Computer Aided Surgery with Lumbar Vertebral Drill-guides, Using Computer Aided Planning, Design and Visualisation

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Abstract. Manual placement of pedicle screws for spinal surgery can be inaccurate. Personalised drilling guides may be designed based on surgical planning on CT image data, and in this study we have evaluated their accuracy. Flexibility was achieved by varying design parameters, so that damaged / abnormal vertebral anatomy was accommodated. The drill-guides were manufactured by rapid-prototyping and then surgery was performed. Surgical outcomes were assessed; results were validated and found to be satisfactory.

1 Introduction

Some procedures in orthopaedic surgery need spinal fixation, where bone-screws are put in the vertebral pedicles, to anchor further devices (e.g. rods etc.), Such a task relies on accurately placing those screws. Since medical imaging may provide limited insight, surgeons must proceed carefully to avoid putting a screw outside the pedicle, which could damage nearby anatomy. A survey [1] of pedicle screw insertion gave a 9.6% intra-operative complication rate (59 of 617 cases), a rate that could be improved. If the path taken by a drill (creating a pilot-hole for the screw to enter) could be pre-defined, the placement of screws could then proceed more accurately. One option is to use computer assisted intra-operative navigation systems. The alternative investigated here is to use a mechanical guide, or template, to transfer the planned trajectory into the surgical field.

Tools are designed with features matched to the patient's anatomy. For example, the surface of the tool could be designed to fit an individual's transverse and spinous processes in a unique position., using pre-operative CT data. Sleeves may then be added based on a trajectory planned in the pre-operative CT images to guide the path taken by a drill-bit Our Belgian collaborators KU Leuven had pioneered the design and usage of spinal drill-guides (see [2-4]). This study was performed to demonstrate that the technique could be transferred to other centres using different equipment and to assess accuracy in-vitro.

2 Methods

2.1 Planning and Segmentation

Axial CT data was acquired from two cadaveric lumbar spinal specimens. Contiguous 2mm thick slices (with edge enhancement), were used to provide 512x512 images of 0.3mm pixel size. The images were used to plan bone-screw implant positions using the surgical planning environment "SurgiCase" (Materialise, Belgium) [6]. The implant co-ordinates of screw-head and -tip defined the screw trajectories. Reference lines were defined in the software from *the middle of the posterior surface of the spinous process at its thickest, to the most posterior boundary of the spinal canal* to give lines of known co-ordinates for use in assessing accuracy of implantation.

Segmentation thresholds were adjusted to create a mask with a well-defined boundary between bone and soft-tissue. The contours were exported in IGES-format to "Mechanical Desktop" (MDT) solid modeler software [7]. Linear interpolation was used to reduce the slice separation to 0.5mm (Figure 1).

2.2 Design Protocol

The trajectories of planned implants and reference lines were imported into MDT. The former were then redrawn as solid-models of drill-bits, which passed through the vertebra for visualization purposes. All elements of a drill-guide solid-model designed in MDT could be altered (e.g. shape, size, orientation, position, dimensions etc.), permitting customization to fit a specific patient's vertebral anatomy.

For a good contact between tool and tissue, a V-shaped knife-edge was designed to rest on the surfaces of a vertebra's transverse and spinous processes. The knife-edge solid model was modified to match the nearby bone

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surface (Figure 1). This region was magnified and inspected to ensure good contacts were made. Placing three knife-edges formed the start of a tripod - a stable platform for guiding drill-bits. To resist rotation of the drill-guide in the sagittal plane, the spinous knife-edge was tilted about the transverse axis to contact the spinous process at roughly 90°. When this design feature was used, it was necessary first to locate the drill-guide on the transverse processes, before tilting the drill-guide through a small angle to rest against the spinous process.
Steel-surfaced sleeves were designed to ensure drilling followed the trajectory. The sleeves were offset a few millimetres above the bone surface, to allow observation of drill-tip entry. Arches curved around the vertebrae (from transverse knife-edges) and met at or near the spinous knife-edge; the arch was then thickened to join the sleeves. Thus a single drill-guide object (made up of 3 knife-edges, 2 tunnels and 1 or 2 arches) was created.
Upon completion of the design, rapid prototyping (by laser sintering) was used to manufacture the drill-guide.

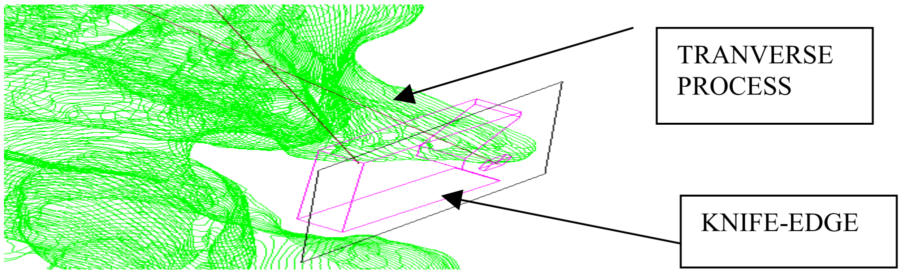

Figure 1 A knife-edge being manoeuvred onto a transverse process

2.3 Surgery

Figure 2 The drill-guide in action (note one Ti pin in place, and depth-marker on drill-bit)

