

Accuracy of robot-assisted cortical bone trajectory pedicle screw placement: CT-based retrospective cohort study

C. MINNAERT², K. VAN DER DONCKT^{1,2}, A. DEPRAETERE¹, B. DEMOOR³, L. PLASSCHAERT², F. PLASSCHAERT²

¹Department of Orthopaedic Surgery, AZ Glorieux, Ronse, Belgium; ²Department of Orthopaedics and Traumatology, UZ Gent, Ghent, Belgium

³Ghent University, Ghent, Belgium.

Correspondence at: Cornille Minnaert, MD, Department of Orthopaedic Surgery, UZ Ghent, Corneel Heymanslaan 10, 9000 Ghent, Belgium.
E-mail: Cornille.minnaert@icloud.com

ABSTRACT

Background and study aims: Pedicle screw placement accuracy is critical for safe spinal fixation, and robot-assisted techniques aim to improve precision. This study evaluated the accuracy of robot-assisted posterior pedicle screw placement in the lower thoracic and lumbar spine using a CBT trajectory as well as determine what factors are associated with accuracy of screw placement.

Materials and methods: A retrospective single-centre cohort study included 100 consecutive patients undergoing posterior spinal instrumentation with pedicle screws between August 2022 and August 2023. Preoperative CT-based planning and robotic guidance (ExcelsiusGPS) were used. Postoperative CT assessed 511 screws using the Gertzbein–Robbins classification, including breach direction. Clinically acceptable placement was defined as grades A or B. Interobserver agreement was evaluated using Cohen's kappa and Gwet's AC1. Multivariable analyses were performed using generalized estimating equations and mixed-effects models.

Results: Clinically acceptable screw placement exceeded 96% at all spinal levels. Perfect placement ranged from 86.7% to 100%. No clinically relevant (Grade C-E) medial, superior, or inferior breaches were observed; lateral breaches occurred in 1.4%. Interobserver agreement was high (AC1 0.953–0.994). For perfect placement (Grade A), L5 showed higher odds compared to L4.

Conclusion: Robot-assisted pedicle screw placement using CBT demonstrates high accuracy and safety, with absence of clinically relevant medial breaches. These findings support the use of robotic guidance as an effective adjunct in spinal instrumentation.

Keywords: Pedicle screw, robotic surgery, cortical bone trajectory, spinal instrumentation, screw accuracy.

INTRODUCTION

Pedicle screw fixation remains the gold standard to achieve rigid spinal fixation in the management of trauma, degenerative disease, deformity, and spinal fusion. Screw misplacement may result in cortical pedicle breaches with potential neurovascular injury and higher pseudarthrosis rates, and subsequent need for revision surgery¹. Consequently, screw placement accuracy remains a critical determinant of both patient safety and clinical outcomes.

Several techniques for pedicle screw placement have been developed, including traditional freehand placement, navigation, and robot-assisted systems. The majority of previous studies evaluating screw accuracy concern traditional pedicle screw trajectories, which follow a lateral starting point with a predominantly lateral to medial path through the pedicle into the

vertebral body. Within this context, the freehand technique has historically demonstrated variable accuracy, with clinically acceptable placement rates of approximately 80%^{2,4}. Kosmopoulos et al. reported an accuracy of 86.6% [3] while a systematic review of Gelalis et al.⁴ highlighted both this variability and a general tendency favouring navigation-assisted techniques^{3,4}. Furthermore, surgical technique influences cortical breach direction: freehand screw placement is more frequently associated with medial breaches, whereas navigation-guided techniques show a higher incidence of lateral breaches⁴. This distinction is clinically relevant, as medial breaches carry a greater risk of neurovascular injury. In contrast to these traditional trajectories, cortical bone trajectory (CBT), first described by Santoni et al.⁵, represents an alternative screw insertion technique designed to maximize cortical bone contact. CBT

uses a more medial entry point with a caudocephalad and mediolateral trajectory, effectively reversing the direction of the traditional pedicle screw path. This approach increases screw purchase by engaging denser cortical bone and was primarily developed to improve fixation strength and reduce loosening, particularly in patients with compromised bone quality⁵.

Postoperative assessment of pedicle screw position is most commonly performed using computed tomography (CT) and graded according to the Gertzbein–Robbins classification⁶. This widely adopted system categorizes screws based on the extent and direction of pedicle wall breach: Grade A indicates a completely intrapedicular screw; Grade B, a breach of less than 2 mm; Grade C, 2–4 mm; Grade D, 4–6 mm; and Grade E, greater than 6 mm. Breaches are categorized by direction as medial, lateral, superior or inferior. Grades A and B are generally considered clinically acceptable, whereas Grades C through E represent increasing degrees of mispositioned screws. The use of standardized grading systems is essential for reliable comparison across studies and surgical techniques.

