the transverse process and facet joint. The transverse image is used to determine the pedicle width, angle, relationship with other anatomical structures, and distance to important anterior vascular structures (e.g. aorta). Similarly, sagittal images yield pedicle dimensional and angular information in addition to the relationships between associated structures. Exact pedicle dimensions can be extracted directly from a CT image. Preoperative planning is complete when the surgeon has traced the pedicle, transverse process, facet joint, and angles of insertion in grease pencil on the radiographs for intraoperative guidance.

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Once the pedicle is surgically exposed, there are three geometric techniques used to locate the pedicle screw entry point, commonly referred to as the intersection technique, the pars technique, and the mamillary process technique [2]. These techniques are based on anatomical landmarks. At the time of surgery, all three methods are used for locating each pedicle. In this way, a clear image of the pedicle and its orientation can be imagined by the surgeon. The surgeon then proceeds with a series of drillings, palpations, and radiographs to ensure that the drilled hole is within the boundaries of the pedicular tube. This is done until the screw is correctly placed.

Such an iterative process is necessary since the diameter of the pedicle is typically only slightly larger than the screw, and complications such as neural damage and vascular injury are possible if the screw penetrates the pedicular cortice.

1.2 Limitations of Conventional Methods

Because the many sensitive structures surrounding the pedicle are not visible during pedicle screw insertion (such as the dural sac, nerve roots near the pedicle, and vessels anterior to the vertebral bodies and sacral ala), accurate screw positioning remains the most important issue in pedicle screw placement [3]. Complications occur in about 10% of implanted screws. Screw malposition is the primary cause of complications which include pedicle splitting and medial pedicle cortical perforation, weak fixation to bone, nerve roots impingement, dural tears, displacement of anterior graft, damage of the sacroiliac joints, and damage to vascular structures. Nerve root impingement alone occurs in 6.6% of all placements [4]. Clinical studies have shown that pedicle screw placement is sub-optimal for 10-30% of implanted screws [5]. Therefore accurate control of screw position and orientation would greatly reduce the occurrence of complications that arise and would enhance the positioning accuracy in pedicle screw placement.

A major contributing factor to surgical complications in pedicle screw placement method is the surgeon's initial lack of experience. As demonstrated by Weinstein et al., failure rate of pedicle screw placements fell from 36.1% to 6.3% with practice[6].

1.3 Motivation for Robotic System

The advantages of robotic (or more generally *stereotactic*) surgery for pedicle screw placement are threefold. First, more accurate placement of the screw will improve the clinical result and reduce the risk of surgical complications. Second, accuracy and control in screw placement will unencumber the surgeon from the iterative process conventionally used, encouraging focus in placing the screw as opposed to details of screw alignment. Third, through stereotactic technique, percutaneous screw placement becomes a viable option, allowing minimally invasive surgery through the skin, as opposed to open surgery.

A stereotactic system can use precise coordinates to align a drill guide with the vertebra at the desired position and orientation of the screw. The precision made possible and the reduction in length of surgical procedure by stereotaxis reduce the chance of surgical complications. A stereotactic system can particularly benefit less experienced surgeons who commonly have higher rates of suboptimal placement and/or complications. Also, by allowing less surgical exposure, the risk of infections, currently about 6% [1], would be reduced.

Another benefit resulting from stereotactic pedicle screw placement is the development of percutaneous technique. Percutaneous placement would result in less trauma, shorter recovery period, less risk of infection, and fewer surgical complications overall. Presently a substantial incision in the soft tissues along the spine is required in order to view the surgical site, and a surgeon can only approximate (imagine) the desired sagittal and

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transverse pedicle angles for screw placement. In stereotactic surgery, screw location and orientation can be selected on fluoroscopic images and do not depend on direct visual observation of the vertebrae.

1.4 Different Philosophies for Spinal Robotic Systems

Currently there are three groups investigating robot-assisted pedicle screw placement systems. These include a group of researchers at Grenoble[7], at Bern[8], and our group at Northwestern University.

The approach undertaken by the Grenoble group involves viewing a full three-dimensional reconstruction of the spine, generated from pre-operative CT data. Intraoperative registration is performed by touching, with a calibrated space pointer, the bony structures of the vertebrae, and collecting their coordinates. These are matched to the 3D model. Finally, using an opto-electronic space digitizer a drill can be aligned with the planned trajectory by superimposing a series of crosses shown on computer monitor. The surgeon then proceeds to drill into the pedicle by viewing the real-time alignment of the drill.

The team from the University of Bern M.E. Muller Institute for Biomechanics, with their collaborators at Wayne State University Department of Neurological Surgery has a approach to registration identical to that of the Grenoble team. The only difference in their philosophies is their approach to intraoperative guidance. As opposed to viewing a real-time image of the alignment of the drill the University of Bern group shows a real-time image of the position of the drill bit. Both of these techniques require the surgeon's attention at a computer monitor for guidance.

