Scientific Research Publishing

Open Journal of Orthopedics, 2026, 16(1), 12-25
https://www.scirp.org/journal/ojo
ISSN Online: 2164-3016
ISSN Print: 2164-3008

TiRobot-Assisted Minimally Invasive Treatment for Upper Cervical Fractures

Junlei Tan[1,2*], Qianhou Zhou[1,2*], Xianhai Zeng[1,2], Wenye Ma[1,2], Mingfu Li[1,2], Chengkua Huang[2#], Guosheng Su[3#]

[1]Graduate School of Youjiang Medical University for Nationalities, Baise, China
[2]Department of Spinal Surgery, Southwest Hospital Affiliated to Youjiang Medical University for Nationalities & Baise People's Hospital, Baise, China
[3]Department of Laboratory Medicine, Guangxi-ASEAN Economic and Technological Development Zone People's Hospital/Nanning Tenth People's Hospital, Nanning, China
Email: 1064319347@qq.com, 2029760573@qq.com, [#]1244943047@qq.com, [#]563449581@qq.com

How to cite this paper: Tan, J.L., Zhou, Q.H., Zeng, X.H., Ma, W.Y., Li, M.F., Huang, C.K. and Su, G.S. (2026) TiRobot-Assisted Minimally Invasive Treatment for Upper Cervical Fractures. *Open Journal of Orthopedics*, **16**, 12-25.
https://doi.org/10.4236/ojo.2026.161002

Received: December 9, 2025
Accepted: January 16, 2026
Published: January 19, 2026

Abstract

Objective: This paper aims to explore the clinical application effect of the "TiRobot" orthopedic surgical robot in assisting surgeries for upper cervical fractures, and to provide an evidence-based reference for the selection of clinical treatment plans. **Methods:** A retrospective analysis was conducted on the clinical data of 35 patients with upper cervical fractures who underwent TiRobot-assisted surgery at Baise People's Hospital from January 2019 to September 2025. General patient information (age, hospitalization number, etc.), perioperative indicators (intraoperative blood loss, operation time, postoperative hospital stay, intraoperative fluoroscopy times), screw placement accuracy (evaluated by postoperative CT combined with the Gertzbein-Robbins standard), and prognostic recovery indicators (Visual Analogue Scale for Pain [VAS], Neck Disability Index [NDI], key muscle strength grading, and postoperative complication rate) were collected and statistically analyzed. **Results:** All 35 patients successfully completed the surgery. The average age of the patients was (46.37 ± 9.58) years; the average intraoperative blood loss was (282.29 ± 213.36) mL, the average operation time was (188.91 ± 34.83) minutes, the average postoperative hospital stay was (9.00 ± 3.63) days, and the average number of intraoperative fluoroscopies was (3.49 ± 0.95) times. Regarding prognostic indicators: the VAS score for neck pain decreased from (7.74 ± 0.98) points preoperatively to (5.54 ± 0.95) points at 1 week postoperatively and (2.74 ± 0.85) points at the last follow-up (6 months postoperatively); the VAS score for upper limb radiating pain decreased from (7.46 ± 0.89) points preoperatively to (4.69 ± 1.02) points at 1 week post-

*Co-first authors.
[#]Corresponding authors.

operatively and (1.77 ± 0.69) points at the last follow-up (6 months postoperatively), with statistically significant differences (all $P < 0.05$). The Neck Disability Index (NDI) decreased from (38.43 ± 3.46) points preoperatively to (23.11 ± 4.33) points at 1 week postoperatively and (8.60 ± 2.12) points at the last follow-up (6 months postoperatively); the key elbow flexor muscle strength increased from (2.26 ± 0.70) grades preoperatively to (3.66 ± 0.59) grades postoperatively, with statistically significant differences (all $P < 0.05$). For screw placement: a total of 164 pedicle screws were inserted according to the specific fracture conditions of each patient, including 138 screws of Grade A (84.1%), 23 screws of Grade B (14.0%), 3 screws of Grade C (1.8%), and 0 screws of Grade D and Grade E. The total screw placement time was 1982 minutes, with an average placement time of 12.09 minutes per screw. The accuracy rate of Grade A + B screw placement reached 98.1%, which is significantly higher than the 65% - 75% Grade A placement rate of traditional free-hand screw placement reported in a recent systematic review [1]. The postoperative complication rate was 8.0% (3/35), all of which were transient nerve pain caused by postoperative surrounding tissue edema. The potential mechanism of this complication may be related to the slight traction of surrounding soft tissues during the insertion of the positioning sleeve in robot-assisted surgery and the compression of nerve roots by local tissue reactive edema after surgery, and its incidence is lower than the 15% - 20% reported in traditional open surgery [2]. The symptoms were relieved after mannitol dehydration treatment, and there were no severe complications such as aggravated nerve injury. **Conclusion:** TiRobot-assisted treatment for upper cervical fractures has significant advantages, including improving screw placement accuracy, reducing intraoperative blood loss and radiation exposure, and promoting postoperative functional recovery, with high safety and precise operation. It is worthy of clinical promotion and application.

