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EXPERIMENTAL LAB RESEARCH

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Accuracy of pin placement in the canine thoracolumbar spine using a free-hand probing technique versus 3D-printed patient-specific drill guides: An ex-vivo study

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Abstract

Objective: To compare pin placement accuracy, intraoperative technique deviations, and duration of pin placement for pins placed by free-hand probing (FHP) or 3D-printed drill guide (3DPG) technique.

Sample population: Four greyhound cadavers.

Methods: Computed tomography (CT) examinations from T6-sacrum were obtained for determination of optimal pin placement and 3DPG creation. Two 3.2/2.4-mm positive profile pins were inserted per vertebra, one left and one right from T7–L7 (FHP [$n = 56$]; 3DPG [$n = 56$]) by one surgeon and removed for repeat CT. Duration of pin placement and intraoperative deviations (unanticipated deviations from planned technique) were recorded. Pin tracts were graded by two blinded observers using modified Zdichavsky classification. Descriptive statistics were used.

Results: A total of 54/56 pins placed with 3DPGs were assigned grade I (optimal placement) compared with 49/56 pins using the FHP technique. A total of 2/56 pins placed with 3DPGs and 3/56 pins using the FHP technique were assigned grade IIa (partial medial violation). A total of 4/56 pins placed using the FHP technique were assigned grade IIIa (partial lateral violation). No pins were assigned grade IIb (full medial violation). Intraoperative technique deviations occurred with 6/56 pins placed using the FHP technique and no pins with 3DPGs. Overall, pins were placed faster (mean ± SD 2.6 [1.3] vs. 4.5 [1.8] min) with 3DPGs.

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Conclusions: Both techniques were accurate for placement of spinal fixation pins. The 3DPG technique may decrease intraoperative deviations and duration of pin placement.

Clinical relevance: Both techniques allow accurate pin placement in the canine thoracolumbar spine. The FHP technique requires specific training and has learning curve, whereas 3DPG technique requires specific software and 3D printers.

1 | INTRODUCTION

Vertebral fractures and luxations represent an important cause of spinal cord injury in dogs.[1–11] The goal of surgery is to achieve rigid fixation while avoiding injury to surrounding neurologic, visceral and vascular structures.[6] Spinal stabilization is technically challenging and associated with risk of vertebral canal violation.[7,12] Use of pins and polymethylmethacrylate (PMMA) offers a strong and versatile method of spinal stabilization.[13] A variety of options exist for insertion of pins or screws in the canine spine, including a free-hand technique based on preoperatively calculated pin entry points and angles,[14] a pedicle-probing technique,[5,6] use of patient-specific 3D-printed drill guides (3DPGs),[7,15–20] and fluoroscopic-guided.[1,21] In people, robotic and image-guided spine surgery allow real-time intraoperative navigation, and are associated with reduced radiation exposure, increased accuracy and safety of implantation, and reduced surgical time; however, there are no clinical reports of use of this technology in veterinary spine surgery.[22]

Investigators have investigated safe corridors for instrumentation of the canine thoracolumbar spine.[23] Fluoroscopic-guided pin placement has been described in a canine ex-vivo study[21] and a small retrospective case series[1]; however, this technique may be associated with greater radiation exposure for the surgeon and patient.[24] A pedicle-probing technique has been described for pedicle screw placement in people and in dogs.[5,6,25] It involves creation of a cortical defect (decortication) at the pedicle screw/pin entry site, probing of cancellous bone of the pedicle to establish a safe trajectory before drilling the pilot hole for the definitive screw/pin.[5,6] Recently, use of 3DPGs has become increasingly popular in veterinary spine surgery.[7,15–18,20,26] This technique is appealing due to the technical challenge associated with spinal instrumentation and the high degree of accuracy required for safe implant placement. Use of 3DPGs has been described for the cervical, thoracic and lumbosacral spine in dogs and is associated with a very high degree of accuracy.[7,15–18,20,26] However, spinal fractures need to be treated without delay, and the hardware and software required to produce these guides are not universally available. Expertise is also required in computer-assisted design (CAD) software and 3D printers may be expensive. Given the variety of techniques for pin placement, more research is needed to compare accuracy between techniques and guide clinical decision making.

Study objectives were to compare a free-hand probing technique (FHP) versus use of 3DPGs for pin placement in the canine thoracolumbar spine. We evaluated accuracy, rate of intraoperative technique deviations, and duration of pin placement in a cadaveric model. We hypothesized that the 3DPG technique would be associated with greater accuracy, a lower rate of intraoperative technique deviations, and decreased duration of pin placement compared with the FHP technique.

2 | METHODS

2.1 | Sample population

Four skeletally mature greyhound cadavers euthanized for reasons unrelated to this study were included. Ethical approval was granted by the primary author's institution (AREC-E-20-11-Mullins). Cadavers were numbered and stored at −20°C until thawed for use.

2.2 | Preinstrumentation computed tomography

A 16-slice helical computed tomography (CT) scanner (SOMATOM Scope, Siemens, Germany) was used. All scans were obtained at the primary author's institution. Transverse sections (0.75-mm thickness) were obtained from T6 to sacrum. DICOM images were exported into image viewing software (Horosproject.org; Annapolis, Maryland). After image acquisition, cadavers were refrozen until instrumentation.

2.3 | Randomization of technique and order of pin insertion

Seven functional spinal units (FSUs) (T7–8 through L6–7) were instrumented bilaterally in each cadaver. The order in

TABLE 1 Randomization of functional spinal units and method of pin insertion.

