NEUROSURGICAL FOCUS

Neurosurg Focus 52 (4):E10, 2022

A novel surgical planning system using an AI model to optimize planning of pedicle screw trajectories with highest bone mineral density and strongest pull-out force

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OBJECTIVE The purpose of this study was to evaluate the ability of a novel artificial intelligence (AI) model in identifying optimized transpedicular screw trajectories with higher bone mineral density (BMD) as well as higher pull-out force (POF) in osteoporotic patients.

METHODS An innovative pedicle screw trajectory planning system called Bone's Trajectory was developed using a 3D graphic search and an AI-based finite element analysis model. The preoperative CT scans of 21 elderly osteoporotic patients were analyzed retrospectively. The AI model automatically calculated the number of alternative transpedicular trajectories, the trajectory BMD, and the estimated POF of L3–5. The highest BMD and highest POF of optimized trajectories were recorded and compared with AO standard trajectories.

RESULTS The average patient age and average BMD of the vertebral bodies were 69.6 ± 7.8 years and 55.9 ± 17.1 mg/ml, respectively. On both sides of L3–5, the optimized trajectories showed significantly higher BMD and POF than the AO standard trajectories ($p < 0.05$). On average, the POF of optimized trajectory screws showed at least a 2.0-fold increase compared with AO trajectory screws.

CONCLUSIONS The novel AI model performs well in enabling the selection of optimized transpedicular trajectories with higher BMD and POF than the AO standard trajectories.

https://thejns.org/doi/abs/10.3171/2022.1.FOCUS21721

KEYWORDS screw trajectory; osteoporosis; surgical planning; artificial intelligence

With population aging, orthopedic surgeons are facing an increasing number of elderly patients who require surgery for degenerative spinal diseases, spinal fractures, and spinal deformity.[1–3] Thoracolumbar fixation with pedicle screw is a classic technique widely used in spinal surgeries in order to achieve stability after aggressive decompression procedures and to reconstruct spinal balance. Nearly half of the elderly patients requiring lumbar surgery have osteoporotic spine, which is associated with high risks of pedicle screw loosening and even reoperation due to symptom recurrence.[2,4–6] Therefore, methods to strengthen the pedicle screw fixation in thoracolumbar spine with low bone mineral density (BMD) are urgently needed.

Based on the surgery reference of the AO Foundation, the protocol of pedicle screw insertion is as follows. The appropriate entry point is at the intersection of the midline of the transverse process and the lateral margin of the superior facet. The ideal trajectory of the pedicle screw in the cranial-caudal direction is parallel to the superior endplate. AO-referenced pedicle screw placement protocol is designed to standardize the freehand pedicle screw in-

ABBREVIATIONS AI = artificial intelligence; BMD = bone mineral density; DEXA = dual-energy x-ray absorptiometry; POF = pull-out force; ROI = region of interest.

SUBMITTED November 29, 2021. **ACCEPTED** January 19, 2022.
INCLUDE WHEN CITING DOI: 10.3171/2022.1.FOCUS21721.

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sertion technique to minimize the risk of surgical complications. However, in patients with severe osteoporosis, the AO trajectory would mainly cover poor cancellous bone and is likely to cause poor strength and complications such as screw loosening. A standard pedicle screw trajectory has limited capacity to adjust to individual needs of the osteoporotic patients.

With the development of surgical robotics and navigation technology, it is possible to insert the pedicle screw with a personalized trajectory to achieve optimal BMD and pull-out force (POF) in osteoporotic patients. A variety of methods for automatic spine screw planning have been reported.[7–10] The computer-assisted preoperative planning tool of Knez et al. enabled these authors to achieve acceptable pedicle screw placement in 96.6% of cases. With the application of 3D modeling of the vertebral body and pedicles,[7] Wi et al. have also developed a preoperative planning system that enables real-time interaction with surgeons, which can help guide less-experienced surgeons in pedicle screw fixation. Wi et al. reported the overall accuracy of screw placement to be 96.4%.[8] However, there have been few studies on automatic planning of screw trajectories with optimal BMD and POF, which will help prevent osteoporosis-related complications. Caprara et al. employed a 3D preoperative planning system to find the optimized trajectories by maximizing the CT-derived bone mechanical properties, and the optimized trajectories had a 26% increase in simulated POF in comparison with AO standard trajectories.[10]