Keywords

Orthopedic Surgical Robot, Upper Cervical Fracture, Minimally Invasive Treatment, Screw Placement Accuracy, Postoperative Recovery

1. Introduction

The upper cervical spine (atlantoaxial vertebrae) is the connecting hub between the skull and the spinal column, with a complex anatomical structure adjacent to key neurovascular structures such as the spinal cord and vertebral artery. It serves as the core pathway for maintaining the function of the vital center and conducting nerve signals [3]. Although the clinical incidence of such fractures is relatively low, most are caused by high-energy trauma, with extremely high disability and mortality rates. Once injured, they directly threaten the patient's life safety [4]. Therefore, how to achieve "timely, safe, and precise" treatment of upper cervical fractures, maximize the restoration of spinal stability, and protect nerve function has always been a key research direction in the field of spinal surgery.

Currently, the mainstream treatment for upper cervical fractures is anterior or posterior pedicle screw internal fixation. However, traditional surgery has obvious limitations: Firstly, the upper cervical pedicle has significant anatomical variations and narrow channels, surrounded by the vertebral artery and spinal cord. Free-hand screw placement requires extensive experience from the surgeon, with an extremely low error tolerance. Intraoperative deviations may lead to severe complications such as spinal cord injury and vertebral artery rupture [5] [6]. Secondly, traditional open surgery requires extensive dissection of neck muscles and ligaments, which not only increases intraoperative blood loss but also may damage the surrounding stable structures of the cervical spine, resulting in slow postoperative neck function recovery and low patient satisfaction [7]. Thirdly, even percutaneous minimally invasive surgery still relies on multiple intraoperative X-ray or CT fluoroscopies for positioning. This not only exposes both doctors and patients to radiation risks but also makes it difficult to adjust the screw after placement. If the position deviation is large, an extended incision is required for correction, which instead increases trauma [8] [9].

In recent years, with the development of artificial intelligence and precision medicine, orthopedic surgical robot technology has provided a new solution to address the above problems. Domestic orthopedic robot systems represented by TiRobot integrate 3D image navigation, intelligent path planning, and robotic arm precise positioning technologies. They can provide a clear intraoperative 3D field of view and perform high-precision rotation, bending, and other operations. Theoretically, they can significantly improve screw placement accuracy, reduce intraoperative radiation, lower the risk of neurovascular injury, and truly achieve minimally invasive treatment of complex fractures [10] [11].

Although the application of TiRobot in spinal surgery has been gradually implemented, current studies mostly focus on lower cervical or thoracolumbar diseases, and clinical evidence for upper cervical fractures remains insufficient. Therefore, this study retrospectively analyzed the data of 35 patients who underwent TiRobot-assisted posterior internal fixation for upper cervical fractures in our hospital from January 2019 to September 2025. It systematically evaluated the perioperative indicators, screw placement accuracy, and postoperative recovery effect of this technology, providing objective evidence for its clinical promotion.

2. Materials and Methods

2.1. Study Subjects

Thirty-five patients with upper cervical fractures who underwent TiRobot-assisted surgery in the Department of Spinal Surgery of Baise People's Hospital from January 2019 to September 2025 were included retrospectively. All surgeries were performed by the same treatment team, and the chief surgeons were chief physicians with more than 10 years of experience in spinal surgery, ensuring the consistency and standardization of surgical operations.

2.2. Case Selection Criteria

2.2.1. Inclusion Criteria

① Preoperative diagnosis of upper cervical fractures (atlas or axis fractures) confirmed by cervical X-ray, 3D CT reconstruction, and MRI;

② Underwent TiRobot-assisted posterior pedicle screw internal fixation;

③ Patients and their family members provided informed consent and cooperated with postoperative follow-up;

④ Complete case data (imaging data, surgical records, follow-up data).

2.2.2. Exclusion Criteria

① Complicated with skin infection, cervical tuberculosis, tumor, or severe osteoporosis;

② Preoperative presence of severe neurological dysfunction (e.g., quadriplegia);

③ Inability to cooperate with evaluation due to mental illness or cognitive impairment;

④ Refusal to undergo robot-assisted surgery or poor follow-up compliance.

