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SURGERY

Comparison of Robotics and Navigation for Clinical Outcomes After Minimally Invasive Lumbar Fusion

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Study Design. Retrospective cohort.

Objective. To compare navigation and robotics in terms of clinical outcomes after minimally invasive transforaminal lumbar interbody fusion (MI-TLIF).

Summary of Background Data. Although robotics has been shown to have advantages like reduced radiation exposure, greater screw size, and slightly better accuracy over navigation, none of the studies has compared these two modalities in terms of clinical outcomes.

Methods. Patients who underwent single-level MI-TLIF using robotics or navigation and had a minimum of 1-year follow-up were included. The robotics and navigation groups were compared for improvement in patient-reported outcome measures (PROMs), minimal clinically important difference, patient-acceptable symptom state, response on the global rating change scale, and screw-related complication and reoperation rates.

Results. A total of 278 patients (143 robotics, 135 navigation) were included. There was no significant difference between the robotics and navigation groups in the baseline demographics, operative variables, and preoperative PROMs. Both groups showed significant improvement in PROMs at below six and six months or above, with no significant difference in the magnitude of improvement between the two groups. Most patients achieved minimal clinically important difference and patient-acceptable symptom state and reported feeling better on the global rating change scale, with no significant difference in the proportions between the robotics and navigation groups. The screw-related complication and reoperation rates also showed no significant difference between the two groups.

Conclusions. Robotics did not seem to lead to significantly better clinical outcomes compared with navigation following MI-TLIF. Although the clinical outcomes may be similar, robotics offers the advantages of reduced radiation exposure, greater screw size, and slightly better accuracy over navigation. These advantages should be considered when determining the utility and cost-effectiveness of robotics in spine surgery. Larger multicenter prospective studies are required in the future to further investigate this subject.

Key words: robotics, navigation, TLIF, minimally invasive, MIS, outcomes, clinical, difference

Level of Evidence: 3.

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Across all fields of surgical practice, there has been a significant shift toward the adaptation of new technologies in the operating room.[1] Spine surgery has followed suit with the evolution of navigation and robotics over the last two decades as new imaging and assistive modalities.[2–9] In comparing the two modalities for lumbar spine surgery, several studies have demonstrated the potential benefits of robotics over navigation. Robotic-assisted pedicle screws have been shown to have greater accuracy[10,11] and allow for greater screw diameter and length when compared with navigation, resulting in more optimal screw placement.[12] Robotics has additionally been shown to decrease intraoperative radiation exposure for both the patient and surgeon compared with navigation.[13] However, although robotics may have certain advantages over navigation, as previously described in the literature, no prior study has assessed any resultant difference in clinical outcomes between the two modalities.

The objective of this study was, therefore, to fill this gap in the literature by comparing robotics and navigation to identify any differences in patient-reported outcomes and reoperation rates after minimally invasive transforaminal lumbar interbody fusion (MI-TLIF).

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METHODS

Study Design and Patient Selection

This was a retrospective cohort study. After Institutional Review Board approval, patients who underwent single-level MI-TLIF (Qureshi-Louie class 2)[14] for degenerative lumbar spine conditions between April 2017 and January 2022 were included in the study. The data were derived from a single-center multisurgeon prospectively maintained database. All patients included had a minimum of one-year follow-up. Patients were split up into two cohorts based on the intraoperative modality: robotics (ExcelsiusGPS, Globus Medical Inc., Audubon, PA) and navigation (Stryker SpineMask, Stryker Corp., Kalamazoo, MI). The robotics and navigation workflows[12,13,15,16] and the MI-TLIF technique[17–22] were utilized, as previously described in the literature by our group.

Data Collection and Outcome Measures

Data were collected and managed using REDCap (Research Electronic Data Capture)[23,24] hosted at Weill Cornell Medicine Clinical and Translational Science Center supported by the National Center For Advancing Translational Science of the National Institute of Health under award number: UL1 TR002384. Following data were analyzed:

1. Preoperative: demographic information (age, sex, body mass index), age-adjusted Charlson Comorbidity Index, and patient-reported outcome measures (PROMs) [Visual Analog Scale (VAS) back and leg, Oswestry Disability Index (ODI), 12-Item Short Form Survey Physical Component Score (SF-12 PCS)].
2. Operative: modality of surgery (navigation, robot), primary/revision surgery, total operating room (OR) time (time from shift-in to shift out), estimated blood loss, postoperative length of stay.
3. Outcome measures: PROMs (ODI, VAS-back and leg, and SF-12 PCS), minimal clinically important difference (MCID), patient-acceptable symptom state (PASS), and global rating change (GRC).

