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Accuracy of Thoracolumbar Spine K-Wire Placement in Toy, Small and Medium Breed Dogs: Novice Surgeons with 3D Printed Patient-Specific Guide versus an Experienced Surgeon with Freehand Techniques

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Abstract Three-dimensional (3D) printing technique has been widely used for accurate screw and pin placement in orthopedic surgery and neurosurgery. However, there are few reports comparing the accuracy between the patient-specific guides and freehand Kirschner wire (K-wire) placement in toy, small and medium breed dogs. This study aimed to assess the accuracy of 3D printed patient-specific guides (PSGs) in pin insertion in the thoracolumbar vertebrae of toy breed dogs and compare the outcomes between novice and experienced surgeons. The experiment was conducted on the thoracolumbar vertebrae of 21 euthanized toy breed dogs (median weight, 5.95 kg). The optimal insertion angle placement was determined and patient-specific guides for K-wire insertion were designed and 3D printed using computed tomography (CT) and a 3D computer-aided design program of three vertebrae (Thoracic 12-Lumbar 1). K-wire tracts were made by experienced and novice surgeons and compared to assess the accuracy based on postoperative CT. Based on postoperative CT, in the experienced group, 61 out of 63 pins (96.8%) were fully contained inside the vertebral body and lamina, whereas two pins (3.2%) had perforated the vertebral canal (grade 3, 2-4 mm breach). However, all the pins in the novice group were fully contained. The use of 3D printed PSGs for pin insertion in the thoracolumbar region is an accurate and safe alternative to freehand screw placement by novice surgeons in toy, small and medium breed dogs. Operations with 3D printed PSGs allow novice surgeons to achieve better or similar outcomes in accurate placement of pin/screws in vertebrae.

Key words patient-specific guide, toy breed dogs, spine, vertebrae.

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Introduction

Stabilization of the vertebrae is necessary for treatment of luxation and fractures due to trauma, congenital malformation, degenerative spinal disease, and tumors (15,18,37). Spinal instability can compress the spinal cord leading to nerve root pain and nerve deficits, including ataxia (15,19). Surgical treatment methods for stabilization have been described in literature including, but not limited to: fixation using bicortical pin and polymethylmethacrylate, vertebral plate fixation, external skeletal fixation, spinal stapling, and spinal process plating (15,26,27,31,32). Spinal stapling is relatively simple and less invasive, but the screw rod system, plate, and cement methods have high stability with rigid forces (15,32,37). Although pin and screw insertion provide the most robust fixation for the spine, securing accurate screw placement is challenging and requires surgical expertise (6,34). The use of screws and pins has been limited due to iatrogenic injuries, such as the cortical breach of implants (1,20,30). Screw misplacement causes instability of the spine; and iatrogenic damage to the nerves, dural sac, and vasculature under the vertebrae which has been documented in human medicine (5,16).

Pin and screw insertion is highly challenging and requires surgical expertise in toy breed dogs because of their relatively small size and variations in the breeds (18). Although general guidelines have been developed for insertion angles and landmarks in thoracolumbar vertebrae, the angle and position should be modified during surgery, due to challenges imposed by soft tissue interference (34). Additionally, it is difficult to apply these guidelines directly to small and toy breed dogs, since they were developed without considering the differences between large and small/toy breed dogs (34). It should also be mentioned that due to the breed-specific features, the implant type and size should be determined based on the vertebral pedicle width and vertebral body dimensions, which can be measured using computed tomography (CT) immediately before surgery (15,34). In this regard, in human medicine, navigation systems and fluoroscopy have been employed to improve surgical placement accuracy (9). However, it is difficult to use the navigation system in veterinary medicine (35) as it takes up a large space for small animals (7), and if the patient's posture is altered by manipulation during surgery, the targeted accuracy may be reduced (35). The navigation system is not considered suitable for manipulating small bones (35). Furthermore, although fluoroscopy can be helpful for spinal surgery, screw malposition has still been reported in human medicine (36).

The use of patient-specific guides (PSGs), as an accurate and low-risk method for pin and screw insertion, has been widely studied (2,8,13,21,29). PSGs can be used in various situations, especially in patients with deformed bones, because it fits the characteristics of individual bone anatomy (25). PSGs can help place the implant in an ideal pre-planned location with increasing stability and reducing the complications of malposition (9,33). Many studies have reported that PSGs allow stable and accurate insertion of screws and pins in cervical, thoracic, and lumbosacral vertebrae in veterinary medicine (8,11,13). This technique with PSGs is relatively inexpensive, easy to manipulate and reduces the duration of surgery (25). Advanced computer programs and manufacturing technology help in exact and constructive application of PSGs with favorable outcomes (3).