Cadaver	Functional spinal units and pin insertion techniques						
1	T9-10	L2-3	T11-12	L4-5	T7-8	L6-7	T13-L1
	FHP	3DPG	FHP	3DPG	FHP	3DPG	FHP
2	T11-12	T13-L1	L2-3	T7-8	L6-7	L4-5	T9-10
	3DPG	FHP	3DPG	FHP	3DPG	FHP	3DPG
3	T9-10	L2-3	T11-12	L4-5	T7-8	L6-7	T13-L1
	3DPG	FHP	3DPG	FHP	3DPG	FHP	3DPG
4	T11-12	T13-L1	L2-3	T7-8	L6-7	L4-5	T9-10
	FHP	3DPG	FHP	3DPG	FHP	3DPG	FHP

which FSUs was instrumented was determined a priori using random sequence generator (www.random.org) (Table 1). Two 3.2/2.4-mm positive profile pins (Interface pins, IMEX, Longview, Texas) were inserted in each vertebra, one left and one right (4 per FSU), and then removed immediately after placement. Method of pin insertion (FHP or 3DPG) in the first FSU of the first two cadavers to be operated was determined a priori by coin toss and then alternated to achieve equal group numbers (Table 1). In total, 56 pins were placed in 28 vertebrae using each technique.

2.4 | Design and creation of 3DPGs

Digital Imaging and Communications in Medicine (DICOM) images were imported into 3D planning software (Mimics v21, 3-Matic v15, Materialise, Belgium) and virtual models of preselected vertebrae and 3DPGs based on safe pilot hole trajectories were created by a board-certified neurologist (J.G.). All guides were unilateral and designed as previously described,[18] with a 2.0-mm internal diameter that matched the pilot hole for the FHP technique, and variable guide tube length ranging from 24 to 30 mm (Figure 1). The footprints of individual 3DPGs were variable in dimensions but were designed in such a way that they incorporated anatomical landmarks with a snug fit. Guides were printed using biocompatible resin using a stereolithography (SLA) printer (Surgical Guide resin, Form 3B, Somerville, Massachusetts) with 0.1 mm layer height (resolution).

2.5 | Preoperative planning for FHP technique

For the FHP technique, primary and assistant surgeons used CT multiplanar reconstruction (MPR) images (Horos) for determination of (i) optimal pin entry and exit points, which were based on a best fit line that bisected the pedicle and exited as close as possible to the ventral vertebral midline in the thoracic spine, and a line that extended from the base of the accessory process (L1–6) and crossed the ventral vertebral midline in the lumbar spine (Figure 2); (ii) pin insertion angles (based on optimal pin entry and exit points) relative to the sagittal plane and (iii) expected pin tract lengths. The optimal pin entry point in the thoracic spine was based on the location of the accessory or mammillary process as previously described.[6] In the lumbar spine (L1–6), the optimal pin entry point was at the level of the base of the accessory process. The optimal entry point for L7 was in a more dorsally located position at the base of its cranial articular process.[5,12] All measurements were obtained from MPR images with the dorsal plane axis parallel to the vertebral canal floor in the sagittal plane, and the sagittal plane axis bisecting the vertebral body in the dorsal plane and the

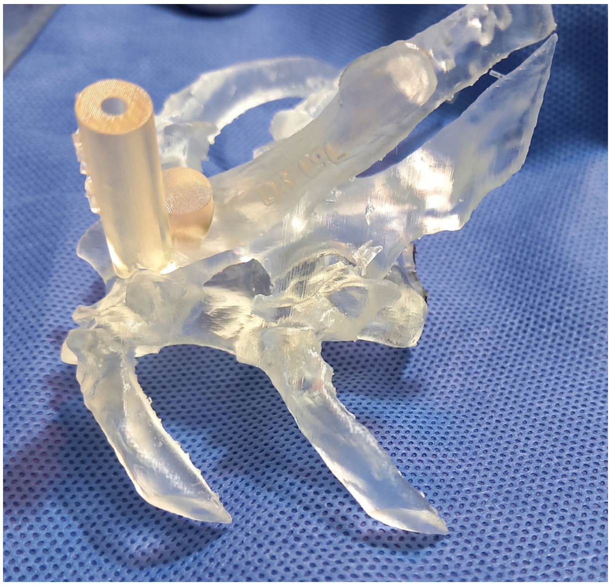

FIGURE 1 3D-printed vertebral model of T9-10 of cadaver 3 with the corresponding left-sided T9 3D-printed drill guide (3DPG) in place.

