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Application of Tianji Orthopedic Robot-Assisted Screw Placement versus Traditional Free-Hand Screw Placement in Upper Cervical Fractures

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Abstract

Objective: To compare the application effects of Tianji orthopedic robot-assisted screw placement and traditional free-hand screw placement in posterior pedicle screw internal fixation for upper cervical fractures, and to provide a more optimal treatment plan for clinical practice. **Methods**: A retrospective analysis was conducted on 58 patients with upper cervical fracture who underwent surgery at Baise People's Hospital from January 2017 to October 2023. The patients were divided into the robot-assisted group (RA group, 27 cases) and the traditional free-hand group (FH group, 31 cases). General data (gender, age, BMI, fracture site, etc.), screw placement accuracy (postoperative CT combined with Gertzbein-Robbins criteria), perioperative indicators (intraoperative blood loss, operation time, postoperative hospital stay), and prognosis (VAS score, NDI score, complications) were compared between the two groups. **Results**: There was no statistically significant difference in general data between the two groups ($P > 0.05$). In the RA group, among 112 screws, 109 were grade A + B (97.3%), with a perfect screw placement rate of 85.7%; in the FH group, among 137 screws, 123 were grade A + B (89.8%), with a

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perfect screw placement rate of 68.6%, and the difference in screw placement accuracy between the two groups was significant ($P < 0.05$). The intraoperative blood loss in the RA group was less than that in the FH group (245.93 ± 216.44 vs 380.65 ± 328.04, $P < 0.05$), the operation time was longer ($P < 0.05$), and the vertebral artery injury rate was lower (7.4% vs 22.6%). The postoperative VAS and NDI scores of both groups were improved compared with those before surgery ($P < 0.05$), and there were no statistically significant differences in postoperative hospital stay and total complications between the two groups ($P > 0.05$). **Conclusion**: Tianji orthopedic robot-assisted surgery has more advantages in improving screw placement accuracy, reducing blood loss, and lowering the risk of vertebral artery injury. It is safe, effective, and precise in operation, and is worthy of promotion.

Keywords

Tianji Orthopedic Robot, Free-Hand Screw Placement, Upper Cervical Spine, Fracture, Pedicle Screw

1. Introduction

The upper cervical spine mainly includes the atlas (C1) and axis (C2). Due to its complex anatomical structure, it is the most mobile part of the spine, providing a large range of neck movements, especially rotation, which also makes it vulnerable to instability [1]. Atlantoaxial fracture fixation with transarticular screws was first described by Margerl *et al.* in 1979. Accurate screw insertion can not only achieve the stability of the upper cervical spine but also provide firm fixation to promote fracture healing [2]. The principles of surgical treatment are to maintain the stability of the upper cervical spine, relieve spinal cord compression, avoid nerve function damage, and create favorable conditions for the recovery of nerve function [3]. However, due to the complex anatomical structure and frequent deformities in the area around the atlantoaxial spine, most patients die on the way to the hospital or on the spot, or die from complications such as respiratory depression caused by spinal cord edema after surgery. Therefore, upper cervical spine surgery is a highly technically demanding and difficult operation.

In traditional upper cervical fracture surgery, due to its high location, difficult exposure, and complex anatomical structure, coupled with the fact that the diameter of the C1 lateral mass and C2 pedicle is relatively small (the narrowest part of the C2 pedicle is about 5 - 7 mm) and the anatomical shape changes due to fractures, the passage of screws in the pedicle is almost unique. If the initial screw placement fails, re-adjusting the position becomes very difficult, further increasing the difficulty of the operation [4]. A study by Zhan [5] showed that about a quarter of the Central European population has at least one high vertebral artery, and about one-third has at least one narrow C2 pedicle. Previous studies have shown that the incidence of vertebral artery injury caused by instruments in the

cervical spine area ranges from 4% to 8%, while the incidence of vertebral artery injury caused by pedicle screw misalignment during upper cervical spine fusion surgery is as high as 8.2% to 21.6% [6] (consistent with the results of this study). The existence of such abnormalities will further increase the risk of vertebral artery injury during upper cervical screw placement [7], and may even damage the spinal cord, leading to serious complications or endangering the patient's life [8]. Therefore, the accuracy of pedicle screw placement directly determines the success or failure of the surgery.