TABLE 1. Comparison of the Robotics and Navigation Groups in Demographics and Operative Variables

	Robotics	Navigation	P
Age (in years)	60.5 ± 12.54	57.7 ± 13.66	0.076
Sex, n (%)	—	—	0.253
Female	68 (47.5)	55 (40.7)	—
Male	75 (52.5)	80 (59.3)	—
BMI (in kg/m^2)	28.52 ± 5.43	28.22 ± 6.45	0.674
Age-adjusted CCI	3.08 ± 1.05	3 ± 1.91	0.841
Type of surgery, n (%)	—	—	0.815
Primary	102 (71.3)	98 (72.6)	—
Revision	41 (28.7)	37 (27.4)	—
Total OR time (in min)	144.24 ± 27.62	139 ± 34.21	0.232
EBL (in mL)	67.53 ± 78.16	55.62 ± 74.32	0.195
Postoperative LOS (in hours)	26.72 ± 4.57	27.21 ± 6.32	0.456

BMI indicates body mass index; CCI, Charlson Comorbidity Index; EBL, estimated blood loss; LOS, length of stay; OR, operating room.

PROMs were collected at two weeks, six weeks, 12 weeks, six months, one year, and two years after the surgery. Two postoperative timepoints were defined, early (below six months) and late (six months or above). Three metrics for clinical improvement were utilized to analyze postoperative outcomes—MCID, PASS, and GRC. MCID achievement at less than six months and six months or above was assessed by analyzing the differences in preoperative postoperative PROM scores. The thresholds utilized for ODI, VAS-back, VAS-leg, and SF-12 PCS were 12.8, 1.2, 1.6, and 4.9, as previously described by Copay *et al.*[25] PASS achievement was defined as an absolute postoperative ODI score of <25.2 at six months or above postoperatively, as previously reported by Shahi *et al.*[26] Finally, patient improvement at less than six months and six months or above postoperatively was assessed via the responses on the GRC scale[27]: "Compared with preoperative, you feel (1) better, (2) same, or (3) worse?)".

Statistical Analysis

Changes between preoperative and postoperative PROMs were analyzed via paired *t* tests. Differences in PROMs and other similar continuous, nonpaired variables between the robotics and navigation groups were compared with independent Student's *t* tests. Categorical variables (MCID/PASS achievement rates, responses to GRC, complication-/reoperation rates) were compared between groups with χ^2 tests or Fisher exact tests when applicable. Statistical significance was taken at *P*-value ≤ 0.05. All analyses were performed using the IBM Statistical Package for the Social Sciences (SPSS) version 25 (IBM Corp., Armonk, NY).

RESULTS

Demographics and Operative Variables

A total of 278 patients were included. One hundred forty-three patients (51.4%) were in the robotics cohort, and 135 (48.6%) were in the navigation cohort. No significant differences were found between the two groups in age, sex, body mass index, ASA class, age-adjusted Charlson Comorbidity Index, primary/revision surgeries, total OR time, estimated blood loss, and postoperative length of stay (Table 1).

Patient-reported Outcome Measures

There was no significant difference between the robotics and navigation groups in the PROM scores at the preoperative and early and late postoperative timepoints. Both groups showed significant improvement in all PROMs at

TABLE 2. Comparison of PROMs Between the Robotics and Navigation Groups

		Robotics	Navigation	*P**
VAS-back	Preoperative	5.61 ± 2.69	5.62 ± 2.9	0.34
	< 6 mo	2.8 ± 2.33 (***P*** **< 0.001**)†	2.88 ± 2.48 (***P*** **< 0.001**)†	0.793
	≥ 6 mo	2.22 ± 2.12 (***P*** **= 0.01**)†	2.87 ± 2.83 (***P*** **< 0.001**)†	0.064
VAS-leg	Preoperative	5.78 ± 2.98	5.35 ± 3.31	0.41
	< 6 mo	2.57 ± 2.62 (***P*** **< 0.001**)†	2.23 ± 2.52 (***P*** **< 0.001**)†	0.297
	≥ 6 mo	2.18 ± 2.59 (***P*** **< 0.001**)†	2.01 ± 2.81 (***P*** **< 0.001**)†	0.666
ODI	Preoperative	40.24 ± 17.98	39.94 ± 18.03	0.94
	< 6 mo	24.62 ± 18.04 (***P*** **< 0.001**)†	27.47 ± 19.43 (***P*** **< 0.001**)†	0.234
	≥ 6 mo	17.47 ± 16.3 (***P*** **< 0.001**)†	20.48 ± 18.22 (***P*** **< 0.001**)†	0.21
SF-12 PCS	Preoperative	33.35 ± 8.61	31.75 ± 8.84	0.41
	< 6 mo	37.22 ± 9.73 (***P*** **< 0.001**)†	37.68 ± 10.11 (***P*** **< 0.001**)†	0.723
	≥ 6 mo	42.89 ± 11,29 (***P*** **< 0.001**)†	41.71 ± 11.56 (***P*** **< 0.001**)†	0.471