The design of the drill-guide meant that the surgeon had to hold the drill-guide in place just above the vertebrae, which aided stability (Figure 2). The specimens provided a good simulation of surgery as they had posterior soft-tissue in place, which needed dissection to expose the vertebrae Easy insertion of drill-guides into body cavities could then be tested. Vertebral surfaces were prepared, but with some soft-tissue remaining. The guide was held in place by moderate finger-pressure; the drill was inserted in one sleeve and advanced down to the pre-set depth. A titanium pin was put in the resulting hole and the process repeated with the other sleeve - the pin in the first hole aided stability. Drill-guides were positioned, then removed and re-positioned, to assess repeatability. 8 pins (L1-L4) were put in one specimen, 6 pins (L1-L3) in the other. The surgeon was asked for comments on drill-guide usage.

2.4 Validation

For verification, the surgeon examined post-operative CT-scans and graded screw locations as: good / acceptable / unacceptable, (defined as: good – within 2mm of planned trajectory; satisfactory – greater than 2mm from trajectory, but within bone; unsatisfactory – definite breach through cortical bone). These grades appear in Table 1. For validation, positions of placed screws were evaluated in relation to those of planned screws. The post-operative CT data were imported into Surgicase and the trajectories of the implanted pins defined. On both pre- and post-operative CT-images, a reference line was defined connecting two characteristic anatomical features: the middle of the posterior surface of the spinous process at its thickest, to the most posterior boundary of the spinal canal. A total of four lines/trajectories were formed: the planned screw plus reference, and the placed screw plus reference.
The four lines were re-drawn in MDT. The transformation necessary to register the planned and actual trajectories was found by aligning the two reference lines were aligned The trajectories were projected onto sagittal, coronal and transverse planes, and the angles between the projected lines determined [5] These angles

appear in Tables 2 and 3. Further measurements were made using SurgiCase: by transversely slicing across the axis of the pedicle, a new stack of CT-images was built along the pedicular axis. The pedicular isthmus was inspected and distances from pin to cortical boundary were measured - in superior, inferior, medial and lateral directions. These cortical thicknesses appear in Tables 2 and 3. This indicated pedicle dimensions, thickness of cortical bone surrounding a pin and how centred the pin was in the pedicle.

3 Results

3.1 Surgeon's Comments

Some transverse processes on one side of the specimens had been amputated close to the body. This made drill-guide placement difficult. The damaged transverse processes simulated inadvertent fractures sometimes found in-vivo. The surgeon was initially unhappy with the inclined spinous knife-edge concept, though usage improved with practice; a pair of opposed inclined knife-edges was suggested for the future. The guides were somewhat flexible, allowing a very small variability in entry point and orientation. The intended position of drill- guide was found to be repeatable. Placement of the guides was simpler in the second specimen, due to familiarisation. No break-out from cortical bone into soft-tissue was felt during drilling in either operation.

Table 1: Post-operative Grading of Placed Screws

Specimen No. 1	Grading	Specimen No. 2	Grading
L1 pedicles	Both acceptable	L1 pedicles	L-acceptable, R-good
L2 pedicles	L-acceptable, R-good	L2 pedicles	Both good
L3 pedicles	L-acceptable, R-good	L3 pedicles	Both good
L4 pedicles	Both good		

3.2 Measurements

Table 2: Specimen no.1 Measurements of Angle and Cortical Thickness

Pedicle	Transverse ±0.1°	Sagittal ±0.1°	Coronal ±0.1°	Superior ±0.2mm	Inferior ±0.2mm	Medial ±0.2mm	Lateral ±0.2mm
L1 left	2.7	3.4	3.0	3.8	6.8	0.9	5.1
L1 right	0.3	6.7	4.1	4.4	2.0	1.7	5.1
L2 left	0.8	6.2	9.1	2.5	8.4	1.7	1.7
L2 right	3.5	8.8	3.3	6.3	2.9	0.9	4.2
L3 left	0.9	2.6	3.2	5.0	5.9	5.1	2.1
L3 right	1.7	5.0	20.2	7.2	1.2	1.2	6.8
L4 left	1.5	3.7	4.9	3.4	5.1	3.0	3.8
L4 right	0.1	1.5	5.9	1.7	4.2	2.5	6.7
Mean	1.3	6.0	7.2				
SD	0.4	0.9	1.9				

Table 3: Specimen no.2 Measurements of Angle and Cortical Thickness

Pedicle	Transverse ±0.1°	Sagittal ±0.1°	Coronal ±0.1°	Superior ±0.2mm	Inferior ±0.2mm	Medial ±0.2mm	Lateral ±0.2mm
L1 left	0.0	8.2	17.1	2.3	11.0	4.2	0.9
L1 right	0.9	7.9	11.8	4.1	8.1	5.0	4.1
L2 left	0.1	1.4	6.2	10.0	2.7	3.7	1.8
L2 right	4.2	4.6	4.1	9.2	3.6	3.3	4.1
L3 left	3.1	5.6	3.0	8.6	4.1	2.3	5.0
L3 right	0.4	8.0	7.9	8.6	5.4	2.4	3.7
Mean	1.4	6.0	8.4				
SD	0.7	1.0	2.0				

4 Discussion

The unusual shapes generated by human anatomy, as well as fractured/broken bone (due to specimen preparation or sometimes encountered in surgery), provided a challenge to the flexibility of the current design approach. The presence of significant amounts of soft-tissue was also problematic. However the nature of the controllably adjustable and visually inspected design method overcame such obstacles (see Figure 1).

