Original Article

Robot assisted navigated drilling for percutaneous pedicle screw placement: A preliminary animal study

Hongwei Wang, Yue Zhou[1], Jun Liu, Jianda Han[2], Liangbi Xiang

Abstract

Background: There is much more radiation exposure to the surgeons during minimally invasive pedicle screws placement. In order to ease the surgeon's hand-eye coordination and to reduce the iatrogenic radiation injury to the surgeons, a robot assisted percutaneous pedicle screw placement is useful. This study assesses the feasibility and clinical value of robot assisted navigated drilling for pedicle screw placement and the results thus achieved formed the basis for the development of a new robot for pedicle screw fixation surgery.

Materials and Methods: Preoperative computed tomography (CT) of eight bovine lumbar spines (L1–L5) in axial plane were captured for each vertebra, the entry points and trajectories of the screws were preoperatively planned. On the basis of preoperative CT scans and intraoperative fluoroscopy, we aligned the robot drill to the desired entry point and trajectory, as dictated by the surgeon's preoperative plan. Eight bovine lumbar spines were inserted 80 K-wires using the spine robot system. The time for system registration and pedicle drilling, fluoroscopy times were measured and recorded. Postoperative CT scans were used to assess the position of the K-wires.

Results: Assisted by spine robot system, the average time for system registration was (343.4 ± 18.4) s, the average time for procedure of drilling one pedicle screw trajectory was (89.5 ± 6.1) s, times of fluoroscopy for drilling one pedicle screw were (2.9 ± 0.8) times. Overall, 12 (15.0%) of the 80 K-wires violated the pedicle wall. Four screws (5.0%) were medial to the pedicle and 8 (10.5%) were lateral. The number of K-wires wholly within the pedicle were 68 (85%).

Conclusions: The preliminary study supports the view that computer assisted pedicle screw fixation using spinal robot is feasible and the robot can decrease the intraoperative fluoroscopy time during the minimally invasive pedicle screw fixation surgery. As spine robotic surgery is still in its infancy, further research in this field is worthwhile especially the accuracy of spine robot system should be improved.

Key words: Computer assisted orthopedic surgery, pedicle screw, robot, spine, lumbar spine

MeSH terms: Computer assisted surgery, bone screws, spine, robotics, minimally invasive surgical procedures

Introduction

Spinal fusion and pedicle screw fixation techniques are usually used in cases of vertebral fractures, dislocation, scoliosis, kyphosis, spinal tumor and for severe back pain that does not respond to other therapies.[1-3] The pedicular screw fixation offers a stable and safe possibility for stabilization during correction of malalignment.[1-3] The pedicle is surrounded by many sensitive structures such as nerve root, dura, cord which are not visible during pedicle screw insertion. Screw malposition pedicle wall perforation, nerve roots and cord impingement and very rarely, damage to vascular structures.[4-6] Therefore, the exact location of entry points and screw orientation is of great importance.

In case of conventional transpedicular fixation especially the minimally invasive pedicle screws insertion, the surgeon is only provided with intraoperative two dimensional x-ray images for the alignment and positioning of the pedicle screws and in up to 40% of the cases a perforation of the pedicle occurrs, depending on both the surgeon's performance and the definition of error.[4-6] There was also much more radiation exposure to the surgeons during minimally invasive pedicle screws placement.[7,8] In order to ease the surgeon's hand-eye coordination and to reduce the iatrogenic radiation injury to the surgeons, a robot assisted

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surgery is expected to increase the quality of percutaneous pedicle screw placement. This study to feasibility and clinical value of robot-assisted navigated drilling in percutaneous pedicle screw placement. Additionally, the results would form the basis for the development of a new robot for pedicle screw fixation surgery.