2.3. Surgical Methods

2.3.1. Preoperative Preparation

All patients underwent skull traction preoperatively to maintain upper cervical stability, and completed cervical X-ray, 3D CT reconstruction (covering the atlantoaxial vertebrae and vertebral artery course), and MRI (to evaluate spinal cord and soft tissue injury). Meanwhile, electrocardiogram, blood routine, and liver and kidney function tests were conducted to assess cardiopulmonary function and surgical risks. Antibiotics were intravenously infused 30 minutes before surgery to prevent infection.

2.3.2. Surgical Operation

Positioning and Sterilization: The patient was placed in a prone position, with the head fixed on a special head frame to ensure a neutral cervical spine position. Routine disinfection and draping were performed, and a posterior midline incision (approximately 8 cm in length) was made centered on the spinous process of the fractured segment. The skin, subcutaneous tissue, and deep fascia were incised layer by layer to expose the spinous process, lamina, and zygapophyseal joints of the fractured vertebrae.

Robot Positioning and Path Planning: The TiRobot was connected to a 3D C-arm machine, and CT scanning was performed on the surgical area. The image data were transmitted to the robot workstation; the system automatically generated a 3D model of the upper cervical spine. The surgeon planned the entry point, angle, and length of the pedicle screw based on the anatomical structure.

Screw Placement: The robotic arm moved to the target vertebra according to the planned path and placed the positioning sleeve. A Kirschner wire was drilled along the planned channel using an electric drill. After reconfirming the correct position of the Kirschner wire via 3D C-arm scanning, tapping, depth measurement, and screw insertion were performed sequentially. Pedicle screws were in-

serted (C1 vertebral screw specification: 3.5 mm × 24 mm; C2 vertebral screw specification: 3.5 mm × 26 mm). The number of screws inserted was adjusted according to the specific fracture conditions of each patient, and a total of 164 screws were inserted in this study. A 70 mm connecting rod and 3.0 mm cross-link were installed to reduce and fix the fractured fragments, and spinal canal decompression was performed if necessary.

Postoperative Management: The surgical cavity was irrigated and fully hemostasized. A bone graft bed was prepared, and autologous bone and allogeneic bone were implanted. A drainage tube was placed, the incision was sutured layer by layer, and the patient was sent back to the ward after gauze dressing.

2.3.3. Postoperative Management

Postoperatively, antibiotics were routinely infused intravenously for 1 day to prevent infection. Meanwhile, treatments such as detumescence (mannitol), pain relief (non-steroidal anti-inflammatory drugs), neurotrophy (methylcobalamin), and promotion of bone healing (calcium + vitamin D) were administered. Cervical CT reexamination was performed 2 - 3 days postoperatively to evaluate screw position and fracture reduction. The drainage tube was removed according to the drainage volume. Patients were instructed to wear a cervical collar for fixation and to gradually conduct neck functional exercises.

2.4. Study Indicators and Evaluation Methods

2.4.1. Perioperative Indicators

① Intraoperative blood loss: Calculated by combining the volume collected by the aspirator and the gauze-weighing method (1 g of blood ≈ 1 mL);

② Operation time: Total time from skin incision to completion of suturing the incision;

③ Postoperative hospital stay: Number of days from the day of operation to the day of discharge;

④ Intraoperative fluoroscopy times: Recorded the number of scans by the 3D C-arm machine during the operation.

2.4.2. Screw Placement Accuracy

Cervical CT reexamination was performed within 1 week postoperatively, and the screw position was evaluated according to the Gertzbein-Robbins standard: Grade A (screw completely within the pedicle), Grade B (screw penetrating the pedicle cortex ≤ 2 mm), Grade C (screw penetrating the cortex by 2 - 4 mm), Grade D (screw penetrating the cortex by 4 - 6 mm), Grade E (screw penetrating the cortex > 6 mm). Grade A was defined as "precise screw placement," and Grade A + B as "acceptable screw placement." The precise screw placement rate (number of Grade A screws / total number of screws) and acceptable screw placement rate (number of Grade A + B screws / total number of screws) were calculated. Meanwhile, the total screw placement time (from robot scanning to completion of the last screw insertion) was recorded, and the average placement time per screw was calculated.

2.4.3. Postoperative Recovery Indicators

① Pain assessment: The Visual Analogue Scale (VAS, 0 - 10 points, higher scores indicate more severe pain) was used to record the neck pain and upper limb radiating pain scores preoperatively, at 1 week postoperatively, and at the last follow-up (6 months postoperatively);

② Cervical function assessment: The Neck Disability Index (NDI, 0 - 100 points; higher scores indicate more severe functional disability) was used, with the same assessment time as the VAS score;

③ Muscle strength assessment: The muscle strength grading method (0 - 5 grades, with higher grades indicating better muscle strength) was used to record the key elbow flexor muscle strength preoperatively and at 1 week postoperatively;

④ Complications: Complications within 1 week postoperatively (e.g., nerve pain, infection, screw loosening) were recorded, and the complication rate was calculated.