In the past, screws were often placed with the assistance of X-ray fluoroscopy. The accuracy of screw placement was ensured by preoperative positioning and repeated intraoperative fluoroscopy to observe the direction and depth of the inserted screws. This not only requires the doctor to have extensive experience but also consumes a lot of physical strength due to the long operation time, which is also a test of the doctor's physical fitness. At the same time, repeated fluoroscopy during the operation increases the risk of malignant tumors in patients and medical staff due to long-term radiation exposure. Orthopedic robots can overcome the disadvantage that X-ray fluoroscopy is unable to clearly identify anatomical structures, and can accurately place screws according to the preoperative plan, which can effectively avoid the risk of injury to large blood vessels, surrounding blood vessels, and nerves, and improve the safety of the operation.

At present, clinical reports on robot-assisted surgery for upper cervical fractures are mainly case reports, lacking relevant systematic controlled studies. The purpose of this study is to explore the application of Tianji orthopedic robot-assisted screw placement and free-hand screw placement in upper cervical fractures. The authors retrospectively analyzed 58 patients who underwent posterior internal fixation for upper cervical fractures in our hospital from January 2017 to October 2023, and compared the safety and accuracy of the Tianji orthopedic robot in upper cervical fractures, so as to provide a safe, reliable, and minimally invasive surgical method for clinical practice.

2. Materials and Methods

2.1. Study Subjects

This retrospective study included 58 patients who underwent posterior cervical pedicle screw internal fixation for upper cervical fractures from January 2017 to October 2023. The patients were divided into the robot-assisted group (experimental group) and the traditional free-hand group (control group). Among them, there were 27 cases in the robot-assisted group (RA group) and 31 cases in the traditional free-hand group (FH group). To reduce the heterogeneity of the operation, all procedures were performed by the team of Chief Physician Wen Wei in the Department of Spinal Surgery of our hospital, and all the main surgeons were chief physicians with extensive surgical experience. Informed consent was obtained from all enrolled patients or their family members, and the study was approved by the Medical Ethics Committee of Baise People's Hospital.

2.2. Case Selection

2.2.1. Inclusion Criteria

① Age > 18 years; ② Pedicle screws implanted using the Tianji orthopedic robot or free-hand technique; ③ Ability to fully comply with the study protocol; ④ Complete medical records and imaging data; ⑤ Patients with upper cervical fractures.

2.2.2. Exclusion Criteria

① Patients with severe systemic diseases who cannot tolerate surgery; ② Patients with a history of bone diseases such as skin infection, tuberculosis, tumor, or severe osteoporosis; ③ Patients with severe spinal pedicle deformities; ④ Patients with mental disorders; ⑤ Patients with a history of previous cervical spine surgery; ⑥ Patients undergoing surgery for fractures in other parts.

2.3. Surgical Methods

2.3.1. RA Group

1) Preoperative Preparation: Routine protective skull traction was performed before surgery. Preoperative imaging examinations such as cervical X-ray, CT three-dimensional reconstruction, and magnetic resonance imaging (MRI) were completed. Routine examinations such as electrocardiogram, blood routine, liver and kidney function, and electrolytes were also completed to evaluate cardiopulmonary function and surgical risk. Attention was paid to preventing complications such as deep vein thrombosis of the lower extremities, and surgical contraindications were excluded. A course of antibiotics was administered intravenously 30 minutes before surgery.

2) Surgical Procedures: The patient was placed in a prone position, with the head fixed on a Mayfield frame. Routine disinfection and draping were performed to determine the diseased segment of the spine. A tracker was fixed on the upper spinous process or the Mayfield frame, and the robotic arm of the surgical robot was isolated with a sterile protective cover. After 3D C-arm circular scanning, the data were transmitted to the robot's main console, and the surgical path was planned in the sagittal, coronal, and axial planes, including the screw entry site, direction, depth, and size. A posterior midline incision was made, the paravertebral muscles were dissected, and the C1 posterior arch or C2 lamina and articular processes were exposed. The robotic arm was controlled to move to the planned path and fine-tuned until the control interface indicated that the accuracy was less than 1 mm. A secondary sleeve was inserted, and a guide wire and screw were inserted along the secondary sleeve using an electric drill. The direction and depth of the guide wire were confirmed by C-arm fluoroscopy at any time. After confirming that the position of the pedicle screw was satisfactory by C-arm fluoroscopy after surgery, decompression and fusion were performed as needed, followed by irrigation. After confirming there was no bleeding, the wound was sutured layer by layer, and the operation was completed.