Materials and Methods

Spine robot system

The spine robot system [Figure 1] was domestically developed by and the department of Science and department of Orthopedics at our University. The robot includes three main parts: Robot arm, base of the robot arm and console [Figure 2]. The robot, composed of six revolute joints, is a serial manipulator with 6° of freedom. The motion patterns of the robot consist of manual traction mode, longitudinal shift mode, angular deflection mode and horizontal shift mode. Therefore, the 6° of freedom robot can provide the surgeon with the appropriate entry point and insertion angle for the drill. The end of the robot arm equipped with bone drill holder which can hold the pneumatic drill. The pneumatic drill can be conveniently sterilized by separation from the robot and used for drilling the pedicle screw trajectory during operation. The bone drill holder integrated six dimensional force/torque sensor, surgeons can feel the stress changes of the drill through handle the operating lever during the drilling process.

Preoperative planning

Preoperative computed tomography (CT) of eight bovine lumbar spines (L1–L5) in axial plane was captured for each vertebra, the entry points and trajectories of the screws were preoperatively planned designed specifically for percutaneous pedicle screw placement. During preoperative planning, we measured angle A and distance L [Figure 3]. This process needs to be done for each of the vertebrae involved in the procedure.

Pedicle screws insertion

Bovine is a tetrapod, its anatomical characteristics and common fracture site is different from the human and bovine spine segments are presumed to have higher bone mineral density than human spines and the pedicles of the bovine spine were much more thin than human spines, all pedicle screws will make cortical perforation, so that we didn't insert pedicle screw into the pedicle to avoid the misjudgement about cortical perforation. The purpose of the preliminary study is to gain first insights into the feasibility and clinical value of robot-assisted navigated drilling for pedicle screw placemen. In each screw insertion, full procedures from preoperative tasks to postoperative tasks were tested and evaluated to determine whether they are proper to apply to clinical fields. We checked preoperative planning, robot movement and surgical procedure in every pedicle screw insertion case. Engineers and orthopedic surgeons participated in these experiments and they agreed that this system had proper roles for percutaneous pedicle screw insertion procedures and that those results were applicable to clinical applications.

We positioned the relative positions of the drill and the bovine lumbar spines, drilled the bovine lumbar spines

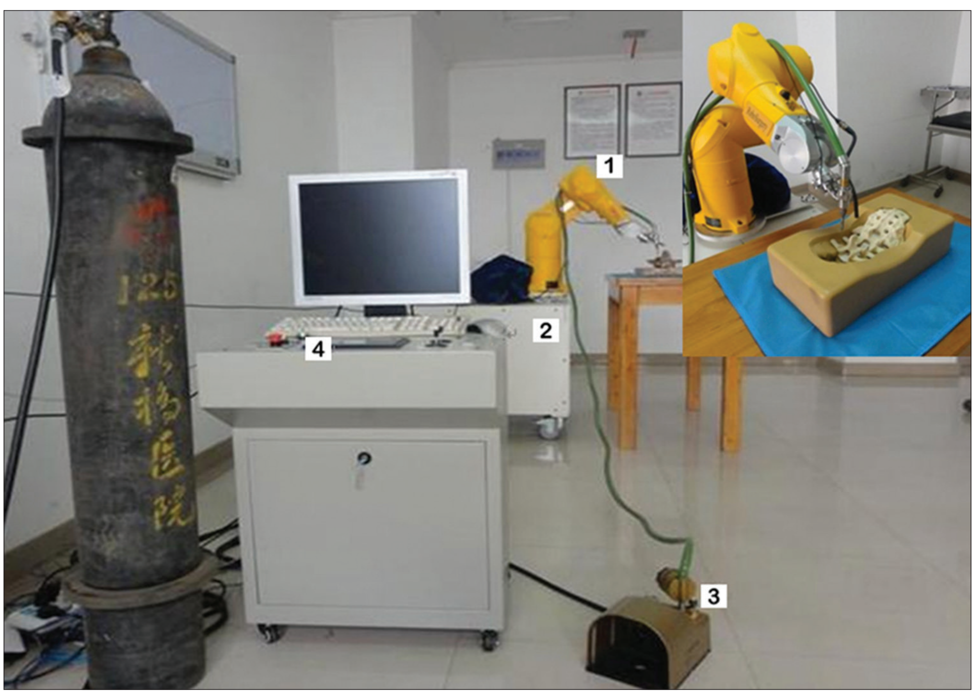

Figure 1: Spine robot system. (1) Robot arm, (2) Base of the robot arm, (3) Controller of the drill, (4) Console