2.5. Statistical Methods

SPSS 27.0 software was used for data analysis. Measurement data were expressed as "mean ± standard deviation (x ± s)." A paired t-test was used for the comparison of preoperative and postoperative indicators, and analysis of variance was used for repeated measurement data at different time points (preoperatively, 1 week postoperatively, last follow-up). Count data were expressed as "cases (%)," and comparison was performed using the χ^2 test. A P-value < 0.05 was considered statistically significant.

3. Results

3.1. Patient Baseline Data and Perioperative Indicators

Table 1. Patient baseline data and perioperative indicators.

Baseline Data	Statistical Range
Gender (Male/Female, n)	22/13
Age (Years, x ± s)	46.37 ± 9.58
Postoperative Hospital Stay (Days, x ± s)	9.00 ± 3.63
Intraoperative Fluoroscopy Times (Times, x ± s)	3.49 ± 0.95
Operation time (min, x ± s)	188.91 ± 34.83
Intraoperative Blood Loss (mL, x ± s)	282.29 ± 213.36

Among the 35 patients, there were 22 males (62.9%) and 13 females (37.1%), with an average age of (46.37 ± 9.58) years; the operation time ranged from 150 to 245 minutes, with an average of (188.91 ± 34.83) minutes; the intraoperative blood loss ranged from 50 to 850 mL, with an average of (282.29 ± 213.36) mL. The wide range of intraoperative blood loss may be related to factors such as fracture complexity (e.g., more blood loss in comminuted fractures or fractures combined with

dislocation), patients' own coagulation function, and intraoperative hemostatic effect; the number of intraoperative fluoroscopies ranged from 1 to 4 times, with an average of (3.49 ± 0.95) times; the postoperative hospital stay ranged from 4 to 11 days, with an average of (9.00 ± 3.63) days. Details are shown in Table 1.

3.2. Screw Placement Accuracy

A total of 164 pedicle screws were inserted in 35 patients. Postoperative CT evaluation showed: 138 Grade A screws (84.1%), 23 Grade B screws (14.0%), 3 Grade C screws (1.8%), and 0 Grade D and Grade E screws; the precise screw placement rate of Grade A was 84.1%, and the acceptable screw placement rate of Grade A + B was 98.1%, which is significantly higher than the 65% - 75% Grade A placement rate for traditional free-hand screw placement reported in a recent systematic review [1]. The total screw placement time was 1982 minutes, with an average placement time of 12.09 minutes per screw.

3.3. Postoperative Recovery Indicators

3.3.1 Improvement of Pain and Cervical Function

VAS score results showed that both neck pain and upper limb radiating pain were significantly relieved over time, with the most obvious pain improvement at the last follow-up (all $P < 0.05$); the NDI index gradually decreased from (38.43 ± 3.46) points preoperatively to (8.60 ± 2.12) points at the last follow-up (6 months postoperatively), with a significant reduction in cervical dysfunction (all $P < 0.05$). Details are shown in Table 2 and Table 3.

3.3.2 Improvement of Muscle Strength

The key elbow flexor muscle strength increased from (2.26 ± 0.70) grades preoperatively to (3.66 ± 0.59) grades at 1 week postoperatively, with a statistically significant difference ($t = 9.0472$, $P < 0.05$), indicating significant recovery of the patient's upper limb motor function.

Table 2. Comparison of preoperative and postoperative NDI scores and key muscle strength (x ± s).

Indicator	NDI Score			Key Elbow Flexor Muscle Strength	
	Preoperation	1 Week Postoperation	6 Months Postoperation (Last Follow-up)	Preoperation	1 Week Postoperation
x ± s	38.43 ± 3.46	23.11 ± 4.33	8.60 ± 2.12	2.26 ± 0.70	3.66 ± 0.59
t Value	16.3523	43.4904	17.8054	9.0472	9.0472
P Value	0.0000	0.0000	0.0000	0.0000	0.0000

Table 3. Comparison of VAS scores before operation, 1 week after operation, and at last follow-up (n = 35, x ± s).

	Symptom	Preoperation	1 Week Postoperation	Last Follow-up	F Value	P Value
VAS Score	Neck Pain	7.74 ± 0.98	5.54 ± 0.95	2.74 ± 0.85	255.05	0.0000
	Radiating Upper Limb Pain	7.46 ± 0.89	4.69 ± 1.02	1.77 ± 0.69	368.22	0.0000

3.4. Postoperative Complications

Among the 35 patients, 3 cases (8.0%) had transient nerve pain caused by postoperative surrounding tissue edema. There were no severe complications such as infection, screw loosening, or spinal cord injury. The potential mechanism of this complication may be related to the slight traction of surrounding soft tissues during the insertion of the positioning sleeve in robot-assisted surgery and the compression of nerve roots by local tissue reactive edema after surgery, and its incidence is lower than the 15% - 20% reported in traditional open surgery [2]. The symptoms of the 3 patients with nerve pain were completely relieved after 3 - 5 days of intravenous mannitol dehydration treatment, with no residual neurological dysfunction.

