Original Article

Autonomous lumbar spine pedicle screw planning using machine learning: A validation study

ABSTRACT

Introduction: Several techniques for pedicle screw placement have been described including freehand techniques, fluoroscopy assisted, computed tomography (CT) guidance, and robotics. Image-guided surgery offers the potential to combine the benefits of CT guidance without the added radiation. This study investigated the ability of a neural network to place lumbar pedicle screws with the correct length, diameter, and angulation autonomously within radiographs without the need for human involvement.

Materials and Methods: The neural network was trained using a machine learning process. The method combines the previously reported autonomous spine segmentation solution with a landmark localization solution. The pedicle screw placement was evaluated using the Zdichavsky, Ravi, and Gertzbein grading systems.

Results: In total, the program placed 208 pedicle screws between the L1 and S1 spinal levels. Of the 208 placed pedicle screws, 208 (100%) had a Zdichavsky Score 1A, 206 (99.0%) of all screws were Ravi Grade 1, and Gertzbein Grade A indicating no breech. The final two screws (1.0%) had a Ravi score of 2 (<2 mm breech) and a Gertzbein grade of B (<2 mm breech).

Conclusion: The results of this experiment can be combined with an image-guided platform to provide an efficient and highly effective method of placing pedicle screws during spinal stabilization surgery.

Keywords: Augmented reality, computed tomography radiography, fusion, lumbar spine, machine learning, pedicle placement

INTRODUCTION

Pedicle screw fixation has become a widespread technique for spinal instrumentation since first described by Roy-Camille.[1] Fusion is often performed in conjunction with pedicle screw instrumentation to achieve rigid stability that enables a higher successful fusion rate than uninstrumented fusion.[2] However, pedicle screw placement has risks of neurological complications, dural tears, vascular injuries, and loss of fixation with erroneous starting points and trajectories.[3,4]

Several techniques for pedicle screw placement have been described including freehand techniques, fluoroscopy assisted, computed tomography (CT) guidance, and robotics.[5-7] The CT-guided technique has been associated with higher accuracy and less radiation exposure to the surgeon than the freehand technique; however, this process requires increased preoperative planning, operative time, and added radiation exposure to the patient.[8-10] Further, robotic pedicle screw placement has the appeal of assisting with minimally invasive techniques and increased accuracy

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but is prone to catastrophic complications with registration errors and patient repositioning mid procedure.[11,12]

No singular method has been able to combine the increased accuracy of image-guided surgery with the decreased preoperative planning time associated with the freehand technique. Incorporation of a neural network into image-guided and robotic screw placement has the potential to significantly reduce preoperative planning time, decrease operative time, and reduce the use of intraoperative imaging. Neural networks have already been used to autonomously identify and label anatomical landmarks and pedicle screw starting points on lumbar spine CT scans.[13,14] Correct pedicle screw length, diameter, trajectory, and angulation could be calculated instantly from preoperative or intraoperative CT scans in real time and coupled to intraoperative imaging platforms result in optimal implant selection (possibly reducing implant pullout and failure); increased placement accuracy, reduce change of neurovascular complications, all while reducing planning time and cognitive load for the surgeon. The purpose of this study is to evaluate the accuracy of planned pedicle screw placement by a neural network on lumbosacral spine of CT scans without human supervision.

MATERIALS AND METHODS

The autonomous pedicle screw planner (Surgalign Spine Technologies, Chicago, IL, USA) uses machine learning techniques to determine the proper pedicle screw position, orientation, length, and diameter. This technique is outlined in Figure 1. The method combines the previously reported autonomous spine segmentation solution with a landmark localization solution [Figure 2], in a multistep process developed to determine a proper medical device placement.[13] The autonomous spine segmentation results are used for defining the consequent volumetric regions of interest subjected to further analysis. The obtained information about the spine anatomical structure is combined with the CT data [Figure 3a] to provide a better understanding of the problem. The result is passed to a convolutional neural network trained in localizing characteristic landmarks. The identified landmarks are afterward used for determining the proper position, orientation, and length of the pedicle screw. The diameter of the pedicle screw is derived from the autonomous spine segmentation results, providing a final pedicle screw definition [Figure 3b]. The method was trained and validated on both preoperative and intraoperative CT images, to allow high-quality preoperative surgery planning and intraoperative guidance.