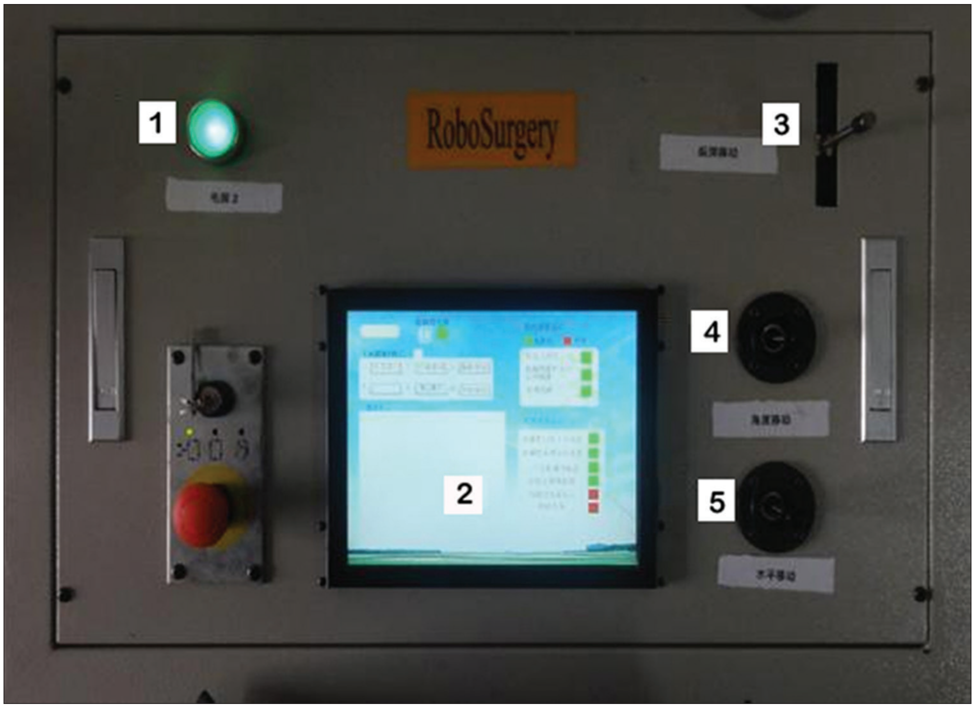

Figure 2: Operation interface of the console. (1) Power button (2) Touch screen operator interface (3) Operating lever longitudinal shift (4) Operating lever angular deflection (5) Operating lever horizontal shift

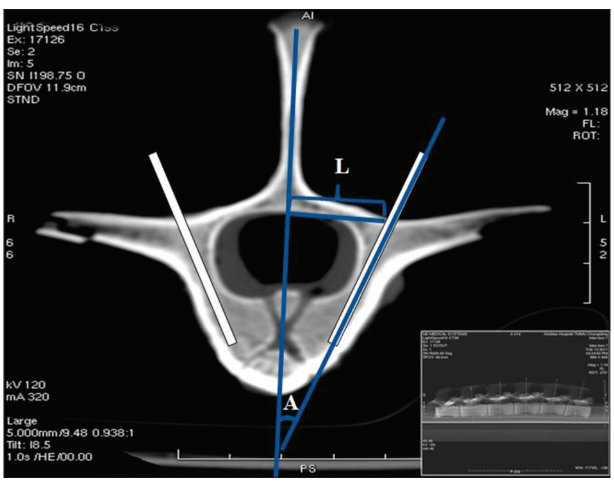

Figure 3: Preoperative plan using the computed tomography scan. L. Distance between the posterior median line of the spinous process and the entry point; (a) Angle between the posterior median line of the spinous process and the insertion line

