Computer Assisted Spine Surgery

P. Sautot, S. Lavallee,
J. Troccaz, P. Cinquin
TIMC, Faculte de Medecine de Grenoble
38706 La Tronche CEDEX FRANCE
Pascal.Sautot@timb.imag.fr

P. Merloz
Service de Chirurgie Orthopedique
CHU Grenoble,
38700 La Tronche FRANCE

Abstract

Computer assisted spine surgery follows the basic ideas developed for Computer Assisted Medical Intervention (CAMI). Quantitative analysis of medical images makes it possible to localize with great accuracy anatomical structures. This is fruitfully used to drive guiding systems. This method tends to minimize invasive surgery and increases the quality of surgical interventions. In this article we present our methodology and develop some results leading to clinical experimentations.

Introduction

Spine is made of 24 articulated vertebrae. Instrumentation may be needed to fix spine segments, in order to reduce deformities (e.g. scoliosis) or fractures. Spinal surgery instrumentation basically consists in three implantable elements: the rod, the hook and the screw (Fig. 1). The pedicle is well known to be the strongest part of the vertebral bone, in which a screw can be driven. Unfortunatly, it is not the widest part of the vertebra. The diameter of a lumbar or thoracic pedicle may vary from 3mm to 10mm [SLL+87]. The surgeon usually exposes the back part of the vertebra and uses his anatomical knowledge to drill into a good direction. A slight error in direction may result in an important error in the position of the tip of the screw. This gesture is performed at least twice, but some times ten or twelve times during an intervention. This is done with no direct visibility on crucial structures (spinal cord, lung, vessels, ...). Statistical anaylsis of series of surgical procedures have proven that about 10% of the screws are not correctly installed [Sim93]. It is therefore interesting to increase security, by a more precise performing of the intervention. Besides, this technique is presently restricted to lumbar vertebrae (where the pedicle is bigger) and it would be interesting to use it for dorsal vertebrae. Finally, per-cutaneous screw driving would contribute to less invasive surgery.
The assistance to pedicular screwing will follow the three classical steps of CAMI [CDT+92]: Perception - Decision - Action, which we will describe in the following sections. We will discuss the first experiments, that have been conducted on anatomical parts.

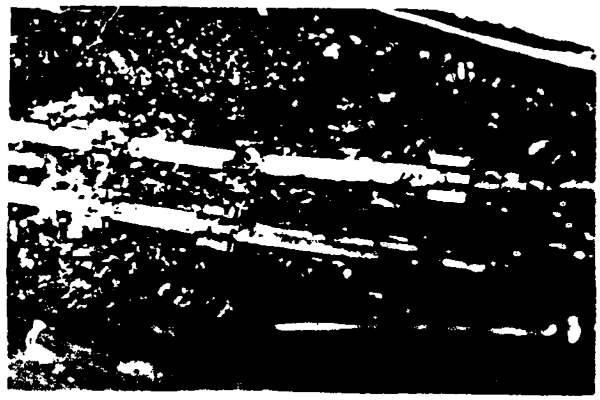

Fig. 1: instrumented spine

Perception

Pre-operative perception

Computed Tomography (CT) or Magnetic Resonance Imaging (MRI) provide sets of 2D images in the volume of interest (typically three vertebrae). CT will be preferred to MRI, which also allows for quick acquisition, but which has the drawback of more difficult definition of bony structures.
Data were obtained from anatomical parts of a cadaver. A segment of the lumbar and of the lower part of the thoracic spine was scanned. Two vertebrae (the second and third lumbar vertebra) have been examined. The first exam consists in a set of 2mm spaced slices and the second in a set of 4mm spaced slices.

Intra-operative perception

Various intra operative sensors (X ray, ultrasound, angiography, endoscopy, arthroscopy), are routinely used for intra or post operative control, but they have the drawback not to be very accurate. Calibration procedures make these sensors more accurate. Optical (Optotrak system) or mechanical localizers (6 axis puma robot) provide complementary information to determine geometrical features and to localize guiding tools.

Palpation When the back part of the vertebra is exposed, it is possible to use a 3D digitizer to pick up the 3D coordinates of the visible surface of the vertebra (Fig. 2). We have used an Optotrak system, which makes it possible to get the coordinates of the tip of a pointer with about 0.2 mm of accuracy. It is very easy to pick up about 100 points, which has proven sufficient for later registration.