3) Postoperative Management: A course of antibiotics was routinely used after surgery, and symptomatic treatments such as detumescence, pain relief, and gastric protection were given. Cervical CT was rechecked on the 2nd day after surgery (see Figure 1).

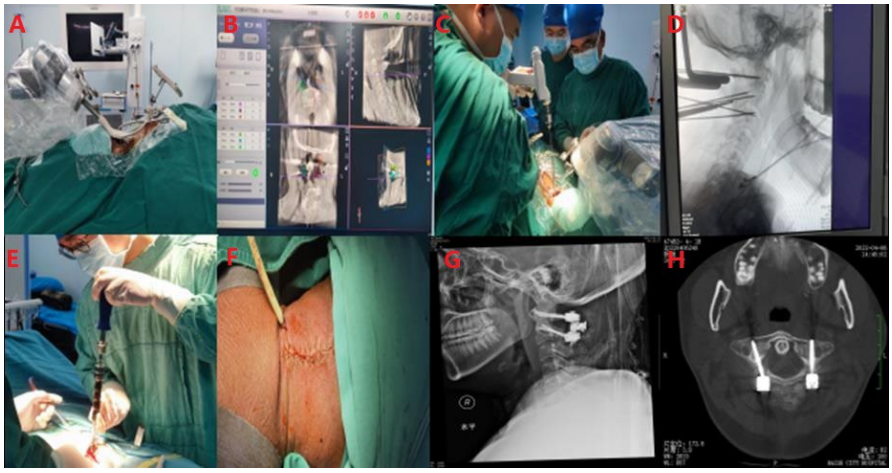

Figure 1. Operational steps of the RA group: (A) Installing the tracker; (B) Preoperative planning of screw direction, length, diameter, etc.; (C) Inserting the guide wire; (D) Intraoperative fluoroscopy to confirm the position of the guide wire; (E) Inserting the pedicle screw along the guide wire; (F) Postoperative skin incision; (G-H) Postoperative recheck to confirm the position of the screw.

2.3.2. FH Group

1) Preoperative Preparation: Routine protective skull traction was performed before surgery. Preoperative imaging examinations such as cervical X-ray, CT three-dimensional reconstruction, and MRI were completed. Routine examinations such as electrocardiogram, complete blood count, liver and kidney function, and electrolytes were also performed to evaluate cardiopulmonary function and surgical risk. Attention was paid to preventing complications such as deep vein thrombosis of the lower extremities, and surgical contraindications were excluded. A course of antibiotics was administered intravenously 30 minutes before surgery.

2) Surgical Procedures: The traditional free-hand open group was operated on through a posterior midline incision. During the operation, pedicle screws were inserted one by one by hand under the examination and verification of C-arm fluoroscopy. After confirming that the position of the pedicle screw was satisfactory by C-arm fluoroscopy after surgery, decompression and fusion were performed as needed, followed by irrigation. After confirming there was no bleeding, the wound was sutured layer by layer, and the operation was completed.

3) Postoperative Management: A course of antibiotics was routinely used after surgery, and symptomatic treatments such as detumescence, pain relief, and gastric protection were given. Cervical CT was rechecked on the 2nd day after surgery.

2.4. Observation Indicators

Primary Outcome: The accuracy of pedicle screw placement was evaluated by rechecking cervical CT on the 2nd day after surgery, and the accuracy of screw insertion and the degree of cortical bone penetration were assessed according to the Gertzbein-Robbins [9] criteria:

- Grade A: No cortical bone invasion;
- Grade B: Cortical bone destruction < 2 mm;
- Grade C: Cortical bone destruction 2 – 4 mm;
- Grade D: Cortical bone penetration 4 – 6 mm;
- Grade E: Cortical bone penetration ≥ 6 mm.

Grade A was considered excellent, and grades A + B were considered clinically acceptable. The accuracy rate for each grade of screw placement was calculated as the number of screws of that grade divided by the total number of screws. Radiological evaluation was performed by two independent observers who were unaware of the study purpose and patient information. If the two observers assigned different classification grades, a third independent observer was consulted for discussion and resolution (see Figure 2).