according to preoperative plans and then placed K-wires in the holes [Figure 4]. The bovine spine used in our study were devoid of skin-soft tissue and muscles, it saved a lot of time. We inserted K-wires according to the preoperative plan designed. We noted surgical time and intraoperative fluoroscopy times and then we assessed the position of the K-wires through postoperative CT [Figure 5]. Eight bovine lumbar spines (L1–L5) were inserted 80 K-wires using the spine robot system. The most important characteristic of the spine robot system is that the angle of the drill can be deflected to keep drill tip in centre. This function is helpful for us to deflect the angle of the drill according to preoperative plan after the tip of the drill touch the entry point of the bony surface and then insert the drill to the bone; the whole operation process is smooth.

Results

Preoperative CT of eight bovine lumbar spines (L1–L5) in axial plane was taken for each vertebra, the entry points and trajectories of the screws were preoperatively planned designed specifically for percutaneous pedicle screw placement [Table 1]. Assisted by spine robot system, the average time for system registration was (343.4 ± 18.4) s, the time for procedure of drilling one K-wire was (89.5 ± 6.1) s, times of fluoroscopy for procedure of drilling one K-wire were (2.9 ± 0.8) s. Overall, 12 (15.0%) of the 80 K-wires violated the pedicle wall. Four screws (5.0%) were medial to the pedicle, and 8 (10.5%) were lateral. The rate of the K-wire wholly within the pedicle was 85% [Table 2].

Discussions

Percutaneous pedicle screw placements with conventional and image guidance techniques have demonstrated acceptable results,[9-12] but there were so much radiation exposure to the surgeons during minimally invasive pedicle screws placement.[7,8] With the development of computer assisted surgery, spine robot system had been developed for pedicle screws insertion and even some spine robot system

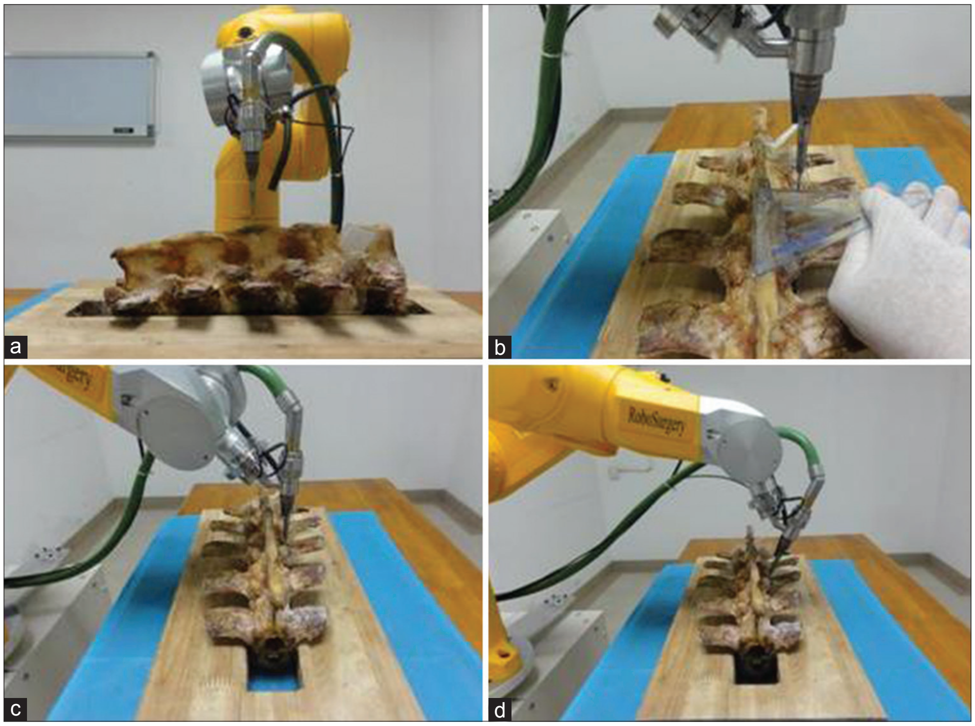

Figure 4: Percutaneous pedicle screws insertion. (a) Adjustment the pneumatic drill parallel to the upper vertebral body end plate, (b) Adjustment the distance between the tip of the drill and the posterior median line according to preoperative planned distance, (c) Longitudinal shift of the drill to the entry point on the bone surface, (d) Adjusting the entry angle of the drill according to preoperative planned angle

