

Ball-Tipped Probe Type Demonstrates Variation in Detecting Pedicle Screw Tract Breaches by Trainees in Lumbar Spine Model

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Abstract

Introduction: There is a lack of research investigating the variance and accuracy of different pedicle probe designs for detecting pedicle tract breaches. This study aims to assess the accuracy of three different ball-tip probes in detecting pedicle breaches in a lumbar spine model as assessed by orthopaedic surgery trainees

Methods: Pedicle tracts were created bilaterally in six lumbar Sawbones models using a 2mm drill bit. L1-L5 pedicles were randomized to no breach, superior, inferior, medial, or lateral breaches. Breach presence and location were assessed using one of three ball-tip probes with varying head diameter and shaft flexibility. Residency year, spine case logs and probe preference were recorded. Probe accuracy; level of agreement between participants by specific probe; and correlation between accuracy, case volume, and residency year were assessed.

Results: For all probes, breach detection was 80.5%, and location accuracy was 64.1%. There was no difference in breach detection between different probes. Probe B was significantly more accurate (68.8%) than probes A or C (63.3% ; 60.3%; $p=0.02$) in identifying breach locations. Inter-rater reliability was highest for Probe C regarding breach presence and location ($k=0.24$ and 0.21 , respectively; fair) relative to probes A or B. Spine case logs were not correlated with the ability to identify a breach or its location. Residency year was positively correlated with identifying breach location ($r=0.47$, $p=0.04$).

Conclusion: All probes demonstrated high accuracy in breach detection, yet detecting breach location and inter-rater reliability varied between probe designs. Probe design preference did not correlate with accuracy.

Keywords: Orthopaedic surgery resident education; Ball-tip probe; Breach accuracy; Spine surgery

Introduction

Accurate and reliable pedicle screw placement is essential for the safety and success of instrumented lumbar spinal fusion procedures.¹ Despite technological advances, pedicle violation in the lumbar spine is not uncommon and varies widely in the literature, from 1% to 29%.²⁻⁵ Often, numerous surgical factors contribute to these complications, such as multi-dimensional spinal deformities and complex anatomy as seen with idiopathic or degenerative scoliosis.⁶ Having access to reliable and reproducible intraoperative modes of feedback in the operating room is essential to ensure accurate pedicle screw placement and to prevent the potential complications of pedicle breaches. Failure to identify a pedicle violation can result in serious risks to critical neurovascular structures and the potential for postoperative neurologic deficits.⁷⁻⁹

A variety of technologies have been developed to ensure accurate pedicle screw placement, including pedicle probes or “feelers”, pedicle screw stimulators, computer-assisted navigation, and even robot-assisted pedicle screw placement.¹⁰⁻¹² The use of pedicle probes to feel for breaches prior to screw insertion remains a critical skill in spine surgery.^{13,14} Regardless of technological advancements, pedicle probes are often the last line of defense to detect a breach and prevent improper positioning of pedicle screws. Pedicle probes provide a simple means to assess for pedicle violation, despite some literature challenging the overall reliability of using pedicle probes as the sole means for evaluating pedicle integrity.¹⁵

Spine surgery is a complex and technically demanding field. During training, orthopaedic surgery residents often have limited opportunity to develop the necessary surgical skills and competencies to become proficient with spinal instrumentation. Optimal use of a pedicle ball-tip probe can help developing surgeons acquire the manual dexterity and spatial awareness necessary for the successful and safe instrumented spinal fusion procedures. With regards to resident education, the use of bioskills training with pedicle breach uses can be a valuable learning experience.¹⁶ This may include simulation-based training, cadaveric training, and supervised use in live surgical settings. There is a paucity of literature evaluating different pedicle probe designs and overall accuracy in detecting pedicle breaches. The purpose of this study is to compare the accuracy of commonly used ball-tip probes in the detection of pedicle breaches in a lumbar spine model by a cohort of orthopaedic surgery residents.