The goal of our work is to develop a computer-assisted system to find the optimized transpedicular trajectories with maximal BMD and POF. The system we have developed is called Bone's Trajectory, and is a CT image-based artificial intelligence (AI) technique that includes the following major innovative technical components: 1) AI vertebral detection, 2) autosimulation of pedicle screw placement, 3) phantomless bone density estimation, and 4) finite element analysis of screw pull-out simulations to find the optimized surgical placement. The primary objectives of this study were to investigate the BMD and POF of available trajectories for pedicle screw placement in elderly osteoporotic patients and compare the BMD and POF of optimized trajectories with the AO standard trajectories.

Methods

Patients

The use of the CT scans in this study has been approved by the University of Hong Kong–Shenzhen Hospital Ethics Committee. Patients who were hospitalized for lumbar surgery from January to March 2021 were reviewed. Included patients met the following criteria: 1) age ≥ 60 years; 2) diagnosed with osteoporosis by dual-energy x-ray absorptiometry (DEXA) before the surgery; and 3) underwent a lumbar CT scan for preoperative evaluation of degenerative lumbar diseases. The exclusion criteria were the following: 1) presence of spinal tumors, deformity, tuberculosis, or fractures in the L3–5 vertebral segment; 2) history of lumbar surgery; and 3) BMI less than 18.5 kg/m^2 or more than 35 kg/m^2.

CT Scans

CT scans for this study were acquired on a dual-layer detector (IQon Spectral CT, Philips Healthcare). The scanning parameters of CT were set at the values of 120 kVp, 1-mm slice thickness, and 512 × 512 matrix. The standard reconstruction kernel was a soft-tissue kernel. The scan FOV was about 500 mm, and the table height was approximately 150 cm.

Methodology

The developed intelligent system can automatically select the surgical plan with maximal BMD and POF. The methodology is shown in Fig. 1.

3D Spine Segmentation

Through processing clinical lumbar spine CT data, 3D image texture and density features were extracted using customized 3D U-Net volumes and networks to quantify and calculate bone structure regions.

3D Spine Meshing Generation

Spine meshing was performed by use of the Marching Cube (MC) algorithm. First, a series of MC-based algorithms were needed to clarify the concept of "cell." A voxel is a square lattice of eight adjacent voxel points in a 3D image, and the semantics of the Cube in the MC algorithm can also refer to this voxel. Each voxel (except those on the boundary) is shared by eight voxels. Distance is the straight-line distance between two points in the euclidean space.

Vertebral Volume BMD Evaluation

The BMD of the trabecular bone within the vertebral body was measured for each patient. Vertebrae L1–3 were prioritized in selection. The average BMD of L1–3 was recorded. If vertebral fractures were found in these vertebrae, other adjacent vertebrae from T12 to L5 were used as alternatives. The BMD was calibrated by using the CT values of the paraspinal muscle and subcutaneous fat. The region of interest (ROI) is an ellipsoid placed in the central part of the vertebral body, covering more than 80% of the cancellous bone area and not touching the cortical bone, and is mapped against any pathological site, nerve, or blood vessel in the vertebral body. Fat and skeletal muscle have a fixed chemical composition and a known linear attenuation coefficient as a function of x-ray energy, which allows the muscle and fat CT values (Hounsfield units [HU]) to be used as internal reference standards.[11] A phantomless calibration technique was developed in which fat and muscle HU values were linearly regressed against fat BMD (−69 mg/ml) and muscle BMD (77 mg/ml) to establish conversion of HU measurements to mg/ml, and then the CT values of vertebral bone were used to extrapolate equivalent BMD (mg/ml).[12]