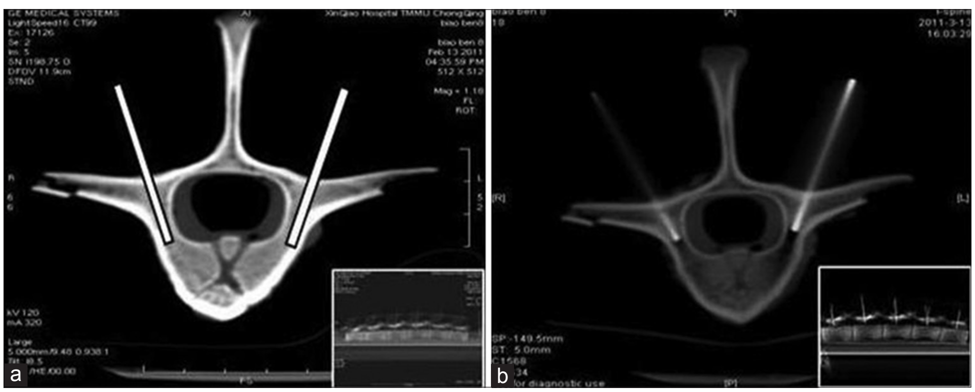

Figure 5: Preoperative and postoperative computed tomography (CT) scan of the bovine lumbar spine. (a) Preoperative plan through the preoperative CT scan, (b) Evaluating the position of K-wire through the postoperative CT scan

Table 1: Preoperative measurement index of the experimental group according to different vertebrae

Items	Distance between the right entry point and posterior median line (mm)	Right insertion angle (°)	Distance between the left entry point and posterior median line (mm)	Left insertion angle (°)
L1	28.6±2.2	28.9±1.0	30.9±2.2	30.0±1.8
L2	25.4±1.3	26.9±2.7	26.0±1.8	26.4±2.7
L3	21.9±1.6	23.1±2.4	22.7±1.8	24.4±2.1
L4	20.7±1.8	22.4±2.4	21.8±1.1	24.3±1.0
L5	22.1±1.9	23.0±3.1	22.8±2.0	24.4±2.3

has already been used in clinic.[13-18] A biplane fluoroscopy guided robot system (BFRS) was developed by Kim *et al*.[15] for surgical robotic systems, minimally invasive surgeries and cooperative robotic systems, as well as enhanced surgical planning and navigation with preoperative and intraoperative image data. They pointed out that the BFRS might be helpful in improving the accuracy of percutaneous pedicular screw insertion procedures. In the future, they will attempt to improve the accuracy and reliability of the BFRS and to determine new clinical applications for the BFRS. The spine robot system in our study has motion patterns of the robot consist of manual traction mode, longitudinal shift mode, angular deflection mode and horizontal shift mode. Therefore, the 6°of freedom robot can provide the surgeon with the appropriate entry point and insertion angle for the drill. The pneumatic drill can be conveniently sterilized by separation from the robot to ensure that sterility is maintained

Table 2: Surgical results of the spine robot system for predrilled pedicle screw trajectory

Specimen	Time for system registration (s)	Time for drilling one K-wire (s)	Fluoroscopy times for drilling one K-wire	Medial to pedicle	Lateral to pedicle
1	335	90	2	1	2
2	342	80	4	1	1
3	360	84	3		2
4	365	85	2	1	1
5	323	93	3		1
6	368	95	2	1	
7	329	91	4		1
8	325	98	3		
Mean	343.4±18.4	89.5±6.1	2.9±6.8	-	-

throughout the entire operation procedure. The bone drill holder integrated six-dimensional force/torque sensor, surgeons can feel the stress changes of the drill through handle the operating lever during the drilling process to ensure more safety during the whole drilling process.