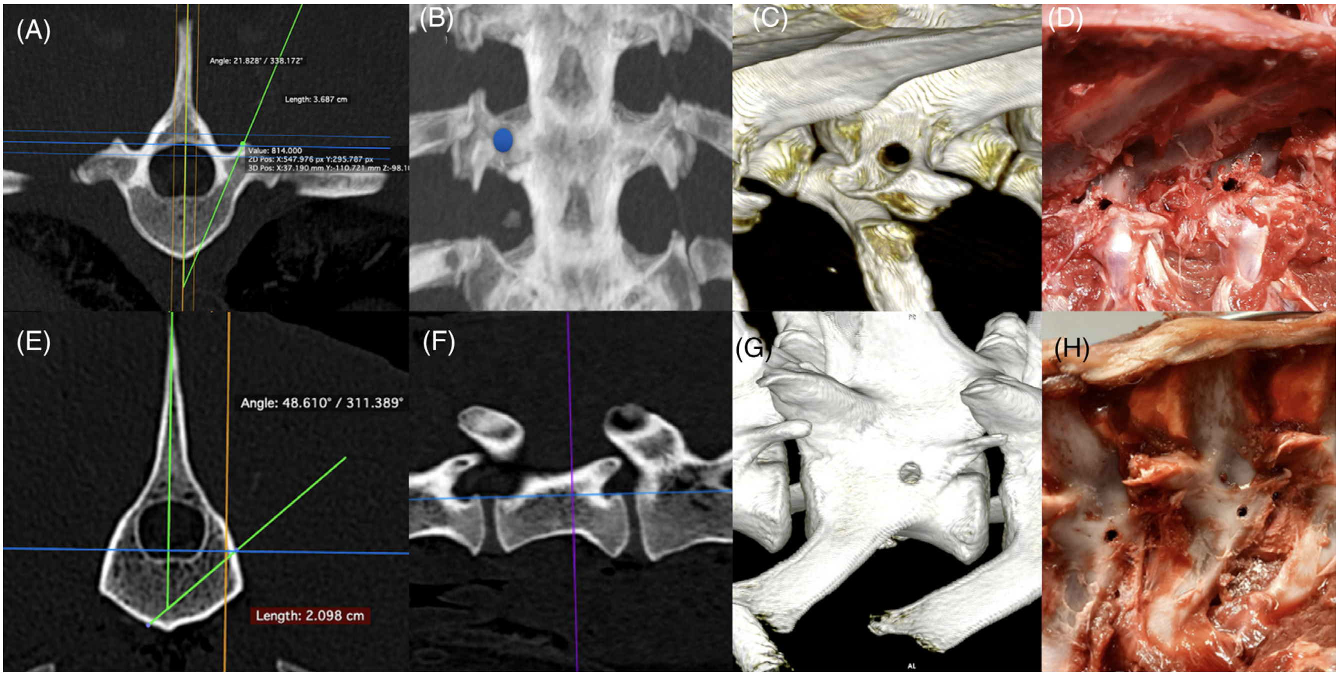

FIGURE 2 Transverse (A, E) and sagittal (F) plane multiplanar reconstruction (MPR) images, maximum intensity projection dorsal image (B), volume rendered 3D reconstruction images (C, G), and intraoperative images demonstrating location of ideal pin entry point in thoracic (D) and lumbar (H) vertebrae. In images (A, E), dog's left is to the right; in image (B), cranial is to the top; and in images (C, D, F, G, and H), cranial is to the left. In image (B), the blue dot represents ideal pin entry point on the left.

spinous process/vertebral body in the transverse plane (Figure 2).

2.6 | Spinal instrumentation

The spine was stabilized with dogs in sternal recumbency, thoracic limbs extended cranially, and pelvic limbs flexed on either side of the abdomen. A dorsal approach to the thoracolumbar spine was performed extending from T6-sacrum. The epaxial musculature was reflected bilaterally, without disruption of the supraspinous or interspinous ligaments. Duration of pin placement was recorded as the time (in seconds) from scraping the surface of the bone with a freer elevator for placement of 3DPGs or to locate optimal pin entry point for the FHP technique until completed pin placement. The time taken to perform initial dissection was not recorded. Occurrence and type of intraoperative technique deviations in pin placement, defined as any unanticipated deviations from planned surgical technique and unrelated to postoperative modified Zdichavsky grade,[15] were recorded and compared between techniques.

2.7 | Free-hand probing technique

The FHP technique (Video S1) involved: (1) creation of a cortical defect (decortication) using a 2-mm drill bit at the optimal pin entry point (based on preoperative CT) and exposure of cancellous bone; (2) palpation of the cortical defect with 1.1-mm Kirschner wire (k-wire) to confirm absence of canal breach; (3) advancement of the blunted 2.0 mm Steinmann pin acting as a probe (Figure 3) for ~5–10 mm at an angle guided by a goniometer, with as much length of pin left exiting the chuck as possible; (4) pin removal and palpation of the initiated tunnel with a k-wire to confirm absence of canal breach;

FIGURE 3 Blunted 2.0 mm Steinmann pin acting as a probe.