Our philosophy, justified in this paper differs from the above in that it maintains a familiar clinical approach to the greatest degree possible. Specifically, and in contrast to related projects elsewhere, we avoid the necessity for three-dimensional reconstructions, specialized surgical instruments, and major modification of the operating environment and instead maintain surgical techniques close to conventional methods. Our system is described below.

2 Pedicle Screw Placement System

2.1 Design Description

Our system consists of three parts: 1) a Unimation PUMA-560 robot; 2) a Varian 'C'-arm fluoroscopic image intensifier system; and 3) a 486 computer with two monitors and an image acquisition card. (shown in Figure 1)

As can be seen in Figure 1, the end effector of the robot has a shape designed such that all eight fiducials (steel balls on the corner of the end effector) are seen from both A/P and lateral fluoroscopic images with none shadowing the other. The coordinates of the fiducials are known to ±.01mm accuracy. The end effector also has a hole to guide the surgeon's drill during surgery. The end effector thus has a dual use as a registration artifact and a drill guide.

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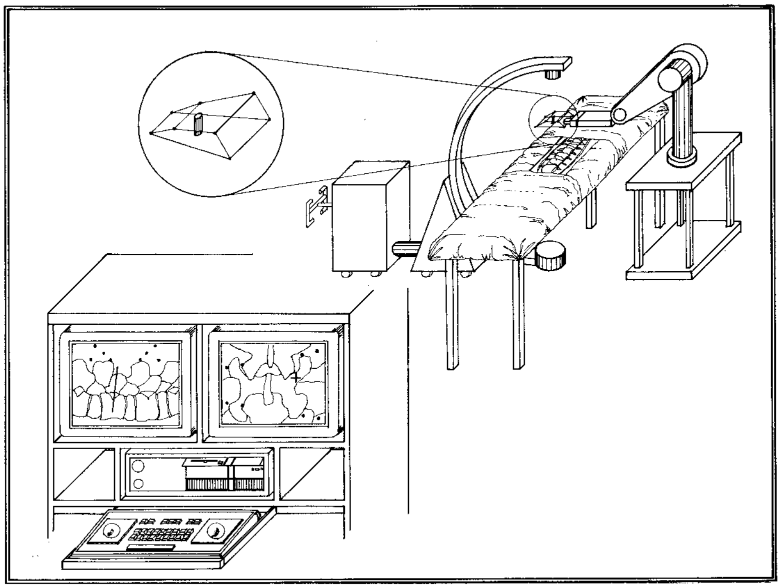

Figure 1 - Overview of spinal pedicle screw placement system. The robot (right) holds a registration/drill guide artifact over the spine, which may be surgically exposed or not. A/P and lateral radiographs are aquired by the C-arm fluorscope (center) and stored and displayed by the computer (foreground). The surgeon positions crosshairs on the images. The robot moves its drill guide to the specified posistion and orientation. Penetration of the spinal pedicle is done manually by the surgeon, using the drill guide for position and orientation.

2.2 Preoperative Planning

As in conventional practice, pre-operative planning is done by the surgeon using transverse CT slices and two-dimensional roentgenograms (radiographs).

Intra-operatively, the dual displays common to C-arms are replaced by dual computer monitors. A single A/P (anterior-posterior) and a single sagittal fluoroscopic image are acquired. Both images are stored and displayed simultaneously on separate monitors.

The surgeon uses a pointing device (a mouse) to position crosshairs on the A/P image at the desired entrance point into the pedicle. Similarly, the desired sagittal angle (Figure 2) of the screw is selected by adjusting the angle of a line segment on the sagittal image using the pointing device.

The remaining datum needed is the desired transverse angle (Figure 2) of the pedicle. The transverse angle is not directly visible in either the A/P or sagittal images. The transverse angle, as in conventional practice, is chosen from CT slices pre-operatively.

Identification and measurement of the features needed for the transverse angle is done on a computer monitor with a pointing device, or is alternatively done on CT hardcopy with a pencil and ruler. The key point is that it is not necessary to form a three-dimensional reconstruction of the spine from CT data, or to integrate selection of the transverse angle into the intra-operative system.