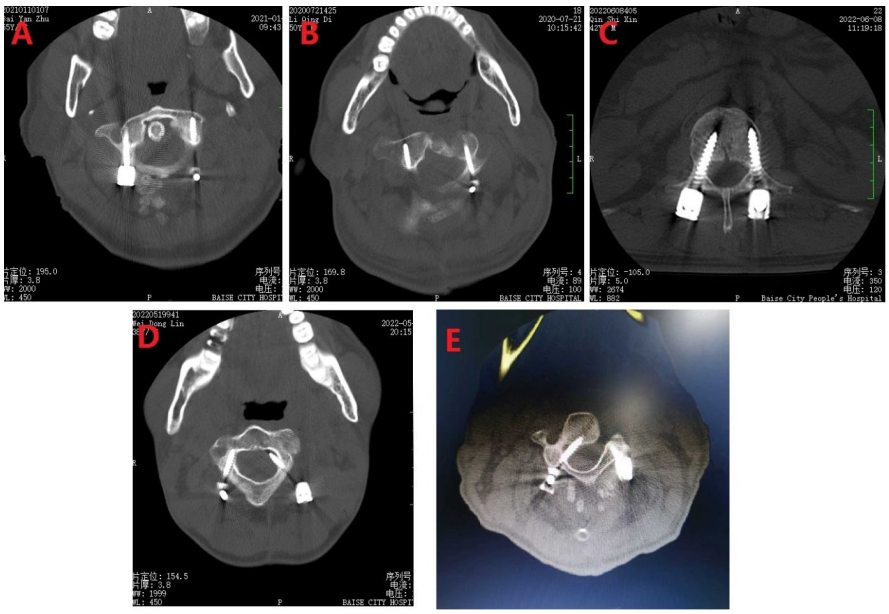

Figure 2. Evaluation of screw placement accuracy using the Gertzbein-Robbins scale: (A) Grade A: Screw placement without damaging the pedicle cortex; (B) Grade B: Cortical defect < 2 mm; (C) Grade C: Cortical defect ≥ 2 mm but < 4 mm; (D) Grade D: Cortical defect ≥ 4 mm but < 6 mm; (E) Grade E: Cortical defect ≥ 6 mm.

Secondary Outcomes

- The VAS score at different time points before and after surgery was used to evaluate the changes in occipitocervical pain of patients, where 0 points indicated no pain and 10 points indicated severe pain.
- The Neck Disability Index (NDI) [10] was modified based on the Oswestry

Disability Index (ODI) questionnaire, first proposed by Howard Vernon in 1991, aiming to allow patients with neck pain to self-assess. The NDI includes 10 items, with a minimum score of 0 and a maximum score of 5 for each item. The total score ranges from 0 points (no disability) to 50 points (complete disability), and a higher score indicates a more severe degree of neck dysfunction.

The postoperative effects of the two surgical methods were compared by evaluating the VAS and NDI scores of patients before surgery, 1 week after surgery, and 6 months after surgery. Perioperative outcomes included intraoperative blood loss, operation time, postoperative hospital stay, postoperative complications (skin infection, vertebral artery injury, spinal cord injury, deep vein thrombosis, or the need for reoperation), and general patient data (gender, age, BMI). The causes of injury included high fall (height ≥ 2 m), fall injury, traffic accident injury, and crush injury. The ASIA scoring standard was used to evaluate neurological deficits.

Considering that the number of screws placed varies among different patients, outcomes such as operation time, intraoperative blood loss, and postoperative hospital stay were weighted according to the number of screws placed to reduce bias. Relevant data were obtained by reviewing surgical records and follow-up data, such as telephone interviews after surgery.

2.5. Statistical Analysis

SPSS 27.0 statistical software was used for statistical analysis of the data in this study. Measurement data (operation time, intraoperative blood loss, postoperative hospital stay, etc.) were expressed as "mean ± standard deviation (x ± s)" and analyzed by t-test. Count data (screw placement accuracy, gender ratio, etc.) were expressed as percentages (%) and analyzed by χ^2 test. Paired t-test was used for comparing preoperative and postoperative follow-up parameters (NDI and VAS scores), and independent t-test was used for comparing surgical outcomes and postoperative imaging measurements between the two different surgical methods. A P-value < 0.05 was considered statistically significant.