Despite increasing use of robotic systems, heterogeneity in study design and reporting limits comparability. Many studies group different surgical techniques together, include heterogeneous patient populations, or apply inconsistent definitions of accuracy and clinical acceptability. These factors hinder comparisons and make it difficult to establish a clear benchmark for accuracy in a consistent clinical setting. The primary objective of this study was to evaluate the accuracy of robot-assisted posterior pedicle screw placement using a cortical bone trajectory in a consecutive cohort of 100 patients using CT-based Gertzbein–Robbins grading. Secondary objectives include assessment of interobserver agreement, effect of BMI, surgeon and spinal level on screw placement accuracy, and a descriptive comparison of the findings with those reported in the existing literature. This study represents Level IV evidence based on its retrospective cohort design.

METHODS

Study design and patient selection

This retrospective, single-centre cohort study included all consecutive adult patients undergoing posterior spinal surgery with pedicle screw placement between August 10, 2022, and August 31, 2023. Inclusion was based on the clinical indication for spinal instrumentation requiring pedicle screws,

irrespective of underlying pathology, age, body mass index or whether the procedure was primary or revision surgery. No additional exclusion criteria were applied. Ethical approval was obtained from the Institutional Review Board (IRB), which granted a waiver of informed consent due to the retrospective nature of the study.

Surgical technique

Approximately 10 days prior to surgery, all patients underwent a preoperative computed tomography (CT) scan, which served as the basis for surgical planning. The imaging data were imported into the ExcelsiusGPS (Globus Medical, Inc., Audubon, PA, USA) robotic planning platform, where optimal screw trajectories, entry points, lengths, and diameters were defined for each pedicle screw. Attention was given to maximizing cortical bone contact in accordance with cortical bone trajectory (CBT) principles⁵, while ensuring safe margins relative to neural and vascular structures.

During surgery, patients were positioned prone, and a standard posterior midline open approach was performed. Following exposure of the posterior elements, the robotic system was registered to the patient anatomy using intraoperative 2D imaging, allowing accurate alignment between the preoperative plan and intraoperative execution. The robotic arm was then used to guide the planned screw trajectories, facilitating precise placement of instrumentation. Screw placement was verified intraoperatively using standard practice 2D fluoroscopy. All procedures were performed by three experienced spine surgeons.

Imaging protocol

Postoperative CT performed on the first postoperative day was used for the evaluation of pedicle screw placement. The imaging protocol utilized a native axial slice thickness of 0.625 mm, with sagittal reformations reconstructed at 3 mm intervals. To ensure precise visualization of the interface and to minimize metal artifacts, all assessments were performed using a specialized bone window setting.

Assessment of screw placement

Two independent researchers, blinded to each other's assessments, evaluated all pedicle screws using the Gertzbein–Robbins classification⁶. Each screw was assessed for cortical breaches across four anatomical directions: medial, lateral, superior, and inferior. This was done by analysis of the axial, coronal and sagittal CT reconstructions. Following

standard clinical literature, placement was defined as clinically acceptable if it received a Grade A or B, representing a breach of less than 2 mm⁶. For analysis, both individual rater scores and a consensus dataset (maximum breach across raters) were used.

Bias

Potential sources of bias include the retrospective design, unequal surgeon contribution and single-centre setting, which may limit generalizability. Selection bias was minimized by including all consecutive patients without exclusion criteria. Measurement bias was reduced through the use of standardized postoperative CT imaging and independent blinded assessment by two raters. Residual confounding may persist, as not all potential influencing factors could be accounted for.

Statistical analysis

Statistical analyses were performed using R statistical software (version 4.5.3; R Foundation for Statistical Computing, Vienna, Austria). The primary outcome, screw placement accuracy according to the Gertzbein-Robbins classification, was analysed as a multinomial categorical variable (Grades A to E). Interobserver agreement was assessed using Cohen's kappa for each breach direction. Given the highly skewed distribution of ratings, Gwet's AC1 coefficient was additionally calculated to account for the paradoxical behaviour of kappa under high agreement conditions. No formal a priori sample size calculation was performed due to the retrospective nature of the study.

Screw placement accuracy was assessed using the worst-case Gertzbein-Robbins score from two independent raters, providing a conservative estimate and enhancing the robustness of the analysis. Descriptive statistics were calculated at both patient and screw level. Categorical variables were reported as counts and proportions, while continuous variables were summarized as mean $\pm$ standard deviation (SD).