To date, few studies have evaluated the outcomes of using PSGs for the thoracolumbar vertebrae of toy, small and middle breed dogs. Therefore, this study aimed to investigate the effectiveness of PSGs in spinal surgery of toy, small and medium breed dogs. Additionally, since three-dimensionally (3D) printed PSGs has been reported to be more accurate and safer than the freehand technique in human medicine, we compared the surgical accuracy pertaining to position and angle among novice surgeons, who have never inserted pins and screws in the spine, with that of experienced surgeons (freehand) (9). We hypothesized that novice surgeons with PSGs could achieve more accurate outcomes than experienced surgeons, and the use of PSGs would help obtain almost identical results to the preoperative plans regardless of the size and breed of the dogs.

Materials and Methods

Specimens and groups

Overall, 21 thoracolumbar vertebrae from toy, small and medium breed dog cadavers were obtained for this study through donations after euthanasia for reasons unrelated to the study. None of the dogs had degenerative and inflammatory abnormalities on radiographic examination. The cadavers were stored at −20°C and thawed at room temperature for 24 h before the surgery. Eight surgeons, one experienced (freehand) and seven novices with PSGs, operated on each vertebra. The side of the vertebra (left or right) was allocated randomly to experienced and novice surgeons.

Imaging and preoperative evaluation

CT (Alexion™, Canon Medical Systems Corporation, Otawara, Japan) images were obtained using bone and soft tissue filters, with operating parameters of 120 kV and 12 mA while all the dogs were placed in dorsal recumbency. Images were obtained with a slice thickness of 1 mm, and the digital imaging and communication in medicine images were imported into computer image processing and modeling software, 3D Slicer 4.10 (available at: https://www.slicer.org/) (10). The thoracolumbar vertebrae from T11 to L2 were segmented and reconstructed. The computer-aided design software (3DS Max, Autodesk, CA, USA) was used to analyze the bone structure and design the surgical plan and PSGs.

Parameters were measured and bone models were constructed according to previously described protocols (2,21). Pedicle wall and pin trajectory were measured in the modeling software program. Insertion points for each pin were planned on the tubercle of the ribs in the thoracic vertebrae and on the junction between the pedicle and transverse process in the lumbar vertebrae (15). Virtual cylinders representing pins were positioned with six degrees of freedom to acquire the ideal corridor angle and bone stock for each pin (Fig. 1). All pins traversed the lamina and vertebral body to achieve maximum length and width with bicortical purchase.

Construction of the 3D-PSG

The PSGs were designed to represent the inverted surface of the bone, so the base of the guide and the bone could fit with manual compression. The unique position of the articular and spinous processes was also considered. The other contact surface of the guide was the dorsal surface of the bone (Fig. 2). Therefore, the PSGs were designed to contact the spinous and articular processes, dorsal vertebral arch, and the lamina to ensure complete attachment between the guide and vertebral surface. Although there was remaining

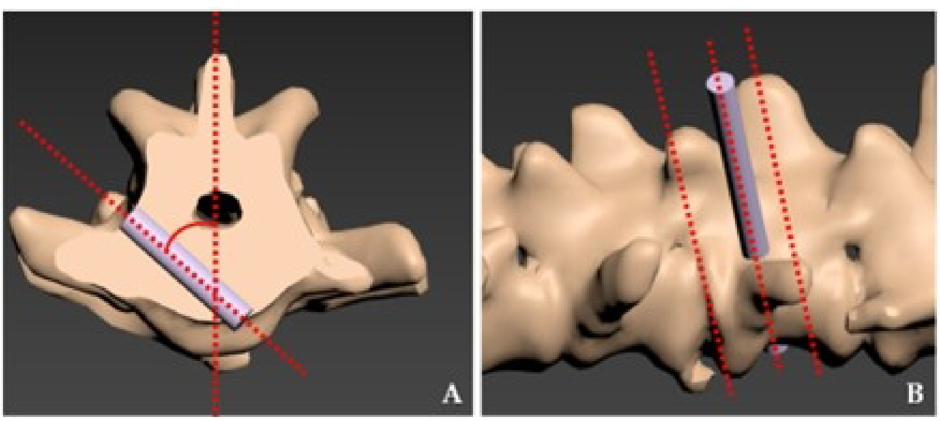

Fig. 1. Preoperative measurement in the computer-aided design software. Transverse reconstructed 3D image of T13 with virtual trajectories of the cylinder in place (A). Sagittal view of T13 with virtual trajectories of pins in place (B). The cylinder was in parallel with the spinous process and endplate.