3. Results

3.1. Comparison of General Data between the Two Groups

In the RA group: 17 males and 10 females; aged 32 - 67 years, with an average of 50.30 ± 10.64 years. Fracture segments: 9 cases of C1, 10 cases of C2, 8 cases of C1 + C2; a total of 112 screws were placed, with an average of 4.15 screws per patient.

In the FH group: 16 males and 15 females; aged 23 - 77 years, with an average of 50.23 ± 12.70 years. Fracture segments: 10 cases of C1, 14 cases of C2, 7 cases of C1 + C2; a total of 137 screws were placed, with an average of 4.42 screws per patient.

There were no statistically significant differences in gender, age, BMI, cause of injury, lesion segment, or ASIA grade between the two groups (P > 0.05) (see **Ta-**

ble 1 for detailed results). One patient in the FH group was lost to follow-up during this period, with a follow-up rate of 96.9%.

Table 1. Comparison of general data between the two groups (n = 58).

Index	Robot-Assisted Group (n = 27)	Free-Hand Group (n = 31)	χ^2/t Value	P Value
Age (years)	50.30 ± 10.64	50.23 ± 12.70	0.0226	0.4910
Gender				
- Male	17	16	0.758	0.3839
- Female	10	15		
BMI (kg/m^2)	24.34 ± 3.54	23.88 ± 2.90	0.5439	0.2943
Fracture Site				
- C1	9	10	0.0076	0.9306
- C2	10	14	0.3927	0.5309
- C1 + C2	8	7	0.374	0.5408
ASIA Grade				
- A	0	0	-	-
- B	0	0	-	-
- C	2	3	-	>0.999
- D	5	6	0.007	0.935
- E	20	22	0.07	0.792
Cause of Injury				
- Fall Injury	6	6	0.072	0.788
-Traffic Accident Injury	4	8	1.063	0.303
-High Fall Injury	14	12	1.008	0.315
- Crush Injury	3	5	-	0.712

Note: P < 0.05 indicates a statistically significant difference.

3.2. Comparison of Pedicle Screw Accuracy between the Two Groups

In the RA group (27 patients), a total of 112 pedicle screws were placed, including 96 grade A screws, 13 grade B screws, 3 grade C screws, and no grade D or E screws; 109 screws were acceptable (grades A + B).

In the FH group (31 patients), a total of 137 pedicle screws were placed, including 94 grade A screws, 29 grade B screws, 6 grade C screws, 2 grade D screws, and 6 grade E screws; 123 screws were acceptable (grades A + B).

Regarding the accuracy of pedicle screw placement, the perfect screw placement rate in the RA group was higher than that in the FH group (85.7% vs 68.6%), with a statistically significant difference (P < 0.05). The acceptable screw placement rate in the RA group was higher than that in the FH group (97.3% vs 89.8%), with a

statistically significant difference ($P < 0.05$) (see Table 2). Meanwhile, 2 grade D and 6 grade E screws appeared in the FH group.

Table 2. Screw placement accuracy of the two groups.

Grade	Robot-Assisted Group (n = 27)	Free-Hand Group (n = 31)	χ^2 Value	P Value
A	85.7% (96)	68.6% (94)	9.967	0.002
B	11.6% (13)	21.2% (29)	4.017	0.045
A + B	97.3% (109)	89.8% (123)	5.508	0.019
C	2.7% (3)	4.4% (6)	-	0.52
D	0	1.5% (2)	-	0.503
E	0	4.4% (6)	-	0.034

Note: $P < 0.05$ indicates a statistically significant difference.

3.3. Comparison of Perioperative Indicators between the Two Groups

The operation time of the RA group was (3.77 ± 0.77) hours, and that of the FH group was (2.74 ± 0.86) hours. Since the RA group required preoperative screw planning, the operation time was significantly longer ($t = 4.7749$, $P = 0.0000$), with a statistically significant difference. The postoperative hospital stay of the RA group (9.33 ± 3.93 days) was slightly shorter than that of the FH group (10.00 ± 4.29 days), but the difference was not significant. The intraoperative blood loss of the RA group was lower than that of the FH group (245.93 ± 216.44 mL vs 380.65 ± 328.04 mL, $P = 0.0336$). Although the operation time of the RA group was longer, the skin was not incised and the muscles were not dissected during preoperative planning. At the same time, since the screws were planned preoperatively in the robot group, the placement speed of each screw during the operation was faster, the number of screw adjustments was fewer, and the blood loss was relatively lower.