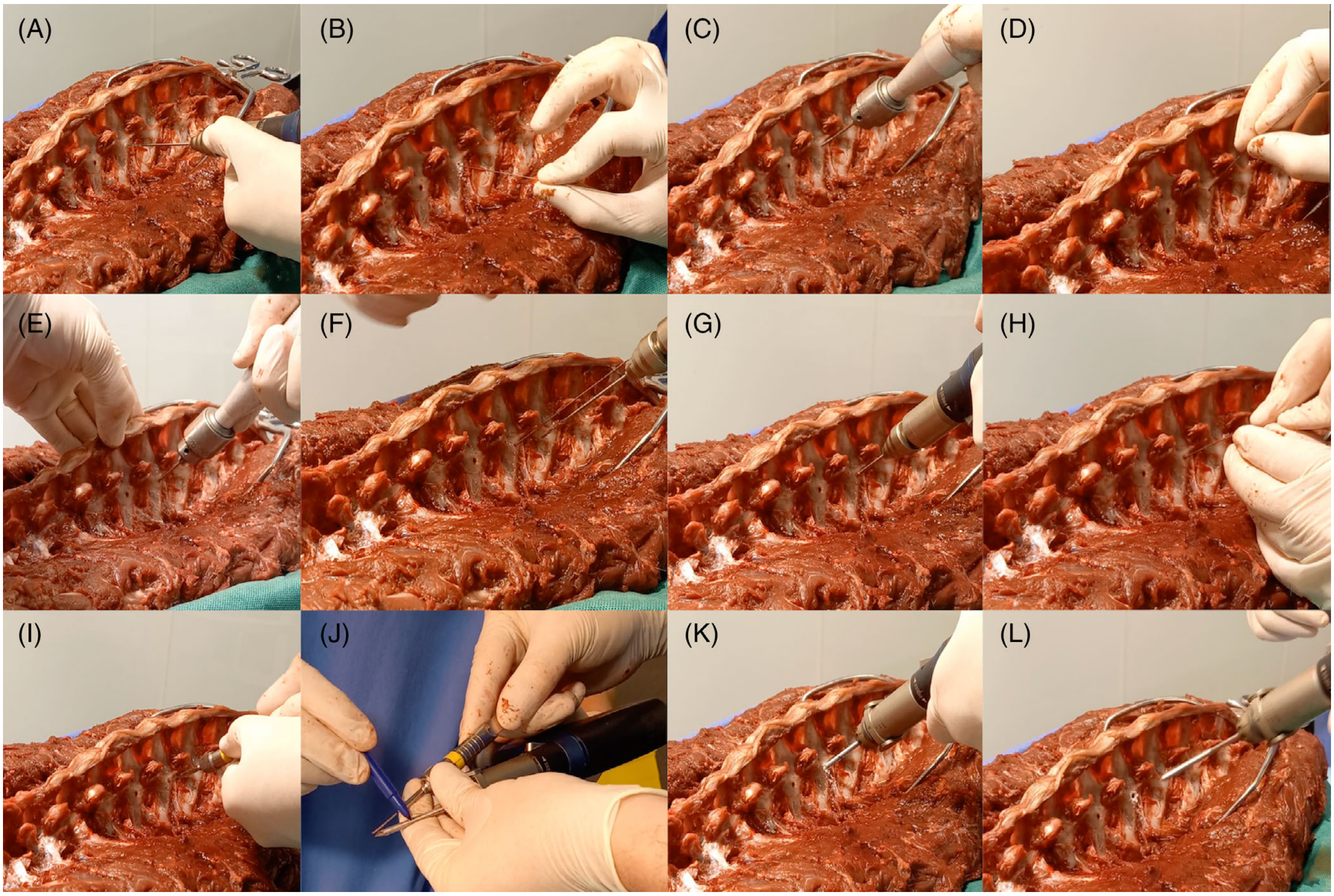

FIGURE 4 Intraoperative images of a dissected thoracolumbar spine demonstrating creation of the cortical defect (A), palpation of cortical defect with 1.1-mm k-wire to confirm absence of canal breach (B), advancement of 2.0 mm blunted Steinmann pin (probe) (C), palpation of initiated tunnel with k-wire to confirm absence of canal breach (D), further advancement of Steinmann pin (E), palpation of tunnel with k-wire to confirm absence of canal breach (F), drilling of pilot hole in same trajectory as probe (G), palpation of pilot hole with k-wire to confirm absence of canal breach (H), depth gauge insertion and measurement of pilot hole length (I), marking of measured pilot hole length on positive profile pin (J), insertion of positive profile pin at low speed (K), removal of positive profile pin (L). In images (A–I, K, and L), cranial is to the left.

(5) further pin advancement a distance of ∼5–10 mm; (6) probe removal and palpation of the tunnel with a k-wire to confirm absence of canal breach; (7) drilling of a 2.0-mm pilot hole, being careful to follow the same trajectory as the probe, and exiting through the ventral vertebral cortex; (8) palpation of the pilot hole with a k-wire to confirm absence of canal breach; (9) measurement of the pilot hole length; (10) marking the measured length on the positive profile pin; (11) insertion of 3.2/2.4 mm positive profile pin at low speed, being careful to follow the pilot hole; and (12) removal of the positive profile pin (Figure 4). The same technique was repeated on the contralateral side of that vertebra, before proceeding to the next vertebra of that FSU. The probe size corresponded to ∼50%–75% the width of thoracic pedicle on preoperative MPR transverse plane images. The angle of Steinmann pin insertion was checked on all occasions before advancement using a goniometer. Two 3.2/2.4-mm pins were placed in each vertebra, with the right pin directed slightly cranially and the left pin slightly caudally. All pins were inserted by a board-certified surgeon (R.A.M.) assisted by third year ECVS resident-in-training (J.E.R.), over a period of 2 weeks. The primary surgeon had substantial experience in spinal surgery in dogs, had performed the FHP technique in a small number of clinical cases, and adapted the FHP technique from previous descriptions[6] and in consultation with one author (K.H.K.).[6] In the T7–T10 spine, the accessory process was identified and the pin entry point created just medial thereto in the mid-to-cranial aspect of the transverse process (Figure 2). For T10–T13, at which the mammillary process typically becomes associated with the cranial articular process and the accessory process transitions from the transverse process to a more medial location similar to the cranial lumbar vertebrae, an additional measurement consisting of the distance

from the costovertebral junction to the ideal pin entry point was obtained from preoperative MPR images. In the lumbar spine (L1–6), the optimal pin entry point was at the level of the base of the accessory process (Figure 2).

2.8 | 3DPG technique

Soft tissues were meticulously removed over areas of bone to ensure precise and complete contact of guide footprint. 3DPGs were held firmly in position by hand, and a 2.0-mm drill bit was used to create a pilot through the guide sleeve. The guide was removed, pilot hole measured with a depth gauge, and appropriate length of positive profile pin inserted at low speed. The pin was then removed.

2.9 | Post-instrumentation CT

CT was repeated after spinal instrumentation from T6-sacrum using the previously described protocol and assessed in Horos. Using MPR, the dorsal and transverse plane axes were aligned with each pin tract trajectory and graded on transverse plane images (Figure 5). Grading was performed once by two independent observers (board-certified radiologist [S.H.] and board-certified neurologist [J. G.]) using a modification of the modified Zdichavsky classification (Figure 6) described by Elford and colleagues.[15] Discrepancies between observers were reviewed together on one occasion and a consensus reached.

2.10 | Statistical analysis

Descriptive statistics were used. Data are summarized by N (%) or mean ± SD. Data related to modified Zdichavsky classification grade and duration of pin placement for each technique are presented for the thoracic spine, lumbar spine, and overall.

3 | RESULTS

Four greyhound cadavers were included, two males and two females. Bodyweights included 25.0, 27.0, 31.0, and 34.5 kg.

3.1 | Accuracy of pin placement

Agreement between the two observers was present for 104/112 pin tracts. Disagreement was present for eight pin tracts and consisted of three cases in which a discrepancy between a grade IIa versus grade I was agreed by consensus as being a grade I, a further three cases in which a discrepancy between a grade IIIa versus grade I was agreed by consensus as being a grade I, one case in which a discrepancy between a grade IIa versus grade I was agreed as being a grade IIa, and a further case in which a grade IIIa versus grade I was agreed as being a grade IIIa.

Overall, 54/56 pins placed with a 3DPG were assigned grade I compared with 49/56 pins placed using the FHP technique (Figure 7, Table 2). Two pins placed with a 3DPG were assigned grade IIa, whereas 3/56 pins placed using the FHP technique were graded IIa (Figure 8). Four pins placed using the FHP technique and no pins placed with a 3DPG were assigned grade IIIa (Figure 9). No pins were classified as grade IIb or IIIb.