Transpedicular Screw Trajectory Simulation

Vertebrae L3–5, the most common segments for lumbar surgery, were prioritized for selection for this procedure. To simplify analysis, the dimensions of pedicle

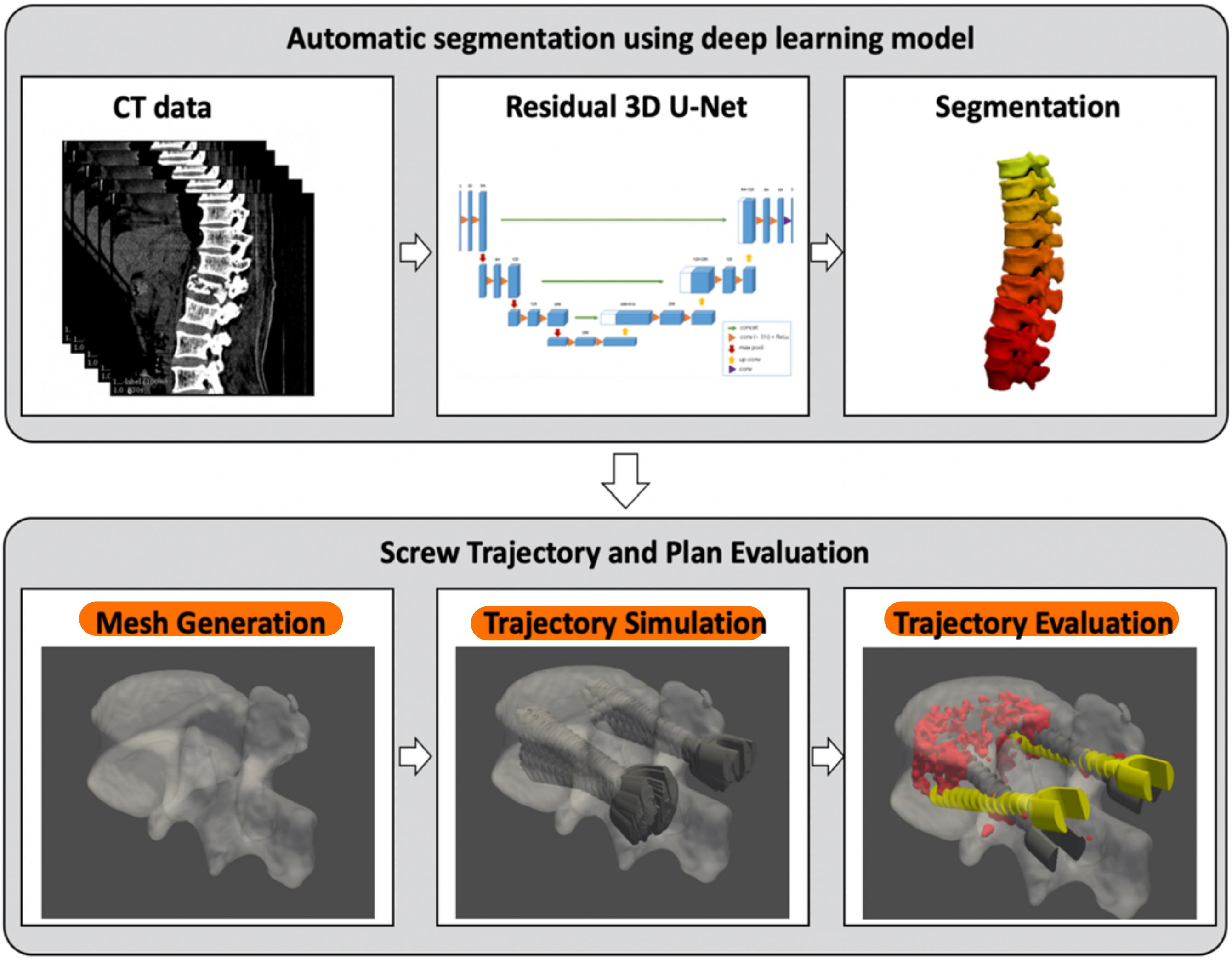

FIG. 1. The workflow of Bone's Trajectory.