The incidence of postoperative complications in the RA group (29.6%) was lower than that in the FH group (32.3%), but the difference was not statistically significant ($P > 0.05$). In the RA group, 5 patients had incision exudation after surgery, which healed well after dressing changes; 1 patient had numbness in both upper limbs, and the symptom disappeared during follow-up. In the FH group, 3 patients had incision exudation after surgery and were discharged after active dressing changes; 1 patient had a mental stress disorder after surgery, which improved after symptomatic treatment. Although there was no significant difference in the total complications between the two groups, the vertebral artery injury rate in the RA group was significantly lower than that in the FH group (7.4% vs 22.6%). A study by Tomasz showed that about a quarter of the Central European population has at least one high vertebral artery. The Tianji orthopedic robot plans the direction, length, and diameter of the screw preoperatively, and places the screw

according to the navigation direction during the operation, which improves the accuracy of screw placement, greatly reduces the probability of vertebral artery injury, and reduces blood loss at the same time. No reoperation cases occurred in either group after surgery (see Table 3).

The VAS scores and NDI scores of the RA group and FH group at 1 week after surgery and at the last follow-up were significantly improved compared with those before surgery ($P < 0.05$), but there was no statistically significant difference between the two groups in the longitudinal comparison after surgery, indicating that both surgical methods can improve neck function and relieve pain (see Table 4, Figure 3, Figure 4).

Table 3. Comparison of various indicators between the two groups.

Group	Intraoperative Blood Loss (mL)	Operation Time (h)	Postoperative Hospital Stay (days)	Vertebral Artery Injury (%)	Complications (%)
Robot-Assisted Group (n = 27)	245.93 ± 216.44	3.77 ± 0.77	9.33 ± 3.93	7.4% (2)	29.6% (8)
Free-Hand Group (n = 31)	380.65 ± 328.04	2.74 ± 0.86	10.00 ± 4.29	22.6% (7)	32.3% (10)
t/χ^2 Value	1.8671	4.7749	0.6168	-	0.002
P Value	0.0336	0.0000	0.2699	0.192	0.962

Note: $P < 0.05$ indicates a statistically significant difference.

Table 4. Comparison of VAS and NDI scores at different time points between the two groups.

Group	VAS Score (Preop)	VAS Score (1W Postop)	VAS Score (6M Postop, Last Follow-up)	NDI Score (Preop)	NDI Score (1W Postop)	NDI Score (6M Postop, Last Follow-up)
Robot-Assisted Group (n = 27)	8.33 ± 0.62	6.93 ± 0.27*	1.15 ± 0.86*	43.56 ± 2.61	36.04 ± 4.17*	5.48 ± 5.60*
Free-Hand Group (n = 31)	8.26 ± 0.68	6.94 ± 0.36*	1.52 ± 0.85*	43.84 ± 2.67	37.35 ± 3.48*	7.00 ± 6.12*
t Value	0.4073	0.1182	1.6446	0.4026	1.3041	0.9813
P Value	0.3427	0.4532	0.0528	0.3444	0.0988	0.1653

Note: * indicates a statistically significant difference compared with the preoperative period ($P < 0.05$).

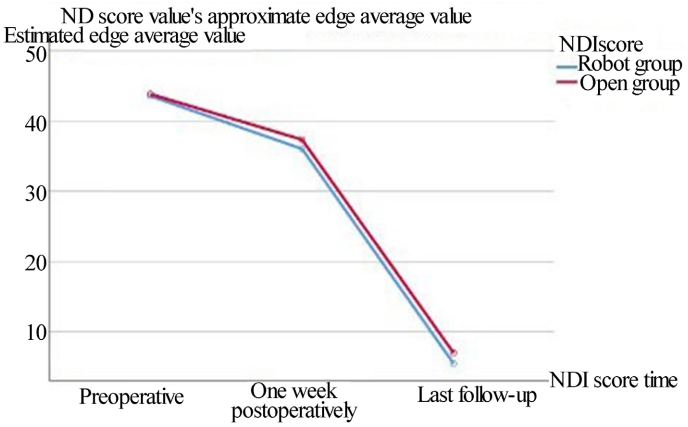

Figure 3. NDI scores of the two groups at different time points.