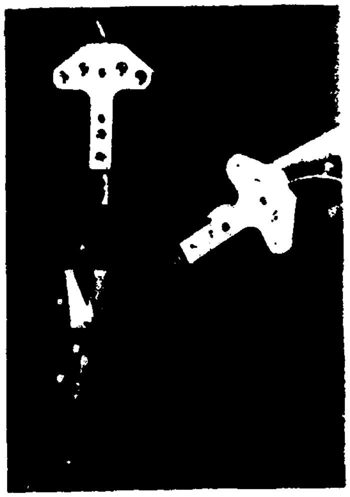

Fig. 2: optotrak digitizer

X rays A classical portable X ray device is used (Fig. 3). Several views can be acquired by moving the X ray source around the spine. The advantage of this sensor s that it may be used for per cutaneous surgery. It puts some calibration problems, that have been overcome by using camera calibration methods [CLSC92]. We have developed special calibrating plates for accurate registration. The first assumption is that the vertebra does not moves. This can be verified in the lumbar region. n the thoracic region the rib cage may move. This artefact can be corrected using a 3D localizer. Each ime an image is acquired, we store the position of the vertebra and the position of a calibration image relative o an absolute reference coordinate system. So, we can apply the method previously mentionned method.

ig. 3: X ray device

Ultrasounds Ultrasonic images of bony structures re known to be very poor, because of the specular reflexion of ultrasounds. However, we only need the external part of the vertebra, and may therefore use this technique [BTML93]. It is necessary to know the spatial position of all the pixels that may be seen on the ultrasonic images. We have therefore equipped the ultrasonic probe with diodes, that make it possible for the Optotrak system to locate with great accuracy the position and orientation of the ultrasonic slice (Fig. 4). There again, per cutaneous techniques may be applied.

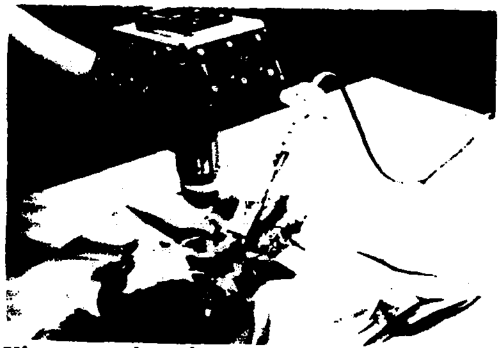

Fig. 4: Ultra sound probe

Decision

Image Analysis

The classical taxonomy for 2d segmentation distinguishes two kinds of techniques: contour based or region based methods. It can be extended in three dimensions by surface based or volume based methods. Segmentation of medical images often relies on a priori knowledge and interactive procedures. We have developed several deformable surface tools, that are used to modelize preoperative images with minimal interaction with the user (Fig. 5). These tools create an isotropic segmented volume of data, which is used for later registration.

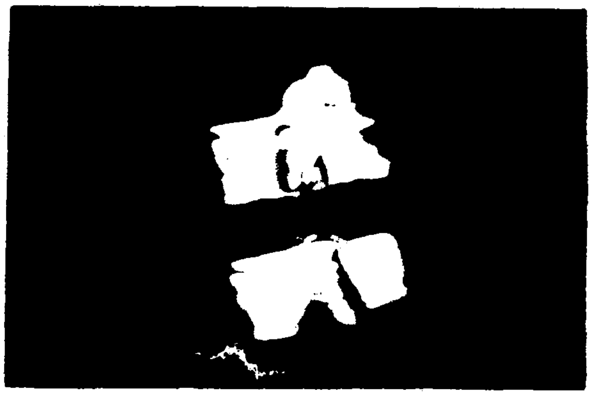

Fig. 5: 3D smoothed surface of the vertebra

Surgical Planning

Before performing the intervention, relying on the use of medical images, surgeons choose an optimal surgical strategy. In the litterature, several quantitative parameters are proposed to describe a vertebra [SLL+87]. These parameters can be related to direct measurements on CT scan images [OSK+90]. It has encouraged us to design a user interface to plan the position of a screw inside a pedicle. CT slices are used to determine this situation. The software visualizes three perpendicular sections passing through the axis of the pedicle and allows to select a trajectory represented by a set of two points in the CT frame reference system $P1_{CT} = (x1, y1, z1, 1)^t$ $P2_{CT} = (x2, y2, z2, 1)^t$ (Fig. 6).