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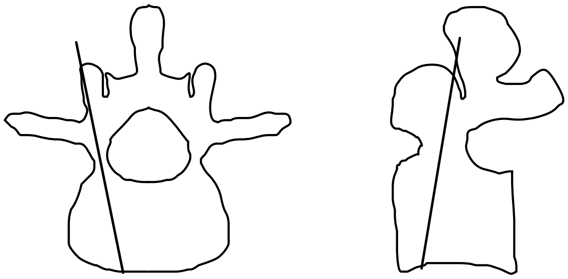

Transverse View Sagittal View

Figure 2 - Transverse and Sagittal View

Determining the transverse angle independently on a pre-operative CT slice has many advantages. First, spinal surgeons are familiar with this method of determining the transverse angle. Second, while the quality of CT images is not always sufficient for computer analysis or accurate three dimensional reconstruction, it is generally sufficient for visual interpretation. Finally, a fair amount of inconvenience is sometimes involved in importing the CT data in computer-readable form, and in requiring the surgeon to sit down with specialized software to view it. Determination of the transverse angle would be the sole justification for this inconvenience. Our design philosophy is not to automate as much as possible, but rather to stay as close to conventional practice as possible, while offering stereotactic accuracy.

After the desired transverse angle has been determined pre-operatively and the transverse tilt of the patient in the operating table has been registered, its numerical value is entered into the computer. The sagittal angle is selected intra-operatively on the sagittal display, and the entrance point into the pedicle is selected intra-operatively on the A/P display. It remains to register the images to the robot’s coordinate system, and based on that registration and the plan, to move the drill guide into the desired position and orientation accurately.

In order to register the transverse tilt of the patient on the OR table we use a geometric technique based on the intra-operative A/P image. This allows the numerically-entered transverse angle to be referred to the prepared spine. The necessary adjustments to the position and orientation of the drill guide can then be calculated and executed.

At the surgeon's discretion, new A/P and sagittal images can be acquired at this point or subsequently, using a K-wire in the drill guide socket, to give the surgeon confidence that the drill guide axis is in fact properly positioned. Finally a drill guide is slipped into the socket and the pedicle screw implantation is performed through the guide.

There is little specialized fixturing, aside from some stabilization of the torso. We believe, based on informal preliminary studies and orthopaedic experience, that the stability of the spine when the patient is in the prone position is adequate for stereotactic surgery, so that rigorous fixtures and stereotactic frames are not required.

In conventional pedicle screw placement, the surgeon's unobstructed vision (and, as a consequence, the requirement for open surgery) is most needed in order to choose an entrance point into the pedicle. In contrast, the transverse and sagittal angles, and safe advancement of the drill, are initially approximated by the surgeon. Then they are confirmed and refined through frequent fluoroscopic imaging. In our stereotactic system, the entrance point as well as the angles are selectable based on fluoroscopy, without direct vision.

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3 Engineering Issues

3.1 Robot Accuracy

Industrial robots are designed for repetitive tasks. They are highly precise, but surprisingly inaccurate. Highly effective calibration is necessary to achieve the accuracy needed to match the accuracy of diagnostic images. We have developed a particularly simple calibration technique, based on kinematic parameter identification, which is suitable for serial kinematic chains such as robotic manipulators.

Absolute accuracy is defined as the disparity between the six coordinates (position and orientation) adopted by the robot endpoint, and the values commanded by the controlling computer. The primary source of error is the kinematic model of the robot, consisting of the dimensional parameters of the robot links, which the controller uses to compute the joint angles needed to achieve a requested endpoint. Calibration methods that reevaluate the parameters of the kinematic model (such as link lengths, joint offsets, and encoder slopes) are known as parameter identification methods. Those that reevaluate the complete set of parameters (typically several dozen) are full-parameter identification methods.

Our technical approach [9] is based on single degree-of-freedom external measurements, obtained from an extensible ball-bar containing a linear displacement transducer, which are collected automatically as the robot is exercised. To our knowledge this is the simplest technique developed to date that results in full-parameter identification. It requires no metrological equipment other than the single linear transducer. The technique is quick and uncomplicated, and for a PUMA-560 robot has resulted in a decrease in error by a factor of twenty.

3.2 Image Linearization

Image-intensifier tubes with electron focusing lenses can have five mayor types of aberration [10]: distortion caused by the input phosphor screen, curvature of image field, coma, spherical aberration, and astigmatism. Distortions caused by the input phosphor surface curvature alter the image more than any other type of aberration. This type of abberation can be characterized as radial and tangential distortion. Radial distortion causes image points to be displaced from their true positions toward or away from the image center and are the result of imperfect lens design. Tangential distortions on the other hand, cause image points to be displaced in the direction perpendicular to the radius connecting it to the center and are due to decentering of lens elements during manufacturing [11,12]. The error in image size from a fluoroscopic image intensifier may be as large as 20% in the image periphery [13].

Since surgical strategies are based entirely on nominal values from a set of fluoroscopic images, compensation for such distortions is crucial in order to maximize the *absolute accuracy* of the image. An image's absolute accuracy represents the closeness with which an objects true location can be determined from the image. Computer-assisted surgery requires accuracies in the sub-millimeter range.

Image linearization is commonly performed by finding a relation between pixel coordinates in the image and the physical coordinates that project to the pixel, or by fitting a camera model to given data. Our approach is based on the former method, transforming control points (features of an image) to known coordinates by way of a model surface.