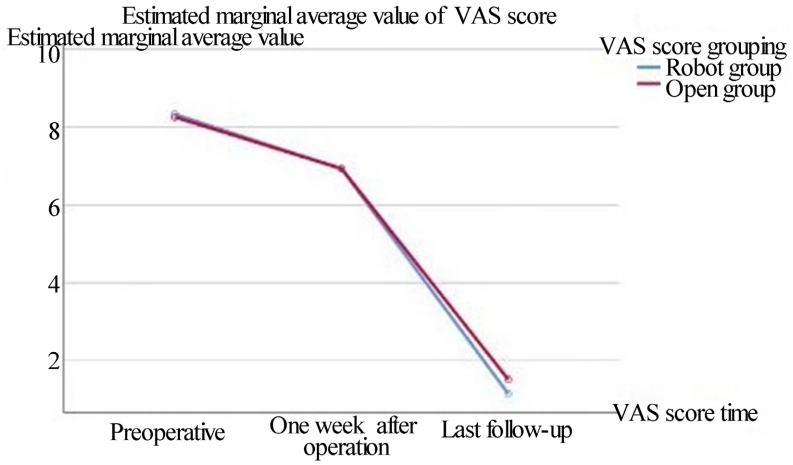

Figure 4. VAS scores of the two groups at different time points.

4. Discussion

Upper cervical fractures are relatively rare among cervical fractures, but their incidence is increasing year by year. Spinal cord injury is the most serious complication and the main cause of death. Previous studies have shown that the incidence of spinal cord injury in patients with cervical fractures is about 10% - 51%, which is why patients with cervical fractures, especially upper cervical fractures, often have high mortality and disability rates [11]. However, some patients often have no obvious neurological symptoms and only show mild neck pain and other symptoms. The main reason for this situation is that the sagittal diameter of the upper cervical spinal canal is wider than that of the lower cervical spinal canal, and the spine and spinal cord can move up and down according to the movement of the cervical spine [12]. The *Evidence-Based Guidelines for the Clinical Diagnosis and Treatment of Adult Acute Atlantoaxial Combined Fractures* (2023 *Edition*) [13] state that for patients with atlantoaxial fractures who only have occipitocervical pain or mild limb neurological symptoms, conservative treatments such as cervicothoracic braces and Halo external fixation stents can be used. If cervical external fixation treatment fails, and patients have obvious neck pain, deformity, high spinal cord injury, or atlantoaxial instability, surgical treatment can be performed. For patients with severe atlantoaxial fractures, surgical treatment still mainly includes decompression and pedicle screw fixation.

Boucher *et al.* formally proposed pedicle screw internal fixation in 1959. Pedicle screw placement is a key step in the success of spinal surgery. Compared with the thoracolumbar spine, cervical spine surgery, especially upper cervical spine surgery, is almost the most complex and risky spinal surgery, with a steep learning curve. The unique anatomical structure of the upper cervical pedicle and craniocervical junction means that failed pedicle screw placement may lead to serious complications [14]. The success of traditional free-hand surgical screw placement depends on the surgeon's extensive clinical experience, and the failure rate is even higher for patients with cervical deformities or osteoporosis. However, robot-as-

sisted surgery only requires obtaining intraoperative 3D fluoroscopic images through 3D C-arm scanning before surgery, which are transmitted to the main console. The surgeon pre-plans the screw placement site, direction, and depth on the console, with an error of less than 1 mm, which has obvious advantages over traditional screw placement techniques [15]. At the same time, long-term surgery is a severe test of the doctor's physical strength, leading to reduced accuracy of screw placement. The robot-assisted system overcomes the limitations of human physiological fatigue, has the advantages of high operation accuracy, good operation repeatability, and strong stability [16], and compensates for the physiological limitations of surgeons in vision and operation [17].