Materials & Methods

Lumbar spine Sawbones (Pacific Research Company, Vashon, WA) models with normal L1-sacrum anatomy were acquired. Pedicle screw tracts were created bilaterally in all models from L1-L5. A random number generator was used to assign each pedicle to one of five possible pedicle tracts: no violation, superior breach, inferior breach, medial breach, or lateral breach (Figure 1). The breaches were made using a 2-mm drill bit at the appropriate start point using landmarks for pedicle screws but headed in an aberrant trajectory to simulate a Lenke probe breach.

A total of six L1-sacrum sawbones with lumbar spine holders were used and set up for three stations. Three pedicle feelers (marked as probe A, B, or C) with different shaft flexibility and different size ball tip probe heads were assigned to each station. A digital fractional caliper was utilized to measure the ball-tip probe head diameter. The caliper was accurate to ± 0.03 mm. Probe A had the stiffest shaft, greatest diameter head (1.98 mm), shortest length, and thickest handle. Probe tip B had a medium flexibility shaft, medium sized head (1.95 mm) and notched handle. Probe tip C had the most flexible shaft, smallest head diameter (1.94 mm) and a short, notched handle. (Figure 2).

Probe A was used to feel 20 pedicles for lumbar spine models A1 and A2, probe B for lumbar spine models B1 and B2, and probe C for lumbar spine models C1 and C2. Residents had ten minutes to complete the two lumbar spine models at each station. The total time to complete all six models using all three probes (60 pedicles) was capped at thirty minutes (Figure 3). The participants were blinded to the breach location using cotton around the lumbar spines (Figure 1). This ensured that residents could only rely on tactile feel to determine the presence and location of a breach if present. Participants were asked to rank the probes in order of their preference.



Figure 1. Representative lumbar sawbones model for pedicle ball-tip probe bioskills model. Cotton was utilized to blind participants against the presence and directionality of any breach.

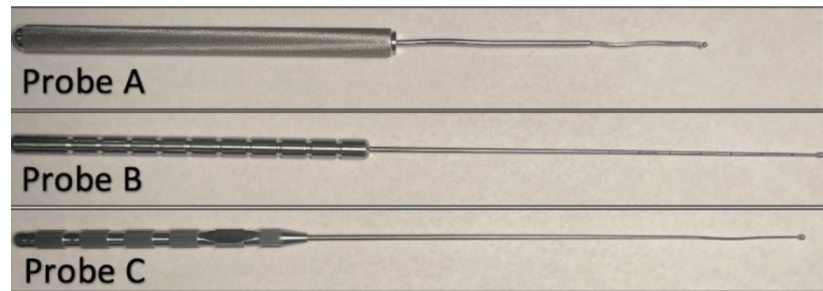


Figure 2. Probe A had the stiffest shaft, greatest diameter head, shortest length, and thickest handle. Probe tip B had a medium flexibility shaft, medium sized head, and notched handle. Probe tip C had the most flexible shaft, smallest head diameter and shortest, notched handle.



Figure 3. Residents completing each respective bioskills station.

The post-graduate year (PGY) and the total number of spine procedures performed prior to the date of the test were recorded for each participant. PGY2 to PGY5 residents participated, all of whom had prior rotations on the spine service and had used ball tip probes intraoperatively. Participants were asked to 1) identify if a breach was present and 2) identify the location of the breach, if present. The accuracy of each participant was determined by dividing the number of correct responses by the total number of questions.

Chi squared tests were utilized to assess for statistically significant differences in accuracy between the different probe types. A Fleiss Kappa statistic was calculated to determine the level of agreement between participants for each probe type used ($0.6 \leq k < 0.8$, moderate; $0.4 \leq k < 0.6$, fair; $k < 0.4$, poor). Additionally, a Pearson correlation coefficient was calculated to assess for a correlation between accuracy and case volume as well as accuracy and year in residency. A p-value of <0.05 was considered statistically significant.