3.2 | Intraoperative technique deviations

Intraoperative technique deviations in pin placement occurred during placement of 6/56 pins placed using the

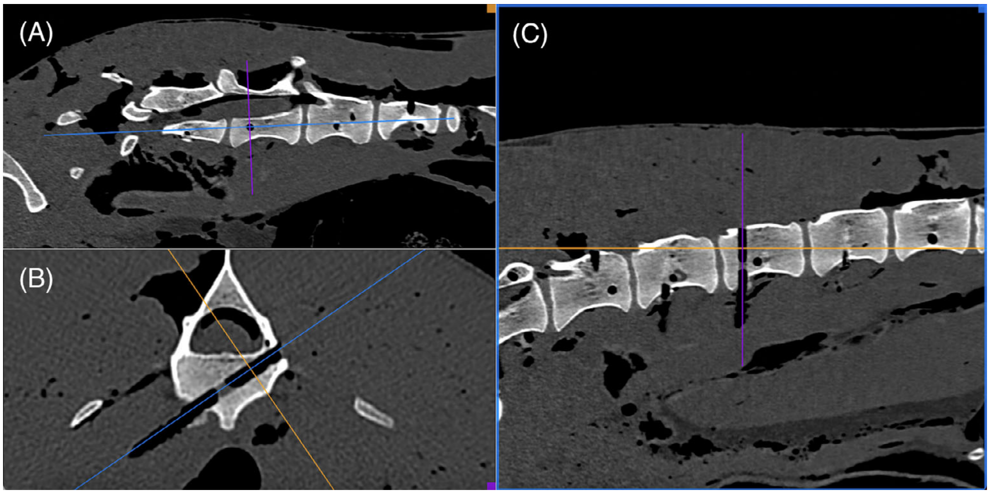

FIGURE 5 Sagittal (A), transverse (B) and dorsal (C) oblique plane multiplanar reconstruction (MPR) images with dorsal and transverse plane axes aligned with each pin tract trajectory and grading performed on transverse plane images. In images (A and C), caudal is to the left. In image (B), the dog's left is to the right.

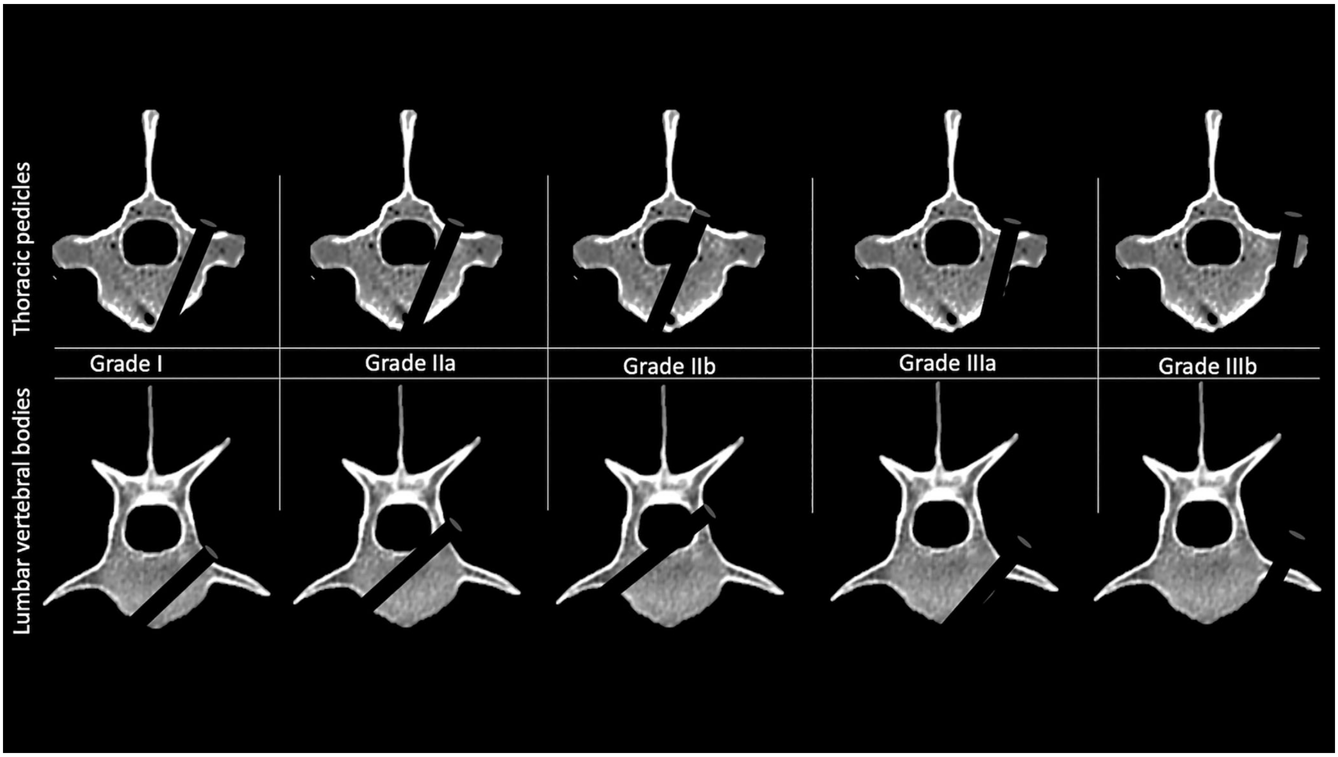

FIGURE 6 Modified Zdichavsky classification with grade I corresponding to optimally placed pin tract fully contained within pedicle (thoracic spine) or vertebral body (lumbar spine), grade IIa denoting partial penetration of the medial pedicle wall, grade IIb corresponding to full penetration of the medial pedicle wall (whole of screw diameter within canal), and grades IIIa and IIIb denoting partial and full penetration of the lateral pedicle (thoracic spine) or vertebral body (lumbar spine) wall, respectively.