3.5. Typical Case

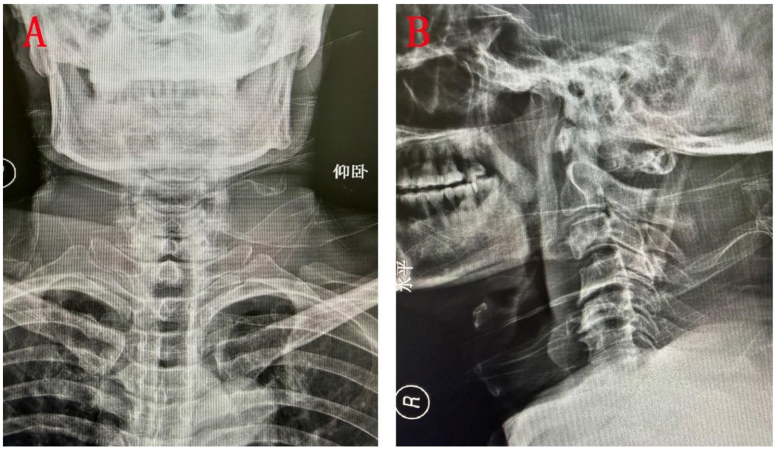

Figure 1. Preoperative X-ray fluoroscopy images.

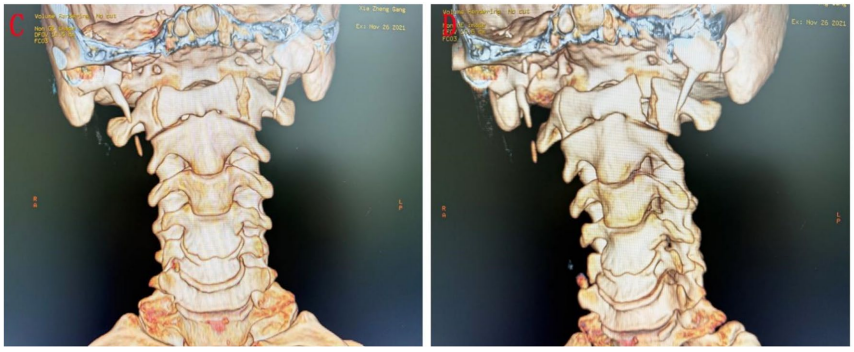

Figure 2. Preoperative 3D reconstruction showing the fracture site.

A middle-aged male patient was admitted to the hospital due to "neck pain and limited movement caused by a heavy object impact for 4 days." Preoperative 3D CT reconstruction confirmed "atlas anterior arch + posterior arch fracture." After TiRobot-assisted posterior pedicle screw internal fixation, the patient's neck pain was immediately relieved; CT reexamination at 1 week postoperatively showed

accurate screw position and good fracture reduction; at the last follow-up (6 months postoperatively), the patient's neck movement function had returned to normal, the elbow flexor muscle strength reached Grade 5, the VAS score decreased to 1 point, and the NDI index decreased to 6 points. The preoperative and postoperative cervical imaging data of the patient and the TiRobot operation process are shown in Figures 1-5.

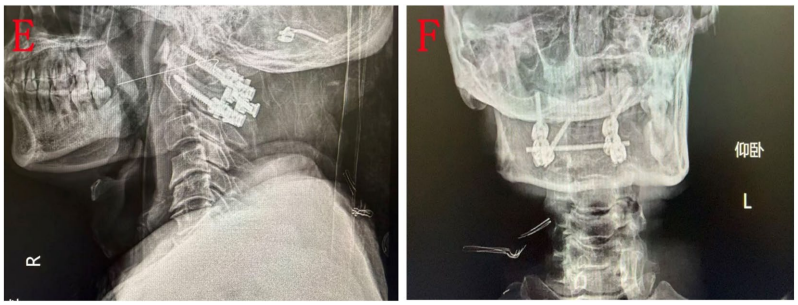

Figure 3. Cervical X-ray reexamination at 1 week postoperatively.