**represents P-value comparing the preoperative to the postoperative values.*

†represents P-value comparing the robotics and navigation groups, bold values represent a significant P-value.

ODI indicates Oswestry Disability Index; PROMs, patient-reported outcome measures; SF-12 PCS, 12-Item Short Form Survey Physical Component Score; VAS, Visual Analog Scale.

less than six months and six months or above compared with preoperative (Table 2). The change scores for PROMs (preoperative minus postoperative) also showed no significant difference between the groups at below six months and six months or above, signifying a similar magnitude of improvement (Table 3).

MCID/PASS Achievement Rates and Responses on GRC

No significant difference was found in the MCID achievement rates for PROMs between the robotics and navigation groups, with most patients achieving MCID at below six months (range 53%–67%) and 6 months or above (range: 57%–70%). PASS achievement rates at six months or above were also statistically similar for the two groups (robotics 73%, navigation 67%; $P = 0.282$). Responses on the GRC similarly showed no difference between the groups, with most patients reporting feeling "better" after surgery at less than six months (robotics 80%, navigation 69%; $P = 0.082$) and six months or above (robotics 86%, navigation 82%; $P = 0.725$). These findings are demonstrated in Table 4.

Screw-related Complications/Reoperation

Only one patient in the robotics cohort (versus 0 in navigation) returned to the OR for screw revision due to an

TABLE 3. Comparison of Magnitude of Improvement Between Robotics and Navigation Groups

		Robotics	Navigation	*P*
ΔVAS-back (mo)	< 6	−2.82 ± 3.05	−2.75 ± 3.35	0.86
	≥ 6	−3.14 ± 2.68	−2.33 ± 3.62	0.08
ΔVAS-leg (mo)	< 6	−3.08 ± 3.33	−3.21 ± 3.71	0.774
	≥ 6	−3.44 ± 3.41	−3.12 ± 4	0.55
ΔODI (mo)	< 6	−15.5 ± 18.51	−12.74 ± 20.41	0.283
	≥ 6	−18.67 ± 16.38	−17.4 ± 18.96	0.616
ΔSF-12 PCS (mo)	< 6	3.63 ± 10.91	6.25 ± 11.8	0.09
	≥ 6	8.44 ± 10.36	9.3 ± 12.91	0.62

Δrepresents change score (preoperative–postoperative).

ODI indicates Oswestry Disability Index; PROMs, patient-reported outcome measures; 12 PCS, 12-Item Short Form Survey Physical Component Score; VAS, Visual Analog Scale.

TABLE 4. Comparison of MCID/PASS Achievement Rates and Responses on the GRC Scale Between the Robotics and Navigation Groups

		Robotics (%)	Navigation (%)	P
<6 mo	MCID ODI	56.3	52.8	0.584
	MCID VAS-Back	66.6	65.6	0.863
	MCID VAS-Leg	62.7	60.1	0.688
	MCID SF-12 PCS	59.4	57.7	0.86
	GRC			
	Better	80	69.3	0.082
	Same	10.4	18.3	0.436
	Worse	9.6	12.4	0.581
≥6 mo	MCID ODI	65.5	62.1	0.619
	MCID VAS-Back	69.6	59	0.123
	MCID VAS-Leg	63.6	57.2	0.364
	MCID SF-12 PCS	62.1	66.3	0.55
	PASS	73.4%	66.6%	0.282
	GRC			
	Better	85.7	81.7	0.725
	Same	8.3	7.3	0.673
	Worse	6	11	0.44

GRC indicates global rating change; MCID, minimal clinically important difference; ODI, Oswestry Disability Index; PASS, patient-acceptable symptom state; SF-12 PCS, 12-Item Short Form Survey Physical Component Score; VAS, Visual Analog Scale.

inferior right L5 pedicle breach that led to postoperative neurological symptoms. Reoperation rates between the robotics and navigation groups were not statistically different, though the rate of reoperation was lower for the robotic group (5.5% *vs.* 10.3%; $P = 0.14$) (Table 5).