screws were set at 45 mm in length and 6 mm in diameter; thread pitch was 2.75 mm, and depth was 1 mm. Screw trajectory requirements were as follows: 1) The possible entry points were set within a circle with a diameter of 6 mm, the center of which was the confluence of the lateral border of the superior articular facet and middle transverse process. 2) The pedicle screw was placed within the vertebral pedicle. In particular, safety distances of at least 1 mm were retained in the inferior and medial walls of the pedicle. 3) The pedicle screw never penetrated the upper and lower endplates, the vertebral body wall, or the articular surface of the small joints. 4) The pedicle screw never damaged the superior articular facets. 5) Precision of the screw was 0.5 mm.

Requirements for the AO standard pedicle screw trajectories were the following: 1) The pedicle screw trajectory entry point was at the intersection of the midline of the transverse process and the lateral margin of the superior facet. 2) The trajectory in the cranial-caudal direction was parallel to the superior endplate.

Screw Trajectory Plan Evaluation

Through finite element analysis and AI calculation, the trajectory BMD and axial POF were calculated through the simulation analysis of screw placement. Screw trajectory determination according to BMD was based on anatomical and functional tissue assessment using a cascaded 3D framework for spine segmentation from CT imaging and phantomless measurement of local BMD. The shape of the resulting ROI simulates the screw thread geometry. BMD is calibrated by the CT value of the paraspinal muscle and subcutaneous fat that is localized by the region closest to the target vertebrae. Chapman et al. performed a biomechanical analysis of the POF of cancellous bone screws and determined the effects of screw thread geometry, tapping, and cannulation on the holding power of screws.[13] In their study, Chapman et al. developed an equation to estimate the screw POF, which we also incorporated in our model to calculate the POF of every screw trajectory. The equation is $F_s = S \times A_s = (S \times L \times \pi \times D_{major}) \times TSF$; F_s = pre-

TABLE 1. Number of alternative trajectories, trajectory BMD, and POF of L3–5

	L3		L4		L5	
	Lt	Rt	Lt	Rt	Lt	Rt
No. of alternative screw trajectories	218.6 ± 37.9	217.3 ± 29.0	313.2 ± 57.1	164.7 ± 24.3	289.7 ± 65.0	314.1 ± 43.9
AO trajectory BMD, mg/ml	94.9 ± 8.3	88.2 ± 7.6	100.2 ± 7.2	98.4 ± 7.1	107.8 ± 8.0	128.0 ± 9.3
Max trajectory BMD, mg/ml	208.7 ± 12.7	192.1 ± 10.5	207.6 ± 11.9	216.5 ± 11.6	229.8 ± 15.5	243.5 ± 14.4
AO trajectory POF, N	435.1 ± 50.5	396.0 ± 45.9	463.9 ± 46.8	450.5 ± 44.7	496.0 ± 56.7	692.8 ± 79.8
Max POF, N	1387.5 ± 115.1	1244.7 ± 110.2	1374.1 ± 119.3	1458.7 ± 113.1	1611.2 ± 159.5	1751.0 ± 139.6
Max POF/AO trajectory POF	4.2 ± 0.6	4.6 ± 0.9	3.6 ± 0.5	3.7 ± 0.3	4.0 ± 0.6	3.0 ± 0.3

Values are presented as mean ± SD.

dicted shear failure force (N); S = material ultimate shear stress (MPa); A_s = thread shear area (mm^2); L = length of thread engagement in material (mm); D_{major} = major diameter (mm); TSF = thread shape factor (dimensionless) = 0.5 + 0.57735 d/p; d = thread depth (mm) = (D_{major} − D_{minor})/2; D_{minor} = minor (root) diameter (mm); p = thread pitch (mm).