Institutional Review Board (IRB) review was not applicable due to the nature of this study. The study did not involve any interaction, intervention, or access to identifiable information about individuals.

Results

A total of 20 residents participated in the study. There were 10 junior residents (PGY2-3) and 10 senior residents (PGY4-5). The overall accuracy of the group in identifying whether a breach was present was 80.5%, however the overall inter-rater reliability was poor ($k=0.17$).

There was no statistically significant difference in accuracy based on probe type in determining if a breach was present. Probe C was the most reliable probe ($k=0.24$, fair vs. $k<0.2$, poor for probes A and B) (Table 1).

Regarding accuracy in identifying the location of a breach, the overall accuracy of the group was 64.1% with all probes. The overall inter-rater reliability was poor ($k=0.19$). Probe B was significantly more accurate than probes A or C, respectively (68.8% vs. 63.3% and 60.3%, $p=0.02$). Probe C was once again the most reliable probe ($k=0.21$, fair vs. poor for probes A and B) (Table 2.)

The number of spine cases performed was not significantly correlated with the accuracy of identifying a breach ($r=0.016$, $p=0.95$) nor the location of a breach ($r=0.14$, $p=0.56$). Year in residency was significantly correlated with identifying the breach location ($r=0.47$, $p=0.04$) but not with identifying a breach. When surveyed, the order of probe preference was Probe C, followed by Probe B, then Probe A (Table 3.)

Table 1. Detecting presence of a pedicle breach (Fleiss Kappa score).

	Accuracy		Agreement	
All	80.50%	P = 0.65 (Chi Square)	0.17	poor
A	82.00%		0.14	poor
B	79.80%		0.12	poor
C	79.80%		0.24	fair

Table 2. Detecting location of a pedicle breach (Fleiss Kappa score).

	Accuracy		Agreement	
All	64.10%	P = 0.65 (Chi Square)	0.19	poor
A	63.30%		0.17	poor
B	68.80%		0.19	poor
C	60.30%		0.21	fair

Table 3. Pearson's r.

	r	P Value
Spine Cases and Accuracy of Breach Location	0.14	0.56
Spine Cases and Identify Breach	0.016	0.95
PGY Year and Accuracy of Breach Location	0.47	0.04
PGY Year and Identify Breach	0.43	0.06

Discussion

Pedicle screw insertion is an essential skill for orthopaedic surgery trainees to safely perform spinal fusion procedures. The rate of pedicle breaches in lumbar spine procedures varies widely in the literature²⁻⁵ and prior studies have suggested association with a variety of factors including surgeon experience¹⁸, rotational scoliotic deformities^{19,20}, and the use of free-hand versus computer-assisted navigational systems.^{21,22} The complications of improper pedicle screw placement vary widely, from inconsequential to spinal cord or nerve root injuries resulting in neurologic deficits.^{7-9,17,23} The purpose of this study is to compare the accuracy or reliability of three commonly used ball-tip probes in identifying and characterizing pedicle breaches in a sawbones lumbar spine model.¹⁶ Furthermore, the study aims to elucidate whether probe preference, number of spine cases logged and year in residency were associated with the accuracy of identifying and categorizing pedicle breaches.

Our findings suggest that pedicle probe design and post-graduate year of residency training were both associated with overall accuracy of the detection and categorization of pedicle tract breaches using a standardized sawbones model of the lumbar spine. Specifically, probe B (medium flexible shaft, medium diameter head) was most accurate in determining the location of a breach (e.g. superior, inferior, medial, lateral). Subjective preference for either probe and the volume of logged spine cases was not associated with accuracy in determining the presence or location of a breach. The respective year in residency was associated with localizing a breach and nearly associated with identifying a presence of a breach. Inter-rater reliability varied significantly between the different probes used in this study.