DISCUSSION

Spine surgery has seen the advent and evolution of navigation and robotics as intraoperative enabling technologies over the last two decades. Although a few comparative studies between navigation and robotics have been conducted, they have focused on differences in screw accuracy, screw size, radiation exposure, and time demand, and none have assessed the potential difference in eventual clinical outcomes.[10–13] The current study, therefore, attempted to compare these two modalities in terms of clinical outcomes after one-level MI-TLIF. The findings suggested that there were no significant differences between navigation and robotics in the improvement in PROMs, MCID/PASS achievement rates, responses on the GRC scale, and reoperation rates.

There is reasonable evidence in the spine literature that supports the proposed benefits of robotics. A recent systematic review conducted by McKenzie *et al*[28] included 34 articles and reported superior pedicle screw accuracy and less radiation exposure with robotics compared with freehand. Similarly, two other meta-analyses also demonstrated significantly better pedicle screw accuracy with robotic assistance compared with fluoroscopic guidance.[29,30] Bederman *et al*,[31] in their retrospective review of 36 patients undergoing revision spinal fusion under robotic guidance, found a high pedicle screw accuracy and suggested the potential benefit of robotics in navigating altered bony anatomy. Zhang *et al*[32] conducted a prospective cohort study of 100 patients undergoing pedicle screw placement and reported significantly less superior-level facet violations (5.8% *vs.* 27.3%) and larger screw-facet distance (4.16 *vs.* 1.92 mm) with robotics compared with fluoroscopic guidance. Recent meta-analyses also reported decreased proximal facet violation with robotic assistance compared with the freehand technique.[30,33]

In addition to the literature on the comparison of robotics with traditional fluoroscopy, a few recent studies have also compared it with navigation. Yu *et al*[10] conducted a study on 24 spine models and concluded that robotics was more accurate and efficient than navigation in screw placement. In their preliminary results of a randomized prospective study, Roser *et al*[11] also showed higher accuracy for robotic *versus* navigated pedicle screw placement (99 *vs.* 92%). Although it has not been shown to decrease dangerous breaches or screw-related complications compared with navigation, multicenter prospective studies are required to provide evidence concrete enough to make a definitive comment on this. Our group recently published two retrospective cohort studies on the comparison of navigation and robotics for lumbar spine surgery. The first study included 222 patients undergoing MI-TLIF and compared navigation and robotics in terms of pedicle screw accuracy, length, and diameter.[12] We found that robotics allowed for the placement of screws with greater diameter and length. This, in turn, may increase the stability of the construct and provide a more optimal biomechanical environment for successful fusion. The second study included 244 patients undergoing MI-TLIF and compared navigation and robotics in terms of intraoperative radiation exposure and time demand.[13] We found that radiation exposure was significantly reduced with robotics compared with navigation, and the total OR time had no significant difference between the two modalities. However, we did not analyze our patient population for the potential difference between robotics and navigation in the eventual clinical outcomes. The current study attempted to do so and found that the clinical outcomes at below six months and six months or above after MI-TLIF were similar for the two modalities. This shows that even though robotics in spine surgery may have the advantages of higher screw accuracy, greater screw size, and reduced intraoperative radiation exposure over navigation, it does not lead to a significant difference in patient-reported outcomes.

There are several limitations of this study. The retrospective design reduces the level of evidence. Data were

TABLE 5. Comparison of Robotics and Navigation Groups in Screw-related Complication and Reoperation Rates

	Robotics	Navigation	P
Return to OR for screw revision	1	0	—
Reoperation, n (%)	8 (5.5)	14 (10.3)	0.14
	5—pseudarthrosis	8—pseudarthrosis	—
	3—ASD	4—ASD	—
		2—cage migration	—

ASD indicates adjacent segment disease; OR, operating room.

collected at a single center, which limits the generalizability of the findings. Confounding variables may exist due to the multisurgeon nature of the database. The minimum follow-up in this study was one year (maximum two years), and studies with longer follow-ups are required to assess long-term outcomes and complications. Our outcome measures of MCID, PASS, and GRC are associated with a few drawbacks. MCID and PASS have been shown to be dependent on the preoperative baseline,[34] and GRC has been associated with recall bias.[35] Finally, we believe that spinal robotics is still evolving and advancing and, as such, continuous research is required to establish its full utility and potential.