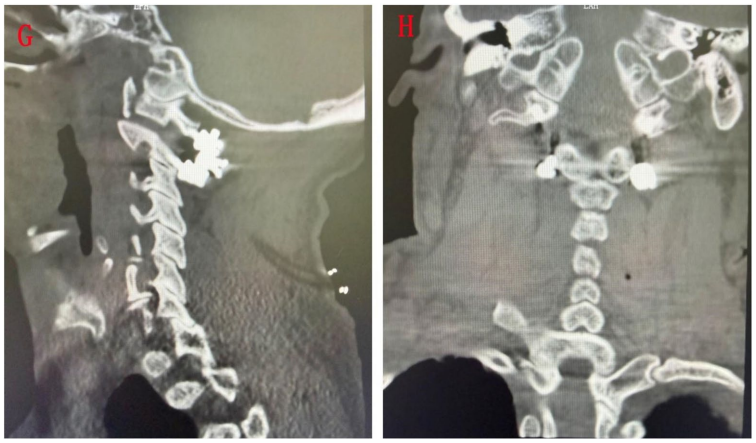

Figure 4. 3D CT reconstruction images at 1 week postoperatively, showing ideal screw placement.

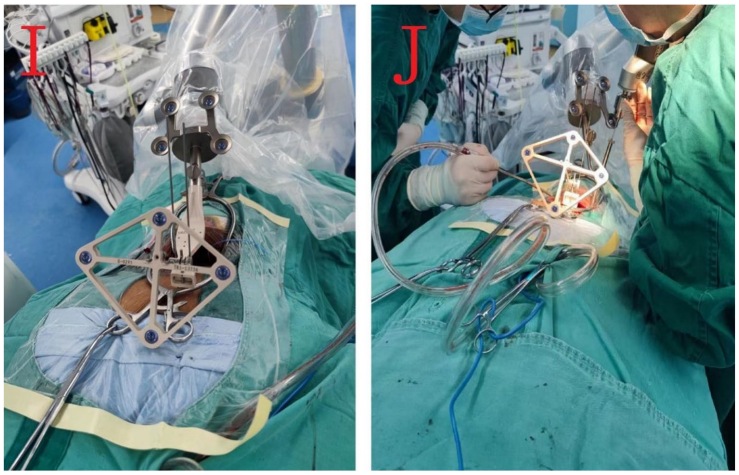

Figure 5. Intraoperative positioning operation of Tirobot.

4. Discussion

4.1. Advantages of TiRobot-Assisted Treatment for Upper Cervical Fractures

4.1.1. Improving Screw Placement Accuracy and Reducing the Risk of Complications

The upper cervical pedicle has a complex anatomical structure and significant individual differences. Traditional free-hand screw placement relies on the surgeon's experience, which is prone to screw penetration through the cortex due to deviations in anatomical landmark identification, leading to vertebral artery injury or spinal cord compression [12] [13]. In this study, TiRobot controlled the screw placement error within the millimeter range through preoperative 3D image modeling and intraoperative real-time navigation. The precise screw placement rate of Grade A reached 84.1%, and the acceptable screw placement rate of Grade A + B was 98.1%, with no Grade D/E screws with severe deviations. This is significantly better than traditional surgery (literature reports that the Grade A rate of traditional free-hand screw placement is approximately 65% - 75%) [1], and a recent systematic review has also confirmed the limitations of traditional free-hand screw placement [1]. This result confirms that robot-assisted technology can effectively reduce the risk of screw placement and provide a guarantee for the precise fixation of upper cervical fractures.

4.1.2. Reducing Intraoperative Trauma and Radiation Exposure

Compared with traditional open surgery, TiRobot-assisted surgery has a smaller incision (approximately 8 cm, while traditional surgery incisions are approximately 12 - 16 cm) and does not require extensive dissection of neck muscles. The average intraoperative blood loss was (282.29 ± 213.36) mL, which was significantly lower than that of traditional surgery (average blood loss of 400 - 600 mL) [2]. The wide range of intraoperative blood loss may be related to factors such as fracture complexity (e.g., more blood loss in comminuted fractures or fractures combined with dislocation), patients' own coagulation function, and intraoperative hemostasis effect. Meanwhile, the robot reduces the number of intraoperative fluoroscopies to (3.49 ± 0.95) times through one preoperative scan for planning and precise intraoperative positioning, which is much lower than that of percutaneous minimally invasive surgery (average 10 - 15 fluoroscopies) [14], greatly reducing the radiation exposure risk for both doctors and patients.

4.1.3. Promoting Postoperative Functional Recovery and Shortening the Rehabilitation Cycle

This study showed that the VAS score for neck pain in patients decreased by 28.4% at 1 week postoperatively compared with preoperatively, and by 64.6% at the last follow-up (6 months postoperatively); the NDI index decreased from (38.43 ± 3.46) points preoperatively to (8.60 ± 2.12) points at the last follow-up, with significant improvement in cervical function; the key elbow flexor muscle strength increased from (2.26 ± 0.70) grades preoperatively to (3.66 ± 0.59) grades postop-

eratively, with good recovery of upper limb motor function. In addition, the average postoperative hospital stay was only (9.00 ± 3.63) days, and the complication rate was only 8.0%, both of which were better than the postoperative recovery effect of traditional surgery [15]. This advantage is attributed to the "minimally invasive" and "precise" nature of robot-assisted surgery—smaller trauma reduces postoperative pain and tissue adhesion, and precise fixation creates favorable conditions for fracture healing and nerve function recovery.