A generalized estimating equations (GEE) approach with a binomial distribution and exchangeable correlation structure was used to model the correlation present from measurements of screws within the same patient. Among others, covariates included body mass index (BMI), surgeon and spinal level. Due to model instability observed with sparse categories and highly imbalanced outcomes, analyses were restricted to lumbar levels L2–L5, with L4 as the reference level. Mixed-effects logistic regression models (GLMM) with a random intercept at patient level were also performed as a sensitivity analysis. Odds ratios (OR)

with 95% confidence intervals (CI) were calculated. Alpha was set at 0.05 for all analyses.

RESULTS

Descriptive analysis

The study population comprised 100 consecutive patients, of whom 61% were female. Average age at surgery was 63 ± 13.2 years and patients had a mean BMI of 28.6 ± 5.2 kg/m². A total of 511 pedicle screws were placed across spinal levels T10 to S1. The distribution of screws per level was as follows: T10 (n=2), T11 (n=3), T12 (n=4), L1 (n=10), L2 (n=30), L3 (n=72), L4 (n=166), L5 (n=160), and S1 (n=64). The majority of procedures were performed by a single surgeon, accounting for 85 patients and 447 screws, while the remaining surgeons contributed substantially fewer cases (Table I).

Clinically acceptable placement (grades A–B) exceeded 96% at all lumbar levels and reached 100% at S1. Perfect placement (grade A) ranged from 86.7% at L4 to 100% at S1. No clinically relevant medial pedicle cortex breaches (grades C–E) were observed, as 98.8% of screws were A graded and 1.2% B graded. For lateral placement, 94.1% were grade A and 4.5% grade B, with 1.4% clinically relevant breaches. Superior and inferior breaches were rare: 99.4% and 98.8% of screws were grade A, respectively, with the remainder grade B and no clinically relevant deviations. Overall, clinically acceptable placement (grades A–B) was achieved in nearly all screws across all directions (Table II). Due to the lack of variance in certain placement categories - specifically, several levels demonstrated zero events for grades C–E - Generalized Estimating Equation (GEE) models could not be computed to provide adjusted prevalence estimates.

Interobserver reliability

Cohen's kappa demonstrated moderate agreement for medial ($\kappa = 0.497$) and inferior breaches ($\kappa = 0.496$), fair agreement for lateral breaches ($\kappa = 0.378$), and poor agreement for superior breaches ($\kappa \approx 0$). However, Gwet's AC1 demonstrated near-perfect agreement across all directions (AC1 ranging from 0.953 to 0.994).

Multivariable regression and mixed-effects analysis

In the primary GEE analysis restricted to levels L2–L5 (due to skewness of the data), BMI was not significantly associated with screw placement accuracy. No

Table I.

Variable	Value
Patients (n)	100
Total screws (n)	511
BMI (mean $\pm$ SD)	28.6 $\pm$ 5.2
Surgeon distribution	
Surgeon 1	85 patients (447 screws)
Surgeon 2	10 patients (42 screws)
Surgeon 3	5 patients (22 screws)

Table II.

Spinal level	Screws (n)	Accuracy A–B (%)	Accuracy A (%)
T10	2	100	100
T11	3	100	100
T12	4	100	100
L1	10	100	100
L2	30	96.7	90.0
L3	72	98.6	93.1
L4	166	98.2	86.7
L5	160	98.8	93.1
S1	64	100	100
Accuracy A–B = Clinically acceptable placement (Gertzbein-Robbins). Accuracy A = Perfect placement (Gertzbein-Robbins).			

significant differences were observed between spinal levels for clinically acceptable placement (grades A–B). Concerning Grade A placement, a significant effect was observed for L5 compared to L4, indicating higher odds of perfect screw placement at L5. No other level-specific differences were identified. S1 could not be reliably included in this model due to complete separation, as all screws at this level were correctly placed.

In the GLMM analysis, BMI was not associated with screw placement accuracy in either outcome definition. For clinically acceptable placement, no significant differences between levels were observed. For the strict outcome (Grade A), screws at L5 had significantly higher odds of perfect placement compared to L4 (OR 2.47, 95% CI 1.05–5.80; $p = 0.037$) (Table III).

DISCUSSION

The present study demonstrates consistently high accuracy of robot-assisted screw placement across lumbar levels, with clinically acceptable placement (Grade A/B) exceeding 96% and perfect placement

(Grade A) exceeding 85% at all levels (ranging from T10–S1).

From a safety perspective, the results are particularly noteworthy. No clinically relevant medial, superior, or inferior breaches were observed. Given the proximity of critical neural structures in these directions, the absence of such violations demonstrates the excellent safety profile of the technique. The few deviations that did occur were predominantly minor (Gertzbein-Robbins grade B) and therefore clinically acceptable. Clinically relevant breaches were limited to the lateral direction (1.4%), which is generally considered of lower clinical concern and may reflect intentional in–out–in trajectories in the setting of narrow pedicles.