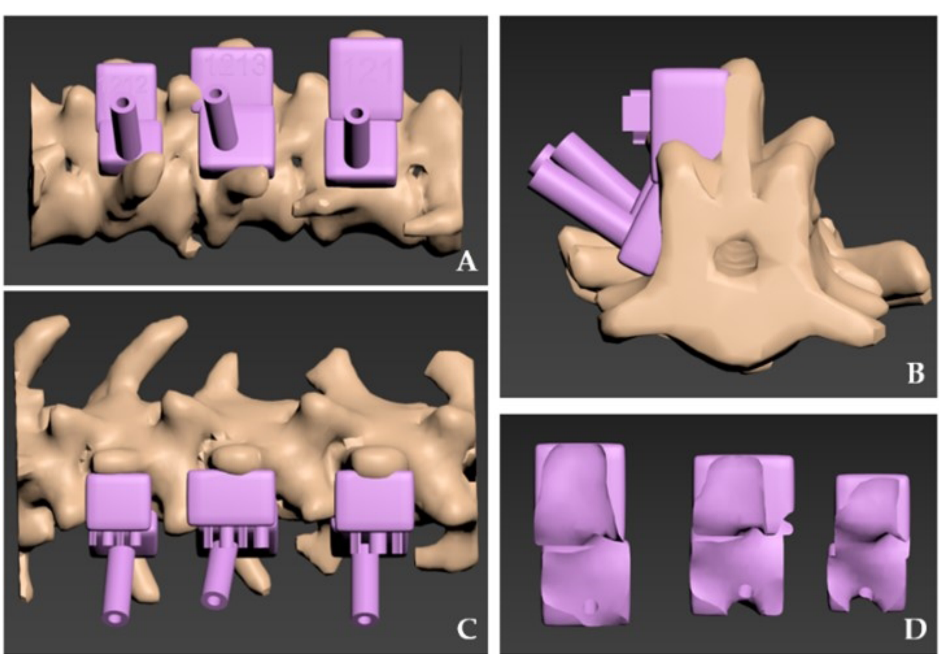

Fig. 2. Thoracolumbar vertebrae bone model and patient-specific guides (PSGs) within the computer-aided design software. Sagittal, craniocaudal, and dorsal view of bone model with PSGs (A-C). The contact surface of PSGs (D). They all were made to resemble an inverted virtual representation of the surface of the bone.

soft tissue on the bone, a latitude of 0 mm between the inverse surface of the PSGs and the surface of bone was chosen because of the compression between the bone and PSGs during surgery. Author (Y.H.R) designed all the PSGs to accommodate a 12-13 mm drill sleeve intended for a 2 mm Kirschner wire (K-wire) to avoid conflict with surrounding muscles. The bone model and PSGs (Fig. 2) were printed using a 3D printer (Finbot-Z420, TPC Mechatronics, Seoul, Korea) and polylactic acid filament (PLA filament, Cubicon, Seongnam, Korea).

Surgical technique

All dogs were positioned in sternal recumbency with the hindlimb drawn forward to adjust the height. A dorsal midline incision was performed at the levels T11 to L2, including dissection and retraction of the epaxial musculature to expose surgical landmarks (lamina arch and spinous, articular, and transverse processes) (15). Interspinous muscles were reserved. In the thoracic spine with ribs, the restricted surface of the lamina above the rib and spinous process were prepared. Any residual soft tissues on the vertebral lamina and articular process, and those lateral to the spinous process were removed using a periosteal elevator to ensure the precise fit between the guide and the bone. In the novice group, the drill guide was held appropriately and compressed to prevent the surgeon's hand from slipping. In the experienced group, the assistants measured the insertion angles of the pins outside the table, and the surgeon tried to obtain the same position and angle as the preoperative plan. All pins were placed with biocritical fixation and were pulled out.

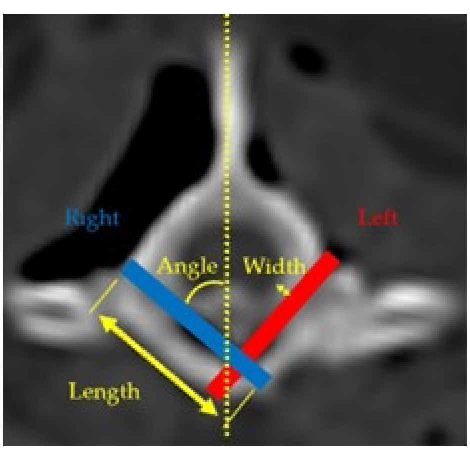

Fig. 3. Postoperative assessment of pin corridor and the pedicle of T12 vertebra on transverse CT images. An experienced surgeon operated the left side, and the right side was operated with the help of a guide. The insertion angle is the angle between the pin corridor and the spinous process. The minimum width and maximum length were measured according to the insertion path. CT, computed tomography; T, thoracic.