The neural network's placement of pedicle screws was graded according to the Ravi, Gertzbein, and Zdichavsky

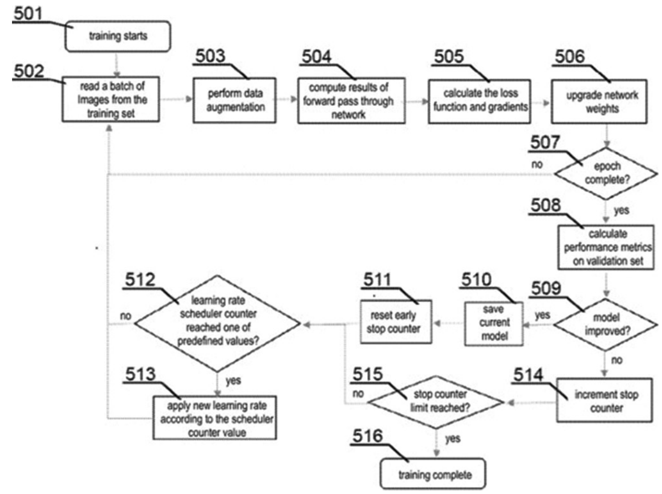

Figure 1: An outline of the machine learning process used to train the neural network which placed pedicle screws on the computed tomography radiographs

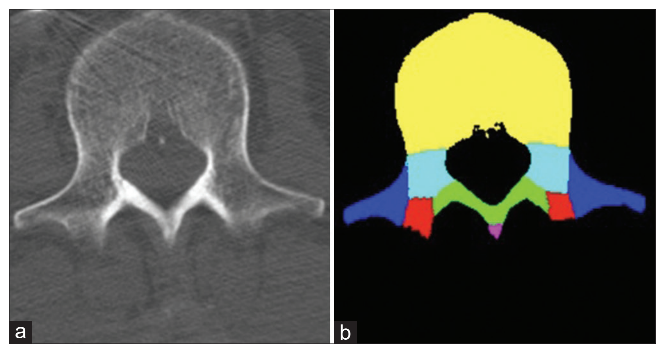

Figure 2: Demonstrates output of semantic spinal segmentation. The original axial computed tomography scan (a) is segmented and labeled by the convolutional neural network into color coded regions representative of the underlying anatomical spinal components (b)

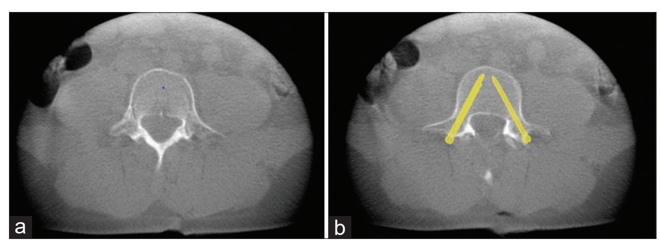

Figure 3: The Digital Imaging and Communications in Medicine radiograph showing the original computed tomography image (a) and the same computed tomography scan with the virtual pedicle screws placed (b)

grading systems.[15-17] Average grade of the pedicle placement for each of the scales was calculated and reported. Screw length, width, and insertion angle were calculated for each lumbosacral segment and reported as averages. Final data were reported as averages with 95% confidence intervals. The angle measurements were determined in the slicer interface manually, and the screw length and diameter were generated from the machine learning program directly.

RESULTS

In total, twenty individual patient CT scans with computer-generated pedicle screw placements were investigated. Of the 208 placed pedicle screws, 208 (100%) had a Zdichavsky Score 1A, 206 (99.0%) of all screws were Ravi Grade 1, and Gertzbein Grade A indicating no breech. The final two screws (1.0%) had a Ravi score of 2 (<2 mm breech) and a Gertzbein grade of B (<2 mm breech). This grading is outlined in Table 1. At each spinal level, an average pedicle screw angle, average screw length, and average screw diameter were collected and these measurements are outlined in Table 2.

DISCUSSION

The use of a machine learning system has proven to be highly accurate at automatically segmenting lumbar vertebral anatomy for landmark identification.[13] In the current study, the same machine learning system planned pedicle screw placement with a high degree of accuracy with only 2/208 Grade 2 pedicle breaches in the Ravi and Gertzbein classifications. However, the clinical ramifications of these pedicle breeches are likely to be clinically irrelevant.[18] Furthermore, the advantage of machine learning applications is that such breaches can be used as examples for the computer during subsequent neural network training and development to ensure higher accuracy rates in future software versions.