Statistical Analysis

Statistical analysis was conducted using SPSS version 23 (IBM Corp.). Since the screw trajectories were not independent from each other within the same lumbar vertebra, the paired-sample t-test was used to compare the BMD and POF of AO trajectories with those of the optimal trajectories; $p < 0.05$ was considered to indicate a statistically significant difference.

Results

This study included 21 elderly osteoporotic patients (3 male and 18 female). The average age and vertebral body BMD were 69.6 ± 7.8 (61–85) years and 55.9 ± 17.1 (26.4–78.9) mg/ml, respectively. A total of 126 pedicles (6 L3–5 pedicles for each patient) were analyzed. The average number of alternative screw trajectories, the trajectory BMD, and the POF for L3–5 are summarized in Table 1.

On both sides of L3–5, the recorded maximal BMD and POF of optimized trajectories were significantly higher than those of AO standard trajectories ($p < 0.05$). On average, the POF of optimized trajectory screws showed at least a 2.0-fold increase compared with AO standard trajectory screws. A representative example illustrating the comparison between optimized and AO standard screw trajectories is shown in Fig. 2.

Discussion

This study developed a novel AI model for optimized planning of pedicle screw trajectories in patients requiring lumbar fixation. Results of this study demonstrate its effectiveness in identifying transpedicular trajectories with high BMD and POF in elderly osteoporotic patients. In comparison, the standard AO trajectories correspond to lower

FIG. 2. An example used to compare the optimized trajectory and AO trajectory in a female patient aged 65 years. The BMD of her vertebral body was 78.9 mg/ml. All the alternative trajectories are shown on both sides. The simulated screws are *gray* in the left pedicle and *yellow* in the right pedicle (**left**). AO trajectories and optimized trajectories were shown on both sides of L4. The simulated screws of the AO trajectories are *gray* (**right**). The AO trajectory BMDs were 81.5 mg/ml on the left side and 98.1 mg/ml on the right side. The POFs of the AO trajectory were 326.8 N on the left side and 432.3 N on the right side. The simulated screws of the optimized trajectories are *yellow*. The optimized trajectory BMDs were 213.8 mg/ml on the left side and 292.5 mg/ml on the right side. The optimal POFs were 1400.8 N on the left side and 2249.1 N on the right side.

BMD and POF. One challenge associated with our AI model is that the optimal screw trajectory is highly personalized and may be difficult to achieve freehand. Therefore, our future work will focus on integrating our AI model with surgical robotics and navigation technology. The data will be transmitted from the software to the robotic and navigation system via the DICOM protocol. The transmission content comprises the coordinates of the pedicle screw position (screw entry point and screw endpoint) and the parameters of a screw (screw diameter and screw length).

Low BMD is a widely reported risk factor of pedicle screw loosening and is more common in the elderly population. There is a 50% prevalence of osteoporosis in elderly patients requiring lumbar fusion, and the screw loosening rate in the osteoporotic spine is 30%–60%.[2,4,6,14,15] The POF of a standard screw trajectory is less than 500 N in osteoporotic patients but more than 1000 N in nonosteoporotic patients.[16] To prevent osteoporosis-related screw loosening, various screw augmentation techniques have been developed and adopted into clinical practice, such as cement-augmented screws, expandable screws, and cortical bone trajectory screws.[17] Cement augmentation, the most frequently used technique in osteoporotic patients, offers a 1.8- to 2.1-fold increase in axial POF in the thoracolumbar spine.[18] The axial POF of cement augmentation in osteoporotic spine was reported to be 1200–1600 N.[19]