3.3 Registration

Registration requires that we determine the transformation between the coordinate system of the robot and the projections that appear in the two fluoroscopic images. It is implemented by positioning an alignment artifact, held by the robotic manipulator, in close proximity to the involved vertebrae. A detail of the alignment artifact is shown in Figure 1. It is X-ray (and visually) transparent with the exception of opaque spheres at its corners, and the faint outline of a socket for a snap-in metal drill guide through its center. Initially the artifact is positioned roughly over the involved vertebra and within the field of view of the C-arm. The corners show up as distinct dots on the A/P and sagittal images. (The shape of the artifact is designed so that the dots will not shadow one another.)

Planning for the drill trajectory is done on the equivalent of a 3-view orthographic projection of the vertebra: a transverse view obtained preoperatively from CT, and intraoperative A/P and sagittal views obtained via fluoroscopy. Metal spheres mounted on x-ray transparent end-effector are present in the fluoroscope images, and serve to register the robot to the vertebra. Once registered, a drill guide in the end effector can be correctly positioned over the pedicle. Refer to [14] for a registration connectivity graph of our system.

From the location of the dots in the two images, the current displacement of the drill guide axis from surgeon's specified crosshairs on the A/P image can be computed. Similarly the angular deviation of the current drill guide axis from the surgeon's specified sagittal angle can be computed. It is also possible to identify from the dots the transverse angle of the drill guide axis, the scale factors of the fluoroscopic optical system, and the x-ray beam divergance angle or perspective projection.

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References

[1] R. Roy-Camille, G. Saillant, C. Mazel; "Internal Fixation of the Lumbar Spine with Pedicle Screw Plating"; *Clinical Orthopaedics and Related Research*, Number 203, February, 1986.

[2] S.I. Esses, D.Al. Bednar; "The Spinal Pedicle Screw: Technique and Systems"; Orthopaedic Review, Vol 18, No. 6, June 1989.

[3] Manuel Reimao Pinto, MD; "Complications of Pedicle Screw Fixation"; Spine: State of the Art Reviews-Vol. 6, No. 1, January 1992

[4] Stanley D. Gertzbein, MD, Stephen E. Robbins, MDI; "Accuracy of Pedicular Screw Placement In Vivo"; *Spine*-Vol. 15, No. 1, 1990.

[5] J.N. Weinstein, B.L. Rydevik, W. Rauschning; "Anatomic and Technical Considerations of Pedicle Screw Fixation"; *Clinical Orthopaedics and Research*, Number 284, Nov. 1992.

[6] J.N. Weinstein, K.F. Spratt, D. Spengler, C. Brick, S. Reid; "Spinal Pedicle Fixation: Reliability and Validity of Roentgenogram-Based Assessment and Surgical Factors on Successful Screw Placement"; *Spine*, Vol. 13, No. 9, 1988.

[7] S. Lavallee, P. Sautot, J. Troccaz, P. Cinquin, P. Merloz; "Computer Assisted Spine Surgery: a technique for accurate transpedicular screw fixation using CT data and a 3-D optical localizer";

Proceedings of the 1st International Symposium on Medical Robotics and Computer Assisted Surgery, Vol. 2, Pittsburgh, Penn, Sept. 1994, pg. 315-321.

[8] L.P. Nolte, L.J. Zamorano, Z. Jiang, Q. Wang, F. Langlotz, E. Arm, H. Visarius; "A Novel Approach to Computer Assisted Spine Surgery"; *Proceedings of the 1st International Symposium on Medical Robotics and Computer Assisted Surgery*, Vol.2, Pittsburgh, Penn, Sept. 1994, pg. 323-328.

[9] A. Goswami, A Quaid, M.A. Peshkin; "Complete paramter identification of a robot from partial pose information"; *Control Systems,* 13 (5), October 1993. (special issue).

[10] Csorba, I.P.; Image Tubes; Indianapolis: Howard W. Sams & Co.; 1985, Chaps. 3,4.

[11] Ardeshir Goshtasby; "Correction of Image Deformation from Lens Distortion Using Bezier Patches"; *Computer Vision, Graphics, and Image Processing*, Vol. 47, pg. 385-394, 1989.

[12] H.M. Karara, Y.I. Abdel-Aziz; "Accuracy Aspects of Non-Metric Imageries"; *Photogrammetric Engineering*, 1974.

[13] Ewa Pietka; H.K. Huang; "Correction of Aberration in Image-Intensifier Systems"; *Computerized Medical Imaging and Graphics*, Vol. 16, No. 4, pp. 253-258, 1992.

[14] J.T. Lea, J.J. Santos-Munné, M.A. Peshkin; "Diagramming Registration Connectivity and Structure"; *Proceedings, Medicine Meets Virtual Reality III*, San Diego, CA, January 1995.