Table 1: A summary of the pedicle screw grades

Grade	Number of pedicle screws
Ravi grade	
Grade 1	206
Grade 2	2
Grade 3	0
Grade 4	0
Gertzbein grade	
A	206
B	2
C	0
D	0
Zdichavsky score	
IA	208
IB	0
II A/B	0
III A/B	0

Image guidance in spine surgery increases the accuracy of pedicle screws and potentially decreases implant-related complications.[19-21] However, some of the difficulties of image guided surgery include additional training for operating room staff and increased planning time in the preoperative phase. The current study demonstrated that it is feasible to develop a neural network with the ability to plan pedicle screw placement with the correct starting point, transverse trajectory, screw length, and diameter autonomously. The calculated trajectories were consistent with previous studies describing pedicle morphology of the lumbosacral spine.[22-24] Further applications of this software could eliminate preoperative planning time, increase implant placement accuracy, and decrease operative time.

Machine learning algorithms for pedicle screw placement have been described by other authors with a similar high degree of accuracy. Automatic segmentation with cone-beam segmentation in a cadaver model by Burström *et al*. demonstrated a 95.4% accuracy with pedicle screw planning.[25] However, this accuracy was reduced when to 86.1% when there was inclusion of spinal deformity. In the current study, only instances where the pedicle diameter was smaller than the smallest commercially available pedicle did the program fail to place the pedicle screws entirely within the pedicle or with the correct angulation. Abnormally small pedicles are frequently encountered in deformity surgery, especially on the concave side of scoliotic curves.[26] This could prevent neurologic injury by giving the surgeon alternative fixation options, such as sublaminar bands or transverse process hooks.[27,28] This is in accordance with the current literature that showed that an automated method could place pedicle screws within 1 mm of the expert reference.[16] Currently, the technology is available to match the pedicle screw diameter to the pedicle isthmus with high

Table 2: A summary of the pedicle screw length, angle, and diameter

Spinal level	Average screw angle (range) (°)	95% CI (°)	Average screw length (mm) (range)	95% CI	Average screw diameter (mm) (range)	95% CI
L1	21.3 (13.4-27.7)	19.8-22.9	45.2 (35-55)	42.7-47.8	5.5 (4.5-7.5)	5.1-5.9
L2	21.3 (16.2-27.7)	20.4-22.2	46.8 (40-55)	45.0-48.5	5.3 (4.5-6.5)	5.1-5.6
L3	23.4 (16.2-29.9)	22.6-24.3	46.6 (40-55)	45.2-48.0	5.9 (4.5-8.5)	5.5-6.2
L4	26.6 (20.3-36.6)	25.7-27.5	45.3 (35-50)	43.9-46.5	5.8 (4.5-7.5)	5.5-6.1
L5	34.1 (23.1-43.9)	32.6-35.6	45.3 (35-55)	43.8-46.7	6.7 (4.5-9.5)	6.2-7.2
S1	36.3 (23.6-45.6)	34.6-37.9	46.8 (35-55)	45.4-48.3	7.8 (4.5-9.5)	7.4-8.2

CI – Confidence interval

accuracy ensuring a proper fit.[29] The surgeon has the ability to control the percentage of pedicle fill depending on patient age, bone density characteristics, or the presence of prior instrumentation.

There were several limitations to the current study. The pedicle screws were only planned on the lumbar and sacral levels. Further experimentation should be done to assess the accuracy of screw placement at the thoracic and cervical levels on the spine. Integration of these annotated images into an image projection device is needed to assess how the pedicle screw placement information would be accessible to the surgeon during the procedure. Further analysis should be done to see if the high levels of accuracy found in this experiment are maintained in analysis of various spinal pathologies.

This machine learning algorithm offers increased versatility when combined with previous neural networks that autonomously identify vertebral body anatomy and dimensions.[13] Future studies should investigate how these two networks would work cooperatively. This combination has the potential to accurately place pedicle screws along a wide array of vertebral anatomy and pathologies.

CONCLUSION

Accurate pedicle screw placement is a critical element of success for spinal surgery. High accuracy prevents complications of spinal canal encroachment leading to neurologic complications, dural tears, and vascular injuries and ensures high strength of fusion following these procedures. Image-guided surgery has proven to be effective in increasing the accuracy of pedicle screw placement. This study has shown that a neural network can potentially minimize the preoperative time previously needed for image-guided surgery while maintaining a high accuracy in the measurements to be used during the procedure. To our knowledge, this is the first study to validate neural network accuracy for placing pedicle screws in a CT spine model. The results of this experiment can be combined with an image-guided platform to provide an efficient and highly effective method of placing pedicle screws during spinal stabilization surgery.

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Conflicts of interest
The following authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Dr. Siemionow – Holosurgical Inc.; Dr. Luciano – Holosurgical Inc.; and Dr. Gawel – Holosurgical Inc.

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