Unlike the thoracic and lumbar spine, where a pedicle screw breaking through the cortex by less than 2 mm is clinically acceptable, the cervical spine has a smaller size and thinner, narrower pedicles. Studies have shown that about 75% of them have a diameter of less than 4 mm, and 0.9% of C2 pedicles have no medullary cavity. Therefore, a pedicle screw breaking through the cortex by 2 mm is relatively large for the cervical spine. It is generally believed that the surgical navigation system can have an error of at most 1 mm; otherwise, serious complications may occur [18]. At the same time, both sides of the C2 pedicle are often accompanied by the course of the high vertebral artery, which is often accompanied by a narrow safety zone, further increasing the challenge of accurate screw insertion [19]. A large number of relevant studies at home and abroad have confirmed that orthopedic robots have the advantages of improving surgical success rate, reducing trauma, and reducing doctor radiation in thoracic and lumbar spine surgery. However, there are few literature reports on the effectiveness and safety of upper cervical fracture surgery. This study intends to explore the comparative study of Tianji orthopedic robot-assisted screw placement and traditional free-hand screw placement in upper cervical fractures, so as to provide a new, safe, reliable, and minimally invasive surgical method for clinical practice.

Compared with the thoracic or lumbar spine, the cervical spine has anatomical variations, steep pedicle angles, and small pedicles. At the same time, atlantoaxial fractures or dislocations lead to changes in their anatomical shape, which increases the difficulty of surgery and results in low accuracy of cervical pedicle screw placement. Tian Wei [20] *et al.* reported the first case of atlantoaxial transarticular screw fixation using the TiRobot system. The results showed that robot-guided complex upper cervical spine surgery based on intraoperative 3D images is feasible, safe, and accurate, and has significant clinical potential in spinal surgery. Amanda *et al.* used the Excelsius GPS robot to assist in posterior cervical pedicle screw placement for C1 and C2 Hangman fractures in two case analyses. Postoperative CT showed good fixation of the pedicle screws, and the previous symptoms of the two patients did not recur. A meta-analysis by Zhou [21] *et al.*, which included 7 domestic and foreign studies (5 of which used the Tianji orthopedic robot independently developed in China for assisted screw placement, including 160 patients and 719 screws), showed that the optimal screw placement rates for the C1 and C2 segments were 96.2% and 89.7%, respectively, and the

clinically acceptable screw placement rates were 100% and 96.4%, respectively. This indicates that robot-assisted technology is feasible and safe in upper cervical screw placement surgery, which is consistent with the results of this study.

The high accuracy of screw placement in robot-assisted surgery is mainly due to the following reasons: First, compared with robot-assisted surgery, traditional open surgery is prone to deviation due to the resistance of soft tissues around the spine, while robot-assisted surgery places screws through a sleeve, which can effectively avoid screw deviation caused by muscle traction. Second, surgeons may experience a decrease in accuracy due to physiological fatigue during long-term surgery, while the robotic arm can perform tasks accurately for a long time without errors due to fatigue. At the same time, robot-assisted technology pre-plans the optimal screw insertion point, direction, diameter, and depth on the main console before surgery, avoiding the possibility of serious complications caused by the surgeon's lack of experience. On the contrary, some studies have found that there is no significant difference in accuracy between the robot group and the free-hand group [22], and they attributed their results to incorrect drilling pressure during the operation and guide wire slipping or sleeve dislocation due to uneven bone quality near the screw entry point.

At the same time, the results of this study showed that the RA group had more advantages in postoperative blood loss, VAS score, and NDI score compared with the FH group, but there was no significant statistical difference in postoperative complications, postoperative hospital stay, and operation time between the RA group and the FH group, and the operation time of the RA group was significantly longer.

5. Conclusions

1) Compared with the traditional free-hand screw placement method for upper cervical fractures, Tianji orthopedic robot-assisted surgery is safer, more effective, simpler, and more accurate to operate, and is easy to promote and apply.

2) Robot-assisted upper cervical fracture surgery has greater advantages in improving screw placement accuracy, reducing intraoperative blood loss, and avoiding vertebral artery injury.

6. Limitations of the Study

1) This study is a single-center, retrospective case-control study with a relatively small number of enrolled cases. Multi-center, large-sample, prospective cohort studies are needed.

2) The follow-up time of this study is relatively short, and long-term follow-up clinical results are needed to clarify the advantages and disadvantages of robot-assisted technology.

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Conflicts of Interest

The authors of this study declare that no relevant corporate sponsorship was received during the study period, there are no relevant economic interests, the publication of the research results is not related to personal interests, the data are true, there is no academic misconduct, and there is no conflict of interest.

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