Prior literature has shown that accuracy of pedicle breach detection with manual probing can vary depending on several factors, including the level of the spinal column, directionality of the breach, size of the breach, the probe's size, the probe tip's shape, and the surgeon's experience.^{15,29-34} Much of the literature regarding the accuracy of manual pedicle probing has specifically investigated the thoracic spine.^{15,29-31} The flexible shaft of the ball-tip probe provides an advantage by allowing the probe to deflect from cortical bone, particularly the medial cortical bone of the pedicle.²⁹ However, there is limited research investigating how the shape, size, and flexibility of these probes impact breach detection. Probes with a large diameter provide a larger surface area for detecting breaches. However, pedicle probes with a sharper or more tapered tip could theoretically be more effective at detecting minor breaches. The flexibility or angle of the probe's shaft can also theoretically impact the effectiveness of detecting pedicle breaches at different trajectories (e.g. medial versus lateral breach, superior or inferior breach). For example, a curved probe may be advantageous for pedicle screw insertion in the subaxial cervical spine where a more medial trajectory can minimize vertebral artery injury.³²

Our findings suggest that the probe with the medium diameter head and flexible shaft was more accurate in determining the direction of the breach, perhaps because the flexible shaft and diameter were optimal for maneuvering in the bony pedicle space and assessing directionality. Additionally, the probe's diameter was potentially optimal to detect the 2 mm breach, because the probe head was able to easily enter the breach site, but also large enough to have adequate surface contact within the breach site to provide robust tactile feedback to the user. Another factor to consider is the directionality of the breach. Prior literature has suggested that lateral breaches are often detected less than medial breaches in cadaveric models.³⁴ However, our data did not specifically confirm this previously described finding.

Another critical factor in breach detection is surgeon experience. Surgeons with less experience may be less effective at using pedicle probes, which can lead to missed breaches.³¹ Our findings suggested that even on a residency level, senior residents seemed to have improved accuracy of detecting pedicle breaches relative to junior residents, further corroborating prior literature. However, there was not a significant correlation between the total number of spine cases logged and overall detection of pedicle breaches in our cohort. This may be due to variability in the type of spine cases logged or possibly the level of participation by each individual resident in the respective cases – although these two variables were not readily accessible for analysis.

Our analysis essentially indicates that the probe with medium shaft flexibility and medium head size is the most sensitive for pinpointing the location of a breach. The feedback provided by this combination allows the user to accurately identify the breach site. In contrast, the probe with the largest ball tip diameter and the least flexible shaft was found to be the most accurate in determining the presence of a breach. This suggests that for larger breaches, the stiffness of the shaft and the size of the head make the detection more apparent to the user. Therefore, we recommend that more experienced users (higher PGY year) would benefit most from using the medium shaft and flexible head probe for precise breach location. This is supported by the data in Table 3. Conversely, less experienced users (lower PGY training) might find a probe with a thicker shaft and larger head more beneficial, as they may not yet be adept at detecting the subtle feedback provided by a more sensitive probe.

Several inherent limitations exist with regards to this cohort and study design. The most obvious limitation is that the Sawbones model only partially replicates the intraoperative environment of a pedicle breach. Different patient factors, such as bone quality, can significantly affect the ability to recognize an intraoperative breach with different probes. The standardized Sawbones model used here provided a consistent, durable tactile feel that may overestimate a resident's ability to recognize an intraoperative breach. Another limitation and potential confounding variable is the type of spine cases performed by each resident. We attempted to control for each resident's prior spine surgery experience by accounting for the total number of prior spine cases logged. However, the type of cases and participation level were not identified. For example, minimally invasive fusions often use intraoperative navigation or fluoroscopy to safely place pedicle screws, potentially bypassing the use of a pedicle feeler. Therefore, residents who had a higher minimally invasive case load may have had lower exposure to pedicle probes. Another limitation is the lack of a comparative arm, such as a fellowship-trained spine surgeon.