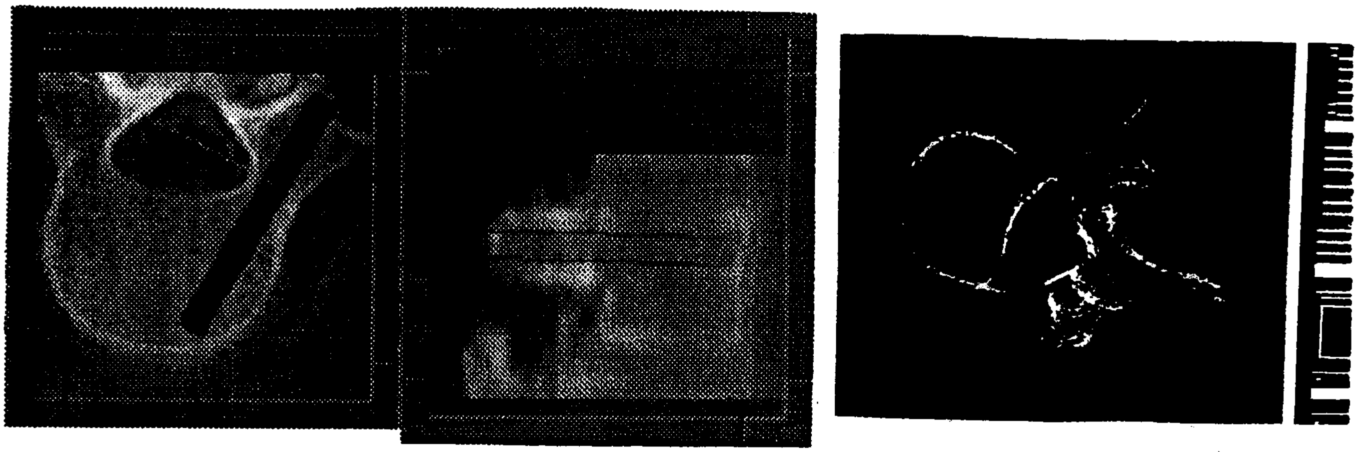

Fig. 6: surgical planning

Registration

Given sensed data in the intra operative sensor coordinate system, and modelled data in the pre-operative model coordinate system, registration estimates the rigid transformation T^{CT}_{Sensor} (4 × 4 rigid transformation homogeneous matrix) that aligns sensed data with the model. We have developed efficient distance maps and implemented least squares algorithms, which are adaptative by nature and converge near a global minimum (that may be found with a very limited apriori knowledge) and that ensure a good accuracy [BL92] [LSB91]. The same algorithm can be applied to 3D/3D and 2D/3D registration. The first case applies to registration between CT and ultrasonic or palpation data. The second one corresponds to registration between CT and radiographic data (which are only 2 dimensional). All these techniques require about 3s, with a Digital DS5000. Once the pre operative and intra operative reference system have been registrated the pre operative trajectory is transformed in the intra operative reference coordinate system as follows $Pi_{Sensor} = T^{CT}_{Sensor}$ Pi_{CT}.

Action

Screw may be guided towards the pedicle through passive or semi-passive aids.

Passive System

Purely passive systems provide a means to compare the current action with a previously planned strategy. Information has to be interpreted by the surgeons. A driller is equipped with diodes, that make it visible by the Optotrak (Fig. 7). The axis of the tool is calibrated and represented by a line segment $(P1_{Driller}, P2_{Driller})$. An adequate user interface provides the surgeon with information about the position of the drill, and helps him go into the previously defined direction.

The strategy to drill through the pedicle consists in superimposing the line segment $(P1_{Driller}, P2_{Driller})$ with the line segment $(P1_{Sensor}, P2_{Sensor})$. Three screws have been introduced succesfully. Quantification of the accuracy of this introduction will soon become available.

Fig. 7:the driller and the exprimental setup

Semi Passive Systems

Semi passive systems differ by their ability to deliver a precise mesure of the action beeing currently performed. A robot carries a laser beam, that indicates the correct direction. An alignment device set on the driller makes it possible for the surgeon to drill into the correct direction. A simulation of that system has been realized We are currently developing a prototype of a surgical system (Fig. 8).

ig. 8:the robot and the calibration plate

ig. 9:an X ray image of 2 screws inside pedicles

Conclusion

xperiments have been conducted on cadaver (Fig. 9) nd plastic vertebrae. Simulations showed that sub milimetric accuracy may be obtained, by any of the comination of the above mentioned perception and action levices. We have just validated all the pre operative teps. We are currently preparing the validation of he intra operative steps and improving the registraion procedure. 2D/3D registration uses the contours f the shape of the vertebra. They are quite difficult to e determined. We propose a method which will take nto account the probabilty of a pixel to belong to conour. This probability depends on pixel attributes such s gradient value, gray level value,... First experiments n human beings will be planned by the middle of 1994, our results meet the surgical requirements.

Acknoledgements

his research has been partially supported by Soamor (Berck,France). We thank F.Leitner, E.Bainville, C.Barbe, B.Mazier, R.Orti for their contribution to this work.

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