In this study, we found that on average the POF of optimized trajectory screws in osteoporotic spine showed at least a 2.0-fold increase compared with that of the AO trajectory screws. For some patients the maximal POF was more than 1600 N, which is comparable to that of cement-augmented screws. Our results suggest that robust screw purchase can be achieved in low-BMD patients by adopting an optimized trajectory without the use of screw augmentation techniques, thereby avoiding associated risks, including cement leakage, pulmonary embolism, and screw removal difficulty.[20]

An additional advantage of our model is the application of phantomless measurement of the BMD of the screw trajectory. Routine preoperative lumbar CT scans are used for BMD analysis without extra cost or radiation. The phantomless model measures BMD using paraspinal muscle and subcutaneous fat as calibration references. Mueller et al. have demonstrated that such a phantomless system is a robust tool for BMD evaluation.[21] In this study, the AI model not only measures the global BMD of cancellous bone within the vertebral body to provide the information about global bone quality, but also measures the regional BMD of each alternative screw trajectory. The results indicate significant differences among the BMDs of different screw trajectories within the same vertebral level, thereby illustrating that global BMD alone is not enough to reflect the true BMD of one specific trajectory. In addition, adjustments of screw trajectory could result in notable changes of regional BMD. Previous research has also demonstrated the BMD inhomogeneity of human vertebral bone,[22–24] and that the regional BMD of the screw trajectory exhibits stronger correlations with POF and screw loosening than global BMD.[24–26] Therefore, our AI model can offer better prediction of BMD-related complications with personalized regional BMD evaluation.

There is a paucity of research focused on developing a preoperative pedicle screw trajectory planning system that aims to prevent screw loosening in patients with poor bone quality. In a study by Caprara et al., the optimized screw trajectories of their 3D planning system achieved a 26% increase of simulated POF compared with AO standard trajectories.[10] The POF of the optimized trajectories ranged from 580 to 1712 N. However, they used the cadaveric lumbar vertebrae rather than real patients for CT scanning, and the demographic information of the donors was missing. Our work selected the elderly osteoporotic patients requiring lumbar surgery as the focus of the study, and the relevant results may be of more clinical significance.

There are three main limitations to this study. First, although the AI model offers the optimized screw trajectory with high POF, the precise insertion of the pedicle screw is difficult to complete freehand. We should therefore integrate this model into a surgical navigation system to achieve personalized lumbar fixation in the future. Second, the POF was estimated using an equation based on previously reported research. We will perform biomechanical tests to check the correlation between estimated and actual POF in future work. Third, in addition to BMD and screw trajectory, many factors can influence the POF. For example, it is well known that how a construct is assembled and the screw size can affect biomechanical robustness. However, this paper focuses exclusively on individual screw trajectories. The AI model will be refined to help select the implants with optimal structure and size.

Conclusions

In elderly patients with osteoporosis, the novel AI model called Bone's Trajectory performs well in identifying optimized transpedicular trajectories with higher POF and regional BMD than AO standard trajectories. In certain patients the POF values of optimized trajectories in osteoporotic bone were comparable to those of standard AO trajectories in normal bone and of cement-augmented trajectories in osteoporotic bone. The Bone's Trajectory AI model can effectively assist with surgical decision-making in selecting screw trajectories and thus preventing osteoporosis-related screw loosening, thereby benefitting millions of elderly patients who require spinal surgery in the near future.

Acknowledgments

We thank Sherley Zhang and Lily Jiang at Bone's Technology Limited for their valuable input on software design, and Junyu Lin and Yuanzhi Weng from the University of Hong Kong for their kind assistance with conducting experiments for this study.

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Disclosures

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author Contributions

Conception and design: all authors. Acquisition of data: Ma, Zou, Zhu, Lu. Analysis and interpretation of data: W Li, Ma, Zou, Lu. Drafting the article: W Li, Ma, Zou. Critically revising the article: W Li, Ma, Zou, Lu. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: W Li. Statistical analysis: W Li, Ma, Zou, Lu. Administrative/technical/material support: W Li, Zhu, Lu. Study supervision: W Li, Zhu, Lu.

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