In conclusion, robotics did not seem to lead to significantly better clinical outcomes compared with navigation after MI-TLIF. Although the clinical outcomes may be similar, robotics offers the advantages of reduced radiation exposure, greater screw size, and slightly better accuracy over navigation. These advantages should be considered when determining the utility and cost-effectiveness of robotics in spine surgery. Larger multicenter prospective studies are required in the future to further investigate this subject.

➢ Key Points

- ☐ This study compared navigation and robotics in terms of clinical outcomes after minimally invasive transforaminal lumbar interbody fusion (MI-TLIF).
- ☐ Robotics and navigation led to similar clinical outcomes following MI-TLIF.
- ☐ There were no significant differences between the two groups in the improvement in PROMs, MCID/PASS achievement rates, responses on GRC, and screw-related complication/reoperation rates.

References

1. Cook RI, Woods DD. Adapting to new technology in the operating room. *Hum Factors*. 1996;38:593–613.
2. Vaishnav AS, Othman YA, Virk SS, et al. Current state of minimally invasive spine surgery. *J Spine Surg*. 2019;5(suppl 1):S2–10.
3. Vaishnav AS, Gang CH, Qureshi SA. Time-demand, radiation exposure and outcomes of minimally invasive spine surgery with the use of skin-anchored intraoperative navigation: the effect of the learning curve. *Clin Spine Surg*. 2022;35:E111–20.
4. Alluri RK, Sivaganesan A, Vaishnav AS, et al. Surface navigation and the influence of navigation on MIS surgery. *Global Spine J*. 2022;12(2_suppl):19S–26S.
5. Weiner JA, McCarthy MH, Swiatek P, et al. Narrative review of intraoperative image guidance for transforaminal lumbar interbody fusion. *Ann Transl Med*. 2021;9:89.
6. Sivaganesan A, Kim C, Kiran Alluri R, et al. Advanced technologies for outpatient lumbar fusion: barriers and opportunities. *Int J Spine Surg*. 2022;16(S2):S37–43.
7. Sivaganesan A, Clark NJ, Alluri RK, et al. Robotics and spine surgery: lessons from the personal computer and industrial revolutions. *Int J Spine Surg*. 2021;15(s2):S21–27.
8. Avrumova F, Sivaganesan A, Alluri RK, et al. Workflow and efficiency of robotic-assisted navigation in spine surgery. *HSS J*. 2021;17:302–7.
9. Alluri RK, Avrumova F, Sivaganesan A, et al. Overview of robotic technology in spine surgery. *HSS J*. 2021;17:308–16.
10. Yu T, Jiao JH, Wang Y, et al. Robot-assisted versus navigation-assisted screw placement in spinal vertebrae. *Int Orthop*. 2023;47:527–32.
11. Roser F, Marcos Tatagiba GM. Spinal robotics: current applications and future perspectives. *Neurosurgery*. 2013;72(suppl1):12–8.
12. Shafi KA, Pompeu YA, Vaishnav AS, et al. Does robot-assisted navigation influence pedicle screw selection and accuracy in minimally invasive spine surgery? *Neurosurg Focus*. 2022;52:E4.
13. Shahi P, Vaishnav A, Araghi K, et al. Robotics reduces radiation exposure in minimally invasive lumbar fusion compared with navigation. *Spine (Phila Pa 1976)*. 2022;47:1279–86.
14. Louie PK, Vaishnav AS, Gang CH, et al. Development and initial internal validation of a novel classification system for perioperative expectations following minimally invasive degenerative lumbar spine surgery. *Clin Spine Surg*. 2021;34:E537–44.
15. Virk S, Qureshi S. Navigation in minimally invasive spine surgery. *J Spine Surg*. 2019;5(suppl 1):S25–30.
16. Sarmiento JM, Shahi P, Melissaridou D, et al. Step-by-step guide to robotic-guided minimally invasive transforaminal lumbar interbody fusion (MI-TLIF). *Ann Transl Med*. 2023;11:221.
17. Shinn D, Mok JK, Vaishnav AS, et al. Recovery kinetics after commonly performed minimally invasive spine surgery procedures. *Spine (Phila Pa 1976)*. 2022;47:1489–96.
18. Shahi P, Dalal S, Shinn D, et al. Improvement following minimally invasive transforaminal lumbar interbody fusion in patients aged 70 years or older compared with younger age groups. *Neurosurg Focus*. 2023;54:E4.
19. Shahi P, Vaishnav AS, Melissaridou D, et al. Factors causing delay in discharge in patients eligible for ambulatory lumbar fusion surgery. *Spine (Phila Pa 1976)*. 2022;47:1137–44.
20. Subramanian T, Araghi K, Sivaganesan A, et al. Ambulatory lumbar fusion: a systematic review of perioperative protocols, patient selection criteria, and outcomes. *Spine (Phila Pa 1976)*. 2023;48:278–87.
21. Subramanian T, Merrill RK, Shahi P, et al. Predictors of subsidence and its clinical impact following expandable cage insertion in minimally invasive transforaminal interbody fusion. *Spine (Phila Pa 1976)*. 2023. doi:10.1097/BRS.0000000000004619. Epub ahead of print. PMID: 36940252.