Using the inclined spinous knife-edge was not intuitive, with some instability or non-uniqueness at times. The thin sections (e.g. arches) of drill-guides were a little flexible; a stiffer design would be better, and could be roughly handled in a theatre setting with confidence. The design required the surgeon to press the drill-guide in place just above the vertebrae, thereby encouraging stability (see Figure 2). Deviations in the contact zone (e.g. tilt etc.) were reduced, which lessened deviations from the desired screw trajectories.

Drill trajectories were planned using axial and sagittal views. In coronal views, screws were seen almost end on, making precise adjustment difficult. This may explain the poor accuracy in this plane (see Tables 2 and 3). The accuracy of defining the trajectory of the pin on the post-operative CT images was limited because the pins were narrow (3.2mm diameter) relative to the CT slice thickness (2mm). For cortical measurements the small circle representing the pin (in cross-section) was difficult to see. Surgical outcomes were very good (perhaps due to precision of trajectory co-ordinates); a 100% success rate was achieved - 9 of 14 screws graded 'good' (see Table 1). Cortical measurements showed a healthy margin of safety in most cases, suggesting low-risk to near-by anatomy, e.g. nerve-roots. Validation figures were satisfactory (see Tables 2 and 3). Drill-guide design is a possible source of error, as is the soft-tissue left on vertebra to interfere with drill-guide placement. The definition of the validating reference-line is also subject to error (especially in the sagittal and coronal planes).

5 Conclusions

The concept of surgical templates as lumbar spinal drill-guides was successfully reproduced at Leeds. A scanning protocol and guide-lines for screw-planning were defined. Seven drill-guides were designed, with features that could be adjusted for optimum position/orientation; unusual or damaged anatomy was catered for by this flexibility. Two lumbar spinal cadaveric specimens were operated on by a surgeon, with fourteen pins placed in L1-L4 pedicles. Post-operative scanning confirmed 100% success rate. Positions of placed screws were evaluated relative to surrounding cortex and in comparison to planned screws. Validation results were satisfactory, and suggestions made by the surgeon will be incorporated into future designs.

Acknowledgements

Karel van Brussel, Katholieke Universitiet Leuven, Leuven (Belgium). Lieve Boeykens and staff at Materialise NV, Leuven (Belgium). Paul Karran, DePuy International, Leeds. Jane Williams and Lisa Fox, St. Luke's Hospital, Bradford. Andrew Marsden and Paul Bell, Keyworth Institute, University of Leeds. Dr. Roger Soames, Dept of Biomedical Sciences, University of Leeds. Lynne Gathercole, Leeds General Infirmary, Leeds. S Abhaykumar, Dept of Orthopaedics, St. James University Hospital, Leeds.

Funding was provided by the EC's BRITE-EURAM program (under contract no. BRPR-CT97-0378), for the Personalised Implant and Surgical Aids (PISA) project (no. BE96-3456).

References

1. Esses SI, Sachs BL, Dreyzin V "Complications associated with the technique of Pedicle Screw Fixation: A Survey of ABS members" *Spine* **18** (15) pp2231–2239, 1993.

2. Goffin J, Van Brussel K, Vander Sloten J et al "3D CT based personalised drill guide for posterior transarticular screw fixation at C1-C2: technical note" *Neuro-orthopedics* **25** (1-2) pp47-56, 1999.

3. Van Brussel K, Vander Sloten J, Van Audekercke R et al "Internal fixation of the spine in traumatic and scoliotic cases: The potential of pedicle screws" *Technology and Healthcare* **4** (4) pp365-384, 1996.

4. Van Brussel K, Vander Sloten J, Van Audekercke R et al "Medical image based design of an individualized surgical guide for pedicle screw insertion" In: *Proceedings 18th Annual Conference of the IEEE Engineering in Medicine and Biology Society: "Bridging Disciplines for Biomedicine"* **1** (1) pp225-226 IEEE, 1997.

5. Martens K, Verstreken K, Van Cleynenbreughel J et al "Image-based Planning and Validation of C1-C2 Transarticular Screw Fixation Using personalized Drill Guides" *Lecture Notes in Computer Science* **1679** pp860-867, Springer, 1999.

6. Materialise NV *SurgiCase v1.1 Reference Guide* Materialise, 1999.

7. AutoDesk *Mechanical DeskTop r4 Manual/User Guide* AutoDesk Press, 2000.