The breach was created using a 2mm drill to ensure its precise location by the test administrators for the sawbone model pedicle breach evaluation. However, this method presents a limitation, as breaches are more likely to occur during Lenke probe insertion or after the tract is tapped, the latter of which would involve cortical tract ridges. Therefore, this sawbone model study does not exactly replicate an intra-operative pedicle breach. Nonetheless, the authors believe that the study demonstrates that the differing pedicle probes provide varying levels of feedback when breaches are present. Understanding this feedback can potentially correlate with what occurs intra-operatively.

Despite these limitations, this study provides a framework and initial investigation of the influence of pedicle probe design and surgeon experience on the manual detection of pedicle breaches.

Conclusion

Pedicle probe design and post-graduate year of residency training were associated with overall accuracy of determining the location of pedicle tract breaches using a standardized Sawbones model of the lumbar spine. The pedicle probe with the largest ball tip diameter and least flexible shaft was the most accurate in determining the presence of breach. The pedicle probe with medium shaft flexibility and medium head size was the most accurate in determining the exact location of a pedicle breach. Inter-rater reliability varied significantly between the different probes used. Interestingly, subjective probe preference had no association with overall accuracy in the detection of a pedicle breach or the exact location of the breach. This study demonstrates that pedicle probe designs may correlate with overall accuracy in the detection of pedicle breach location. Furthermore, it provides a standardized bioskills model that can be utilized for further investigation of resident education and skills training in lumbar spinal fusion procedures.

Ethics Approval

Formal ethics approval was not required given the research involved educational exercises for teaching or training purposes.

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Conflict of Interest Statement

The authors report no competing financial interests that influenced this work.

References

1. Schatlo B, Molliqaj G, Cuvinciuc V, et al. Safety and accuracy of robot-assisted versus fluoroscopy-guided pedicle screw insertion for degenerative diseases of the lumbar spine: a matched cohort comparison. *Journal of Neurosurgery: Spine*. 2014;20(6):636-643.
2. Smith ZA, Sugimoto K, Lawton CD, Fessler RG. Incidence of lumbar spine pedicle breach after percutaneous screw fixation: a radiographic evaluation of 601 screws in 151 patients. *Clinical Spine Surgery*. 2014;27(7):358-363.
3. Parker SL, McGirt MJ, Farber SH, et al. Accuracy of free-hand pedicle screws in the thoracic and lumbar spine: analysis of 6816 consecutive screws. *Neurosurgery*. 2011;68(1):170-178.
4. Wiesner L, Kothe R, Rütther W. Anatomic evaluation of two different techniques for the percutaneous insertion of pedicle screws in the lumbar spine. *Spine*. 1999;24(15):1599.
5. Castro WH, Halm H, Jerosch J, et al. Accuracy of pedicle screw placement in lumbar vertebrae. *Spine*. 1996;21(11):1320-1324.
6. Kim YJ, Lenke LG, Cheh G, Riew KD. Evaluation of pedicle screw placement in the deformed spine using intraoperative plain radiographs: a comparison with computerized tomography. *Spine*. 2005;30(18):2084-2088.
7. Lonstein JE, Denis F, Perra JH, et al. Complications associated with pedicle screws. *JBJS*. 1999;81(11):1519-28.
8. Grauer JN, Vaccaro AR, Brusovanik G, et al. Evaluation of a novel pedicle probe for the placement of thoracic and lumbosacral pedicle screws. *Clinical Spine Surgery*. 2004;17(6):492-497.
9. Amiot L-P, Lang K, Putzier M, et al. Comparative results between conventional and computer-assisted pedicle screw installation in the thoracic, lumbar, and sacral spine. *Spine*. 2000;25(5):606-614.
10. Baaj AA, Beckman J, Smith DA. O-Arm-based image guidance in minimally invasive spine surgery. *Clinical neurology and neurosurgery*. 2013;115(3):342-345.
11. Moses ZB, Mayer RR, Strickland BA, et al. Neuronavigation in minimally invasive spine surgery. *Neurosurgical focus*. 2013;35(2):E12.
12. Staub BN, Sadrameli SS. The use of robotics in minimally invasive spine surgery. *Journal of Spine Surgery*. 2019;5(Suppl 1):S31.
13. Boachie-Adjei O, Girardi FP, Bansal M, Rawlins BA. Safety and efficacy of pedicle screw placement for adult spinal deformity with a pedicle-probing conventional anatomic technique. *Clinical Spine Surgery*. 2000;13(6):496-500.