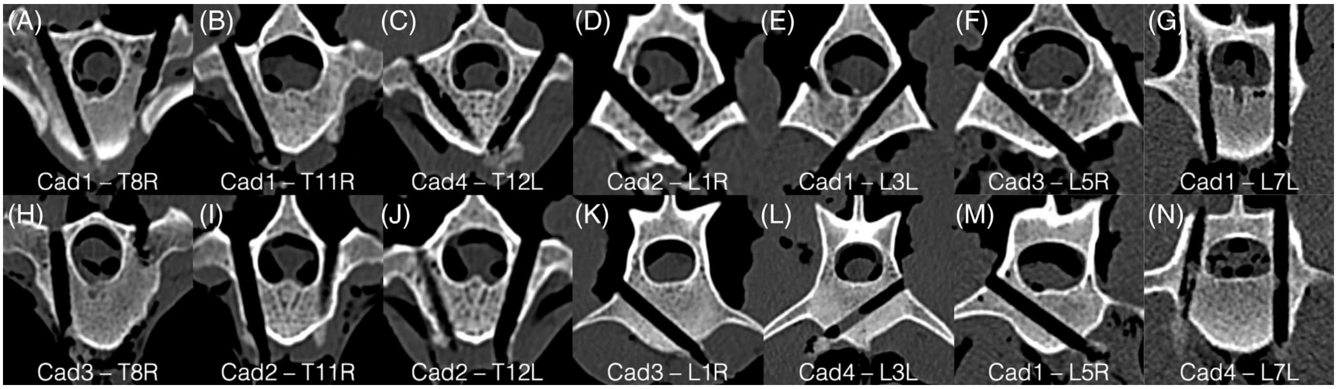

FIGURE 7 Transverse plane multiplanar reconstruction (MPR) images of selected examples of pin tracts (free-hand probing [FHP]: images [A–G], 3D-printed drill guide [3DPG]: images [H–N]) assigned grade I modified Zdichavsky. For all images, the dog's left is to the right.

TABLE 2 Modified Zdichavsky classification grades for pins inserted by 3D-printed drill guides (3DPGs) and free-hand probing (FHP) technique in the thoracic spine, lumbar spine, and overall.

	Grade	Thoracic	Lumbar	Overall
FHP	I	24/28 (85.7%)	25/28 (89.3%)	49/56 (87.5%)
	IIa	1/28 (3.6%)	2/28 (7.1%)	3/56 (5.4%)
	IIIa	3/28 (10.7%)	1/28 (3.6%)	4/56 (7.1%)
3DPG	I	26/28 (92.9%)	28/28 (100.0%)	54/56 (96.4%)
	IIa	2/28 (7.1%)	0/28 (0.0%)	2/56 (3.6%)

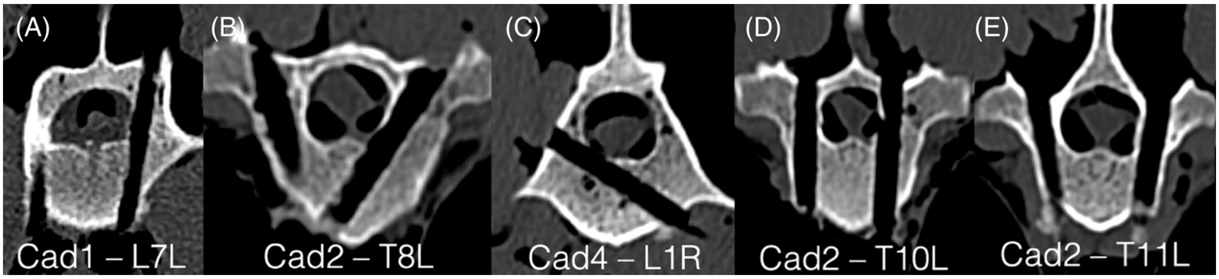

FIGURE 8 Transverse plane multiplanar reconstruction (MPR) images of pin tracts (free-hand probing [FHP] images [A–C], 3D-printed drill guide [3DPG]: images [D, E]) assigned grade IIa modified Zdichavsky. For all images, the dog's left is to the right.

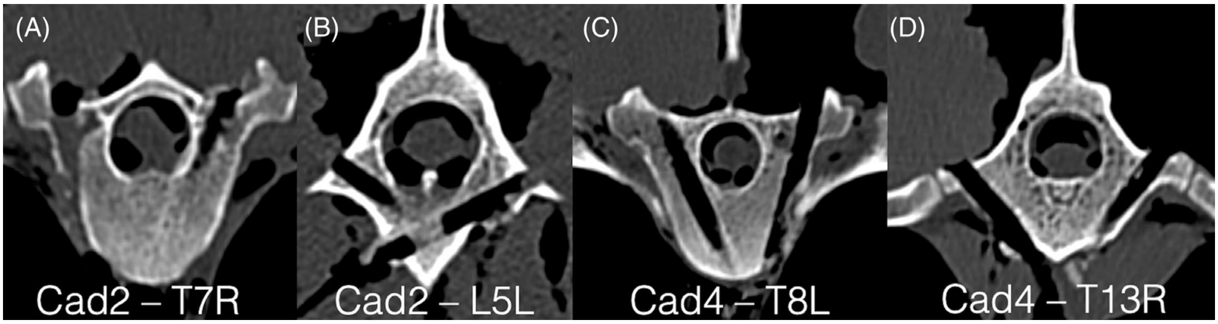

FIGURE 9 Transverse plane multiplanar reconstruction (MPR) images of pin tracts (all free-hand probing [FHP]) assigned grade IIIa modified Zdichavsky. For all images, the dog's left is to the right.

FHP technique and no pins placed with a 3DPG. In cadaver 1, bilateral unintentional penetration of the ventral vertebral cortex of T11 occurred during advancement of the probe; however, both pin tracts were surrounded by bone and subsequently assigned grade I modified Zdichavsky. In the same cadaver, the left-sided cortical defect was created in a too dorsal location at L6 and entry into the vertebral canal was identified with initiation of probing. A second cortical defect was created slightly more ventral, and the technique was completed without further complication. Grade I modified Zdichavsky was assigned on postoperative imaging in this instance. In cadaver 2, the probe exited the dorsolateral pedicle of T13 on the right and the ventrolateral body of L5 on the left. In cadaver 4, the probe exited the dorsolateral pedicle of T7 on the left. In each of these three cases, the probe was redirected more medially and the technique completed without further complication. Two of the latter 3 deviations were subsequently assigned modified Zdichavsky grade I, with the left-sided L5 breach assigned grade IIIa (Figure 10). No intraoperative technique deviations occurred in cadaver 3.

3.3 | Duration of pin placement

Pins were placed faster in the thoracic spine (mean ± SD 2.8 [1.6] vs. 4.2 [1.9] min), lumbar spine (mean ± SD 2.3 [0.93] vs. 4.9 [1.7] min), and overall (mean ± SD 2.6 [1.3] vs. 4.5 [1.8] min) when a 3DPG was used (Table 3).