4.2. Limitations of TiRobot

Although this study confirms the clinical value of TiRobot, its limitations should be acknowledged: ① High equipment cost: The purchase and maintenance costs of the robot system are high, and it requires supporting dedicated consumables, making it difficult to popularize in primary medical institutions at present; ② Dependence on preoperative image quality: If preoperative CT/MRI has artifacts or an insufficient scanning range, it may lead to deviations in robot path planning, so strict control of image quality is required; ③ Lack of active reduction capability: The robot can only assist in screw placement, and fracture reduction still relies on the surgeon's experience, with limited reduction effect for complex comminuted fractures; ④ Long learning curve: The surgical team needs to receive professional training (including robot operation, image processing, and emergency cooperation), and the operation time may be prolonged due to unskilled operation in the early stage.

4.3. Clinical Application Precautions

4.3.1. Preoperative Preparation

① Image evaluation: Clear upper cervical 3D CT reconstruction (slice thickness ≤ 1 mm) and MRI should be obtained to clarify the fracture type, vertebral artery course, and spinal cord injury, avoiding planning deviations caused by blurred images.

② Patient evaluation: Focus on screening for severe osteoporosis (bone mineral density T-score < −2.5). For such patients, screw holding force is insufficient, and bone cement augmentation should be combined.

③ Equipment debugging: Before surgery, the flexibility and positioning accuracy of the robot's robotic arm should be tested, and it should be confirmed that the models of dedicated instruments (screws, sleeves) are matched and sterilized properly.

4.3.2. Intraoperative Operation

① Position fixation: When the patient is in the prone position, the head and cervical spine should be kept in a neutral position to avoid body displacement caused by respiratory movement or muscle spasm. If displacement occurs during the operation, re-scanning and calibration are required.

② Real-time monitoring: During the operation, close attention should be paid to the robot navigation interface and the patient's vital signs. If the robotic arm

has an abnormal alarm, the operation should be suspended immediately and switched to the traditional surgical mode.

③ Combination of experience: Robot positioning should not be relied on entirely. The surgeon's anatomical experience should be combined, and the screw position should be reconfirmed by intraoperative fluoroscopy, especially in the area near the vertebral artery foramen.

4.3.3. Postoperative Management

① Short-term follow-up: Cervical CT reexamination should be performed within 24 hours postoperatively to confirm the screw position and fracture reduction. If screw loosening or cortex penetration is found, timely treatment is required;

② Rehabilitation guidance: In the early postoperative period, patients are instructed to wear a cervical collar (for 6 - 8 weeks), avoid strenuous activities such as neck rotation and flexion-extension, and gradually perform isometric contraction training;

③ Long-term follow-up: Regular follow-up should be conducted at 1, 3, and 6 months postoperatively. Fracture healing should be evaluated through imaging, and the rehabilitation plan should be adjusted to prevent long-term neck stiffness.

5. Conclusion

This study shows that TiRobot-assisted treatment for upper cervical fractures can significantly improve screw placement accuracy, reduce intraoperative trauma and radiation exposure, and promote postoperative functional recovery, with high safety and few complications. It is an efficient and precise minimally invasive treatment method. Although this technology has limitations such as high equipment cost and a long learning curve, with technological iteration and medical insurance policy support, it has great potential for clinical popularization. In the future, multi-center, large-sample prospective studies are needed to further verify the long-term efficacy, and at the same time, promote the upgrading of robot functions such as "active reduction" and "intelligent path optimization" to provide better treatment options for patients with upper cervical fractures.

6. Study Limitations

① This study is a single-center retrospective study with a small sample size (35 cases), which may have selection bias. The results need to be further verified by multi-center, large-sample studies.

② The follow-up time is short (the last follow-up was 6 months postoperatively), and there is a lack of long-term data of more than 5 years, so the long-term stability of screws and the long-term recovery effect of cervical function cannot be evaluated.

③ No traditional surgery control group was set up, so the advantages and disadvantages of the two surgical methods cannot be directly compared. A case-control study needs to be conducted in the future.

Acknowledgements

Thanks to the Medical Ethics Committee of Baise People's Hospital for reviewing this study (Ethics Approval No.: BYFY-2023-036); thanks to the collaboration and support of the Spinal Surgery Team, Radiology Department, and Anesthesiology Department; thanks to all patients and their families who participated in the study.