The spine robot system, which has already been used in the clinic, is SpineAssist.[16-18] Kantelhardt *et al*.[17] reported a retrospective cohort analysis comparing conventional open to open robotic-guided and percutaneous robotic-guided pedicle screw placement. Use of robotic guidance significantly increased the accuracy of screw position while reducing the X-ray exposure. Patients seem to have a better perioperative course following percutaneous procedures. Lieberman *et al*.[18] pointed out that the robotic guidance group had fewer screw placement deviations, less surgeon radiation exposure, lower fluoroscopy time per screw and shorter procedure time compared to the no robotic guidance group. To our knowledge, the SpineAssist robot system only provided the optimized trajectory, the pedicle screws insertion was performed only by the surgeon but not the SpineAssist system itself. In the current study, the surgeons can perform the pedicle screws insertion technique behind the radiation protection screen using the tele-manipulation function of the spine robot system so that the radiation exposure to the surgeons can be decreased and the spine robot system can insert the pedicle screws itself.

Bovine lumbar spine were used for robot-assisted navigated drilling because the bovine lumbar spines can be more easily available than human cadaver specimens. Due to traditional concept in China, a very few people accept body donation, so human cadaver specimens were hard to get. The purpose of the preliminary study is to gain first insights into the feasibility and clinical value of robot-assisted navigated drilling for pedicle screw placement, so we think that the bovine spine were acceptable for the study.[19] The function of the spine robot system is to pre-drill pedicle screw trajectory, the system can't offer help for rod placement, when we have inserted the pedicle screws, we can insert the rod using some special instrument such as instrument in Sextant system to place the rod through minimally invasive technique. The rate of the K-wire wholly within the pedicle in the current study was 85%. The reasons can be divided into the following two points: Firstly, the pedicle of the bovine lumbar spine was too thin, little deviation of the insertion angle can cause the K-wires violated the pedicle wall. Secondly, we can't accurately determine the relative position of the drill and the bovine lumbar spine. So, the accuracy and reliability of spine robot system should be improved.

In order to improve the accuracy and reliability of the spine robot system for clinical use, further research such as building the virtual surgery system and intraoperative electrophysiological monitoring system will be performed. In recent years, many researchers developed simulators for pedicle screw insertion; the simulators offer many helpful features to the surgeon with respect to complex cases and to the surgical trainee learning the basic technique of pedicle screw insertion.[20-22] This technology has also begun to be used in preoperative planning for selected cases, the surgeons can make the surgical plan, practice, and visualize pedicle screw surgery on a particular patient before operation through the simulator.[23,24] However, when the screws are being inserted, there is no projection fluoroscopy image provided to the surgeon. Next, we will develop a CT based patient specific pedicle screw insertion simulator to better prepare surgeons to perform pedicle screw insertion using free-hand technique under the projection fluoroscopy and help reduce the risk of pedicle screw misplacement.[25] The second main research direction is to build intraoperative electrophysiological monitoring system. Based on strong evidence that multimodality intraoperative neuromonitoring (MIOM) is sensitive and specific for detecting intraoperative neurologic injury during spine surgery, it is recommended that the use of MIOM be considered in spine surgery where the spinal cord or nerve roots are deemed to be at risk, including procedures involving deformity correction and procedures that require the placement of instrumentation.[26,27]

Conclusions

The basic function of the spine robot system can satisfy spine surgeons for percutaneous pedicle screw placement. Using the spine robot system, the operation time and intraoperative fluoroscopy times per pedicle screw was less, but we should improve the accuracy and reliability of spine robot system such as building the preoperative planning simulator and intraoperative electromyography monitoring system for clinical use. We think the spine robot system will be used in clinical practice with the development of preoperative planning simulator and intraoperative electromyography monitoring system in the near future.

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