Furthermore, no significant association was observed between BMI and screw placement accuracy, suggesting that patient body habitus does not significantly influence technical performance in the context of robotic guidance. Similarly, no significant differences between spinal levels were identified when using clinically acceptable placement as the outcome, indicating uniform performance across levels. Under a stricter definition of accuracy (perfect/Grade A placement), screws at L5 showed significant higher

Table III.

Variable	Odds Ratio (OR)	95% CI	p-value
BMI	1.07	0.96 – 1.18	0.213
Surgeon			
Surgeon 2	0.48	0.11 – 2.12	0.335
Surgeon 3	0.36	0.05 – 2.74	0.325
Spinal level			
L2 vs L4	1.14	0.26 – 5.09	0.861
L3 vs L4	1.58	0.50 – 4.95	0.437
L5 vs L4	2.50	1.06 – 5.86	0.036*
Reference categories: surgeon 1 and L4 Model: GLMM with random intercept for patient Outcome: perfect screw placement (Gertzbein-Robbins grade A) *p < 0.05			

odds of optimal positioning compared to L4. This finding may be partially explained by the anatomical proximity of L5 to the pelvic reference frame used for robotic registration, potentially reducing spatial error propagation. In addition, the high proportion of screws placed at L4 and L5 in this cohort may accentuate small differences between adjacent levels while limiting meaningful comparisons with less represented levels, as no formal power calculation was performed. Given the overall high accuracy rates, the clinical relevance of this difference remains limited and should be interpreted with caution. Further studies are warranted to confirm this observation.

This study also reports on near-perfect AC1 values, therefore indicate very high interobserver agreement and supporting the reliability of the ratings. The discrepancy between Cohen's kappa and Gwet's AC1 is explained by the highly skewed distribution of ratings with predominant agreement. In this setting, kappa underestimates agreement, whereas AC1 provides a more robust estimate.

When contextualized within the existing literature, these findings compare favourably to previously reported results across different techniques. Freehand pedicle screw placement has consistently been associated with lower accuracy rates, with clinically acceptable placement typically ranging between 85% and 92% and clinically relevant breaches occurring in up to 10–15% of screws^{2–4,6}. Navigation-assisted techniques, including intraoperative CT- and fluoroscopy-based systems, improve accuracy to approximately 92–97%, but clinically relevant breaches remain present^{3,7–10}. Robot-assisted screw placement generally achieves the highest accuracy rates, with clinically acceptable placement reported between 95% and 99% and clinically relevant breaches in approximately 1–5% of screws^{8,11}. The

present study falls within the upper range of these outcomes and, notably, demonstrates a complete absence of clinically relevant medial breaches, which are of greatest clinical concern. This absence contrasts with prior studies reporting small but consistent rates of medial violations^{2–4,7,8,10,11} and may be explained by several factors. Methodological heterogeneity across studies—including differences in surgical technique (navigation versus robotics), robotic platforms and planning software may influence screw accuracy and trajectory. In addition, intraoperative imaging modalities vary (e.g., fluoroscopy, intraoperative CT, cone-beam CT), affecting both guidance precision and detection of cortical breaches. The present cohort is predominantly focused on the lower lumbar spine, where pedicle morphology is larger and potentially more forgiving, reducing the risk of medial wall violation compared to thoracic levels. Furthermore, the use of a cortical bone trajectory, characterized by a mediolateral and caudocephalad path, may inherently shift the risk profile away from medial violations. Finally, the relatively limited sample size and the high proportion of screws placed at L4–S1 may have contributed to the absence of observed medial breaches. These factors should be considered when interpreting the results, and direct comparisons with the literature should be made with caution.

We acknowledge that results of this single-centre retrospective cohort study may not be generalizable. A major limitation is that the highly skewed outcome distribution limited the ability to perform robust multivariable analyses. The near absence of adverse events resulted in highly imbalanced outcome distributions, which in turn led to separation and instability in regression models. As such, the ability to identify meaningful predictors of screw misplacement was limited. These challenges are inherent to studies

evaluating highly accurate surgical techniques and should be interpreted as a reflection of performance rather than a methodological shortcoming. Third and final, the unequal distribution of cases among surgeons may have reduced the ability to detect operator-dependent effects.

At the same time, it is essential to emphasize that robotic guidance should not replace fundamental surgical skills. Proficiency in freehand screw placement remains a critical competency for spine surgeons, particularly in situations where robotic systems are unavailable, malfunction, or cannot be used intraoperatively. Robotic assistance should therefore be regarded as an adjunct that enhances, rather than replaces, surgical expertise.

In conclusion, robot-assisted screw placement using a cortical bone trajectory demonstrates excellent accuracy and an outstanding safety profile, with results that are consistent with or superior to those reported in the literature. These findings support the continued integration of robotic technologies in spinal surgery.

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