4 | DISCUSSION

Our study compared pin placement tracts using FHP and 3DPG techniques in a canine cadaveric model. Our hypotheses were partially supported in that we found a greater rate of intraoperative technique deviations in pin placement and longer duration of pin placement for the FHP technique but a difference in the distribution of grades between the two techniques was not identified.

Our results related to the FHP technique are difficult to compare with others due to paucity of similar studies in the literature. To our knowledge, a FHP technique similar to that described herein has been described in only two clinical reports[5,12] (both involving placement of screws/pins at lumbosacral joint) and one surgical textbook.[6] No evidence of vertebral canal compromise was identified on postoperative radiographs in one retrospective case series[5] involving stabilization of lumbosacral fracture-luxations in five dogs. A limitation of that report[5] is that postoperative CT was not performed, which has been shown to be significantly more accurate in identifying canal violation compared with conventional radiography.[27] In people, the pedicle-probing technique is associated with a high degree of accuracy in

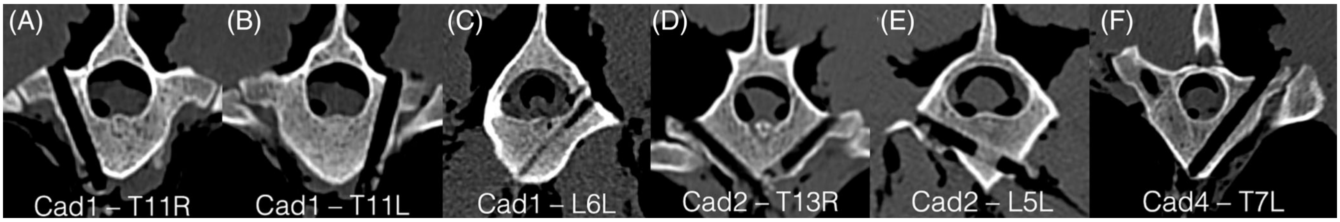

FIGURE 10 Transverse plane multiplanar reconstruction (MPR) images of pin tracts (all free-hand probing [FHP]) of vertebrae in which an intraoperative complication occurred. For all images, the dog's left is to the right.

TABLE 3 Mean (SD) duration of pin placement for pins inserted by 3DPGs and FHP in thoracic spine, lumbar spine, and overall.

		Thoracic	Lumbar	Overall
3DP	Mean (SD) duration of pin placement (min)	2.8 (1.6)	2.3 (0.93)	2.6 (1.3)
FHP	Mean (SD) duration of pin placement (min)	4.2 (1.9)	4.9 (1.7)	4.5 (1.8)

Abbreviations: 3DPG, 3D-printed drill guide; FHP, free-hand probing.

several studies, even in cases of spine deformities.[25,28–31] Five studies[25,28–30,32] that included a total of almost 600 patients undergoing posterior stabilization with transpedicular screws reported medial pedicle wall violation rates of 0.5%–6.3%, with only one screw requiring repositioning and none associated with neurological or visceral complications. The medial cortex of the thoracic pedicle has been shown to be thicker than the lateral cortex in humans,[33–35] a factor that may contribute to a decreased rate of medial cortex breach with the pedicle-probing technique in people.

Creation of the cortical defect (decortication) was performed with a 2-mm drill bit in our study. A spinal burr or awl could also have been used as an alternative, as is described in the veterinary and human literature.[12,31] In clinical cases, loss of the cis cortex associated with use of a spinal burr may not be of structural concern as the polymethylmethacrylate will support this outer cortical defect. In our study, a 2-mm drill bit was used instead of a burr as it avoided this loss of cis cortex. The FHP technique described herein does not negate the need to preoperatively measure ideal pin insertion angles and to follow these angles intraoperatively. However, adhering to preoperatively measured angles requires accurate identification of optimal entry points intraoperatively. In a previous description of the technique,[6] the authors recommend checking the angle of the probe hole with the desired pilot hole angle to ensure accurate trajectory. In our study, following creation of the cortical defect, the probe was inserted at an angle corresponding to the ideal pin trajectory based on preoperative CT. This is particularly important in the lumbar spine because the probe has more "freedom" to travel within the vertebral body compared with thoracic spine where the probe is contained within the confines of the pedicle. Once the probe established the safe trajectory, it is removed and replaced with a drill bit for the pilot hole of the definitive positive profile pin. The probe itself should be placed with a drill or by hand using a Jacob's chuck, making sure to allow as much length of pin exiting the chuck to reduce its stiffness and allow it to follow the path of least resistance within cancellous bone. A positive profile pin should not be used as a probe because it is too stiff and will not follow the path of least resistance. In our study, we used a blunted 2-mm smooth Steinmann pin as the probe, which corresponded to ~50%–75% the thoracic pedicle width. In people, straight and curved pedicle probes/awls are commercially available but are generally larger than would be appropriate for canines because of the relatively larger size of the pedicle in people.[31,36,37] In recent years, probes with an electrical impedance conductivity-measuring device have been developed to improve accuracy of pedicle screw placement in people.[37,38] By monitoring electrical conductivity in surrounding tissues, these probes can alert the surgeon to an impending breach.[37,38]

The 3DPG technique was associated with a very high degree of accuracy in our study, with 54/56 pins assigned grade I. Importantly, no pin tracts were graded grade IIb (full penetration of medial pedicle wall) with either technique. This corroborates the findings of previous studies evaluating use of patient-specific 3DPGs in veterinary spine surgery.[7,15–19] Within such studies involving the thoracolumbar spine,[7,15,17,18] the rate of grade I Zdichavsky (or alternate classification equivalent) ranges from 79.3% to 100%. A similarly high accuracy rate has been demonstrated with use of 3DPGs in cases with vertebral malformations.[15] In human spine surgery, 3DPGs are associated with improved pedicle screw placement accuracy, and decreased surgical time and intraoperative blood loss.[39–41] Unilateral 3DPGs were used in our study and have been shown to be highly accurate and comparable to bilateral guides.[18] In one study,[18] unilateral guides were associated with decreased exit distance deviation compared with bilateral guides. We did not evaluate or compare planned versus achieved insertion angles or entry/exit point deviations in our study as the FHP technique relies on the probe following the path of least resistance and establishing a safe trajectory and would not be expected to have the same degree of accuracy as 3DPGs regarding these variables. A modification of the modified Zdichavsky classification described by Elford and colleagues[15] was created for grading of lumbar pin tracts in our study. The original Zdichavsky classification is validated for thoracic pedicle screws in humans, and is associated with a high rate of inter- and intraobserver reliability.[42]