22. Wetmore DS, Dalal S, Shinn D, et al. Erector spinae plane block reduces immediate postoperative pain and opioid demand after minimally invasive transforaminal lumbar interbody fusion. *Spine (Phila Pa 1976)*. 2023. doi:10.1097/BRS.0000000000004581. Epub ahead of print. PMID: 36940258.
23. Harris PA, Taylor R, Thielke R, et al. Research electronic data capture (REDCap)—a metadata-driven methodology and workflow process for providing translational research informatics support. *J Biomed Inform*. 2009;42:377–81.
24. Harris PA, Taylor R, Minor BL, et al. REDCap Consortium. The REDCap consortium: building an international community of software partners. *J Biomed Inform*. 2019;95:103208.
25. Copay AG, Glassman SD, Subach BR, et al. Minimum clinically important difference in lumbar spine surgery patients: a choice of methods using the Oswestry Disability Index, Medical Outcomes Study questionnaire Short Form 36, and pain scales. *Spine J*. 2008;8:968–74.
26. Shahi P, Shinn D, Singh N, et al. ODI <25 Denotes patient acceptable symptom state after minimally invasive lumbar spine surgery. *Spine (Phila Pa 1976)*. 2023;48:196–202.
27. Shahi P, Vaishnav AS, Mai E, et al. Practical answers to frequently asked questions in minimally invasive lumbar spine surgery. *Spine J*. 2023;23:54–63.
28. McKenzie DM, Westrup AM, O'Neal CM, et al. Robotics in spine surgery: a systematic review. *J Clin Neurosci*. 2021;89:1–7.
29. Fan Y, Du JP, Liu JJ, et al. Accuracy of pedicle screw placement comparing robot-assisted technology and the free-hand with fluoroscopy-guided method in spine surgery: an updated meta-analysis. *Medicine*. 2018;97:e10970.
30. Li HM, Zhang RJ, Shen CL. Accuracy of pedicle screw placement and clinical outcomes of robot-assisted technique versus conventional freehand technique in spine surgery from nine randomized controlled trials: a meta-analysis. *Spine (Phila Pa 1976)*. 2020;45:E111–9.
31. Bederman SS, Jain N, Woolwine S, et al. Accuracy of pedicle screw placement in revision spine surgery using robotic guidance. *Global Spine J*. 2015;5(1_suppl):s-0035-1554210-s-0035-1554210.
32. Zhang Q, Xu YF, Tian W, et al. Comparison of superior-level facet joint violations between robot-assisted percutaneous pedicle screw placement and conventional open fluoroscopic-guided pedicle screw placement. *Orthop Surg*. 2019;11:850–6.
33. Zhou LP, Zhang RJ, Li HM, et al. Comparison of cranial facet joint violation rate and four other clinical indexes between robot assisted and freehand pedicle screw placement in spine surgery: a metaanalysis. *Spine (Phila Pa 1976)*. 2020;45:E1532–40.
34. Shahi P, Subramanian T, Singh N, et al. NDI <21 denotes patient acceptable symptom state after degenerative cervical spine surgery. *Spine (Phila Pa 1976)*. 2023;48:766–1.
35. Kamper SJ, Maher CG, Mackay G. Global rating of change scales: a review of strengths and weaknesses and considerations for design. *J Man Manip Ther*. 2009;17:163–70.