Funding

Baise Science Research and Technology Development Program, Guangxi (Project No.: Baike 20233628).

Conflicts of Interest

All authors declare no sponsorship from relevant enterprises, no economic interest associations, that the data are true, and that there is no academic misconduct.

References

[1] Haddad, E., Al Khoury Salem, H. and Dohin, B. (2024) Diagnosis and Treatment of Cervical Spine Injuries in Children. *Orthopaedics & Traumatology*: *Surgery & Research*, **110**, Article ID: 103762. https://doi.org/10.1016/j.otsr.2023.103762

[2] Liu, Y., Zhao, Z.G., Wang, X., *et al.* (2022) Robot-Assisted Pedicle Screw Fixation for Cervical Fracture and Dislocation. *Chinese Journal of Orthopaedic Surgery*, **30**, 1941-1946.

[3] Qu, X.T., Guan, H.P. and Li, N.H. (2024) Development of Minimally Invasive Surgical Techniques for Upper Cervical Fractures. *Chinese Journal of Orthopaedic Surgery*, **32**, 2246-2250+2256.

[4] Chen, Z.D., He, Y.J., Cai, T.Y., *et al.* (2024) Characteristics and Treatment Progress of Upper Cervical Spine Combined with Discontinuous Lower Cervical Spine Fractures. *Journal of Practical Orthopaedics*, **30**, 434-437.

[5] Wu, G., Feng, R.B., Hu, H., *et al.* (2022) Efficacy and Safety of 3D Microscope-Assisted Pedicle Screw Internal Fixation for Upper Cervical Fracture and Dislocation. *The Journal of Practical Medicine*, **38**, 1782-1787.

[6] Luo, S.J., Wang, H. and Liang, H.N. (2025) Efficacy of Anterior-Posterior Combined Approach Decompression, Reduction, Fusion and Internal Fixation for Cervical Fracture-Dislocation Combined with Spinal Cord Injury. *Journal of Clinical Research*, **42**, 1164-1167.

[7] Zheng, B.Z., Li, J.L. and Ye, J.S. (2025) Retrospective ANALYSIS of treatment within 8 Hours for Patients with Cervical Fracture Combined with Spinal Cord Injury. *China Health Standard Management*, **16**, 184-188.

[8] Dou, R.S., Yan, H., Zhang, Y., *et al.* (2024) Posterior Endoscopic Release and Anterior Fixation for Cervical Fracture and Locked Dislocation: A Case Report. *Chinese Journal of Orthopaedic Surgery*, **32**, 2302-2304.

[9] Xia, Y.Z., Huang, Z.J. and Yan, Y. (2024) Management Strategies for Upper Cervical Fractures Combined with Vertebral Artery Injury. In: Chinese Medical Doctor Association and Spinal Surgery Branch of Chinese Medical Doctor Association, Eds., *Proceedings of the* 18*th Annual Meeting of Spinal Surgery Branch of Chinese Medical Doctor Association—Spine and Spinal Cord*, The First Affiliated Hospital of Chongqing Medical University, 92.

[10] Yan, X.L., Xi, H.T., Li, Z.Y., *et al.* (2024) Nomogram Prediction Model for Surgical Prognosis of Patients with Cervical Fracture and Acute Cervical Spinal Cord Injury. *Journal of Cervical and Lumbar Pain*, **45**, 845-852.

[11] Li, L., Zhou, Y.J., Wang, Y., *et al.* (2024) Research Progress in Surgical Treatment of Lower Cervical Fracture and Dislocation. *Chinese Journal of Spine and Spinal Cord*, **34**, 438-443.

[12] Wu, Y.H., Zheng, Y.W., Chen, X.F., *et al.* (2024) Research Progress of Artificial Intelligence in Cervical Spine Imaging. *International Journal of Medical Radiology*, **47**, 101-105.

[13] Wunder, J., Schirdewahn, C. and von Rüden, C. (2024) Traumatic Posterior Atlanto-axial Dislocation without Fracture of the Upper Cervical Spine in a Female Geriatric Patient: Case Report and Literature Search. *Die Unfallchirurgie*, **127**, 543-546. https://doi.org/10.1007/s00113-024-01445-x

[14] Gao, X.Y. and Li, X.Y. (2025) Current Development Status of Surgical Robots in Orthopedics. *Journal of Changzhi Medical College*, **39**, 377-380.

[15] Brakopp, F.H., Mendel, T., Klauke, F., Hofmann, G.O., Schenk, P., Bäumlein, M., *et al.* (2023) The Halofixator for the Treatment of Un-stable Fractures of the Upper Cervical Spine—Our Own Experience and Narrative Review. *Zeitschrift für Orthopädie und Unfallchirurgie*, **162**, 199-210. https://doi.org/10.1055/a-1957-6053