A higher rate of intraoperative technique deviations in pin placement was found using the FHP technique. Two of these deviations involved bilateral unintentional penetration of the ventral vertebral cortex of T11 with the probe during instrumentation of the first vertebra operated and did not occur in subsequent vertebrae/cadavers. Although both pin tracts were palpated and completely surrounded by bone, and subsequently assigned grade I on postoperative CT, such uncontrolled ventral cortex breach could be associated with injury to intrathoracic structures.[43,44] In people, anterior (ventral) vertebral cortex breach is avoided for this reason,[45] with the medial and lateral cortices of the pedicle contributing a significant portion of pedicle screw pull-out strength.[46] In the same cadaver, the initial cortical defect at L6 was created too dorsal and vertebral canal entry was identified with initiation of probing. This highlights the importance of correct identification of the optimal pin entry point intraoperatively. In our study, we used the accessory or mammillary process in the thoracic spine and accessory process in the lumbar spine as intraoperative landmarks for identification of optimal pin entry points, as previously described.[6] In clinical situations where pin entry point is inadvertently created too dorsal, we suspect that the FHP technique as performed in our study may offer a greater ability to detect this complication compared with the conventional freehand drilling technique, and possibly be associated with less injury to vertebral canal contents. The remaining three intraoperative deviations involved the probe exiting the dorsolateral cortex of the pedicle (thoracic spine) or the ventrolateral vertebral body (lumbar spine), and in all three cases, this complication was recognized immediately and the probe redirected more medially/horizontally. With the exception of varying degrees of canal violation and undesired screw penetration of the ventral vertebral cortex identified on postoperative imaging,[12] no other specific intraoperative complications related to the pedicle-probing technique have been described in the veterinary literature.[5,12] Few studies report the occurrence of intraoperative complications/deviations associated with use of 3DPG in the veterinary literature.[18] In one ex-vivo canine study,[18] breakage of a 3DPG was reported in two cases. We did not observe guide breakage in our study.

Duration of pin placement was longer with the FHP technique in the thoracic spine, lumbar spine, and overall, in our study. Duration of pin placement included all steps that would be required for pin placement in a clinical case once the approach was completed. Duration of pin placement was defined in this way because of soft tissue dissection performed for exposure of one FSU influencing dissection time required for an adjacent FSU. Although duration of pin placement was longer for pins placed by FHP technique, the clinical significance of a mean difference of 1.9 min is negligible in the overall operating time. Furthermore, the time taken to plan both techniques was not recorded. It is likely that the time taken to design and create 3DPGs would have far exceeded the time for FHP planning.

We acknowledge several important limitations. This was an ex-vivo study that included only a single large breed without spinal fracture/luxation and our results may not be replicated in small/medium breeds or different breed conformations. In particular, in the lumbar spine, the ability of the drill bit (associated with decortication) to drop into the cancellous bone between the inner and outer cortices, which is central to the principle of the FHP technique, would be more challenging in smaller breeds with narrower pedicles. The fact that a single breed was used likely advantaged the FHP technique because of uniformity between cadavers and vertebrae. The study also included a small number of cadavers. 3DPGs are associated with a high degree of accuracy in patients with spinal malformation/deformity and whether the FHP technique would perform as well in such cases is unknown.[7,15,17,18] The authors refrained from the use of inferential statistics in this study and instead reported only the raw data. On the basis of the lack of previously published data on the FHP technique, it was not possible to estimate a priori the smallest sample size needed to show a significant difference if it were to exist. Therefore, it is possible that even if one of the techniques evaluated in this study was associated with complete breach of the vertebral canal on one or two occasions, this may not have reached statistical significance but would be of substantial clinical significance. All pins were placed by a single experienced surgeon, and it is likely that this had an effect on the high degree of accuracy with both techniques in this study. Pins were removed following placement to prevent placement of one pin influencing that of a subsequent pin by the same or alternate technique and to eliminate beam hardening artifact on postoperative CT. A disadvantage is that we could not evaluate for deviations such as excessively long pins or pins penetrating/abutting pleural, visceral or vascular structures. The extensiveness of the surgical approach performed in this study would be greater than that required in a clinical case, which is likely to have improved visibility of relevant anatomical structures and the surgeon's ability to place the pins. Finally, no postoperative dissection was performed to evaluate for injury to intrathoracic or abdominal structures.

Our study confirmed both FHP and 3DPG techniques were accurate for placement of spinal fixation pins in canine cadavers. The 3DPG technique reduced intraoperative technique deviations in pin placement and duration of pin placement in our study but this technique requires greater software expertise and equipment for guide design and manufacturing. The FHP technique offers a very versatile and safe method of insertion of spinal fixation pins and can be performed immediately without potential delays associated with guide design, printing and delivery. Further studies are required to confirm our results in clinical cases.

AUTHOR CONTRIBUTIONS

Mullins RA, MVB, DVMS, DECVS, PGDipUTL, MRCVS: Study conception and design; data acquisition, analysis and interpretation; manuscript preparation and review. Espinel Ruperéz J, LV, MS, PhD, DECVS, Ortega C, DVM and Hoey S, MVB, DECVDI, DACVR: Study design, data acquisition, analysis and interpretation; manuscript preparation and review. Bleedorn J, DVM, MS, DACVS-SA, Kraus KH, DVM, MS, DACVS and Guevar J, DVM, MVM, DECVN: Study design, data analysis and interpretation, manuscript preparation and review. Hetzel S, MS: Statistical analysis and manuscript review.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest related to this report.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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