14. Karapinar L, Erel N, Ozturk H, et al. Pedicle screw placement with a free hand technique in thoracolumbar spine: is it safe? *Clinical Spine Surgery*. 2008;21(1):63-67.
15. Sedory DM, Crawford JJ, Topp RF. The reliability of the ball-tipped probe for detecting pedicle screw tract violations prior to instrumenting the thoracic and lumbar spine. *Spine*. 2011;36(6):E447-E453.
16. Boody BS, Hashmi SZ, Rosenthal BD, et al. The effectiveness of bioskills training for simulated lumbar pedicle screw placement. *Global Spine Journal*. 2018;8(6):557-562.
17. Raley DA, Mobbs RJ. Retrospective computed tomography scan analysis of percutaneously inserted pedicle screws for posterior transpedicular stabilization of the thoracic and lumbar spine: accuracy and complication rates. *Spine*. 2012;37(12):1092-1100.
18. Samdani AF, Ranade A, Sciubba DM, et al. Accuracy of free-hand placement of thoracic pedicle screws in adolescent idiopathic scoliosis: how much of a difference does surgeon experience make? *European spine journal*. 2010;19:91-95.
19. Putzier M, Strube P, Cecchinato R, et al. A new navigational tool for pedicle screw placement in patients with severe scoliosis. *Clinical spine surgery*. 2017;30(4):E430-E439.
20. Cuartas E, Rasouli A, O'Brien M, Shufflebarger HL. Use of all-pedicle-screw constructs in the treatment of adolescent idiopathic scoliosis. *JAAOS-Journal of the American Academy of Orthopaedic Surgeons*. 2009;17(9):550-561.
21. Kamimura M, Ebara S, Itoh H, et al. Accurate pedicle screw insertion under the control of a computer-assisted image guiding system: laboratory test and clinical study. *Journal of orthopaedic science*. 1999;4:197-206.
22. Shin BJ, James AR, Njoku IU, Härtl R. Pedicle screw navigation: a systematic review and meta-analysis of perforation risk for computer-navigated versus freehand insertion: a review. *Journal of Neurosurgery: Spine*. 2012;17(2):113-122.
23. Kwan MK, Chiu CK, Abd Gani SM, Wei CCY. Accuracy and safety of pedicle screw placement in adolescent idiopathic scoliosis patients: a review of 2020 screws using computed tomography assessment. *Spine*. 2017;42(5):326-335.
24. Yingsakmonkol W, Karaikovic E, Gaines RW. The accuracy of pedicle screw placement in the thoracic spine using the "Funnel Technique": part 1. A cadaveric study. *Clinical Spine Surgery*. 2002;15(6):445-449.
25. Isley MR, Pearlman RC, Wadsworth JS. Recent advances in intraoperative neuromonitoring of spinal cord function: pedicle screw stimulation techniques. *American journal of electroneurodiagnostic technology*. 1997;37(2):93-126.
26. Zhou L-P, Zhang R-J, Sun Y-W, et al. Accuracy of pedicle screw placement and four other clinical outcomes of robotic guidance technique versus computer-assisted navigation in thoracolumbar surgery: a meta-analysis. *World Neurosurgery*. 2021;146:e139-e150.
27. Móra K, Ferencz A, Haidegger T. What Is Next in Computer-Assisted Spine Surgery? Advances in Image-Guided Robotics and Extended Reality. *Robotics*. 2022;12(1):1.
28. Fatima N, Massaad E, Hadzipasic M, et al. Safety and accuracy of robot-assisted placement of pedicle screws compared to conventional free-hand technique: a systematic review and meta-analysis. *The Spine Journal*. 2021;21(2):181-192.
29. Watanabe K, Matsumoto M, Tsuji T, et al. Ball tip technique for thoracic pedicle screw placement in patients with adolescent idiopathic scoliosis. *Journal of Neurosurgery: Spine*. 2010;13(2):246-252.
30. Donohue ML, Moquin RR, Singla A, Calancie B. Is in vivo manual palpation for thoracic pedicle screw instrumentation reliable? *Journal of Neurosurgery: Spine*. 2014;20(5):492-496.

31. Lehman RA, Potter BK, Kuklo TR, et al. Probing for thoracic pedicle screw tract violation (s): is it valid? *Clinical Spine Surgery*. 2004;17(4):277-283.
32. Lee S, Seo J, Lee MK, et al. Widening of the safe trajectory range during subaxial cervical pedicle screw placement: advantages of a curved pedicle probe and laterally located starting point without creating a funnel-shaped hole. *Journal of Neurosurgery: Spine*. 2017;27(2):150-157.
33. Park JH, Jeon SR, Roh SW, et al. The safety and accuracy of freehand pedicle screw placement in the subaxial cervical spine: a series of 45 consecutive patients. *Spine*. 2014;39(4):280-285.
34. Guillen PT, Knopper RG, Kroger J, et al. Independent assessment of a new pedicle probe and its ability to detect pedicle breach: a cadaveric study. *Journal of Neurosurgery: Spine*. 2014;21(5):821-825.
35. Hagan MJ, Syed S, Leary OP, et al. Pedicle screw placement using intraoperative computed tomography and computer-aided spinal navigation improves screw accuracy and avoids postoperative revisions: single-center analysis of 1400 pedicle screws. *World Neurosurgery*. 2022;160:e169-e179.
36. Ganguly R, Minnema A, Singh V, Grossbach A. Retrospective analysis of pedicle screw accuracy for patients undergoing spinal surgery assisted by intraoperative computed tomography (CT) scanner AIRO® and BrainLab® navigation. *Clinical Neurology and Neurosurgery*. 2020;198:106113.
37. Motiei-Langroudi R, Sadeghian H. Assessment of pedicle screw placement accuracy in thoracolumbosacral spine using freehand technique aided by lateral fluoroscopy: results of postoperative computed tomography in 114 patients. *The Spine Journal*. 2015;15(4):700-704.
38. Park HJ, Wang C, Choi KH, Kim HN. Use of a life-size three-dimensional-printed spine model for pedicle screw instrumentation training. *Journal of Orthopaedic Surgery and Research*. 2018;13(1):1-8.
39. Tanner G, Vojdani S, Komatsu DE, Barsi JM. Development of a Saw Bones Model for training pedicle screw placement in scoliosis. *BMC Research Notes*. 2017;10(1):1-5.
40. Lopez G, Wright R, Martin D, et al. A cost-effective junior resident training and assessment simulator for orthopaedic surgical skills via fundamentals of orthopaedic surgery: AAOS exhibit selection. *JBJS*. 2015;97(8):659-666.
41. Jones DB, Sung R, Weinberg C, et al. Three-dimensional modeling may improve surgical education and clinical practice. *Surgical innovation*. 2016;23(2):189-195.
42. Gardeck AM, Pu X, Yang Q, et al. The effect of simulation training on resident proficiency in thoracolumbar pedicle screw placement using computer-assisted navigation. *Journal of Neurosurgery: Spine*. 2020;34(1):127-134.
43. Boody BS, Rosenthal BD, Jenkins TJ, et al. The effectiveness of bioskills training for simulated open lumbar laminectomy. *Global spine journal*. 2017;7(8):794-800.

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