Postoperative assessment

Postoperative CT images were obtained for analysis of the accuracy of the pin corridor and multiplanar reformation was performed using a computer software (ZeTTA PACS, TaeYong Soft, Anyang-si, Korea). Accuracy was evaluated by measuring the trajectory of pins (Fig. 3). Insertion angle was defined as the angle between the sagittal plane from the spinous process and the pin canal axis on the transverse CT images. The minimum width of the pedicle wall and the maximum length of the pin corridor were measured. Based on a previously described classification, a breach was recorded when the cortical wall of the vertebra was interrupted by the pin (2). This classification categorizes the breaches as grade 0, when no vertebral canal breach is detected; grade 1, when the breach of the cortical bone and perforation of the canal is between 0 to 2 mm; grade 2, when the breach is from 2 to 4 mm; and grade 3, when the breach is more than 4 mm. All outcomes were assessed by one investigator (Y.H.R.).

Statistical analysis

The statistical analyses were performed using SPSS software, version 26.0 (SPSS Inc., Chicago, IL, USA). The optimum position of pin/screw in toy, small and medium breed dogs were reported as median, interquartile range (IQR, 25th to 75th percentile). Breach, postoperative corridor angle and length, and width of pedicles were evaluated between the experienced and the novice group as mean ± standard deviation (SD). Data were assessed for normality with the student

Table 1. The optimum position of pin/screw in toy, small and medium breed dogs

Location	Corridor angle (degree)	Corridor length (mm)	Pedicle width (mm)
T12	51.00	15.2	5.51
Median			
IQR	50-52	12.84-16.52	4.74-6.38
T13			
Median	52	14.99	5.81
IQR	50-53	12.24-15.51	4.9-7.44
L1			
Median	52.00	14.02	5.73
IQR	49-55	11.33-15.3	4.57-7.22

The data were summarized as median and IQR. IQR, interquartile (25th to 75th percentile) range; T12, Thoracic 12th; T13, Thoracic 13th; L1, Lumbar 1st.

T-test and Mann–Whitney U test to compare significant differences between the groups. A p-value of <0.05 was considered significant, and the 95% confidence interval (CI) for the difference in means of each variable was calculated.

Results

Specimens

21 dogs were included according to the inclusion criteria. Included breeds were Pomeranian (n = 3), Cocker Spaniels (n = 8), Miniature Poodle (n = 1), Japanese Spitz (n = 2), Maltese (n = 2), and crossbreed (n = 5). From these, 20 were female and one was a castrated male. The dogs had a median weight of 5.95 kg (range, 1.7-8.85 kg) and a median body condition score of 4 (range, 2-6).

Preoperative plan and assessment

The characteristics of the ideal insertion angle and site were determined based on the anatomical landmark to achieve maximum bone purchase (Table 1). The ideal insertion corridor angles, maximum lengths of pin corridor and minimum widths of the pedicle in the thoracolumbar vertebrae were evaluated (Table 1).

Postoperative assessment

Assessment of corridor accuracy

The postoperative pin placement accuracy was evaluated by comparing the insertion angle, the corridor angle, the maximum length of the pin and the minimum width of the pedicle (Table 2).

The insertion angle differed between the preoperatively planned and the postoperatively measured values for T12, T13, and L1 in both groups. However, the differences between the planned and postoperative values in the novice group were less than the differences in the experienced group in all vertebrae (p-value < 0.05). The corridor angle differences were 5.95° ± 3.05 in T12, 5.46° ± 3.52 in T13, and 4.72° ± 3.5 in L1 for the experienced group, whereas in the novice group, these differences were 2.04° ± 1.59, 2.24° ± 2.11, and 42.65° ± 2.19, respectively.

The maximum postoperative lengths of the pin corridors were 10.13 mm ± 0.62 in T12, 9.82 mm ± 0.79 in T13, and 9.50 mm ± 0.88 in L1 for the experienced group. In the novice group, the respective measures were 10.45 mm ± 0.35 in T12, 10.21 mm ± 0.54 in T13, and 10.08 mm ± 0.67 in L1. Since the 95% CI did not contain the null value, there was a difference between the two groups.

The minimum postoperative widths of the pedicle were 1.18 mm ± 0.6 in T12, 1.30 mm ± 0.58 in T13, and 1.58 mm ± 0.53 in L1 for the experienced group while these were 1.49 mm ± 0.44 in T12, 1.59 mm ± 0.65 in T13, and 1.7 mm ± 0.53 in L1 for the novice group. The 95% CI contained zero, and there was no statistically significant difference between the two groups.

Evaluation of breach

A total of 63 pins were inserted by the experienced and novice groups (Table 2). Based on postoperative CT, 61 out of 63 pins (96.8%) in the experienced group were fully contained inside the vertebral body and lamina, and two pins (3.2%) were perforating the vertebral canal (grade 3, 2-4

Table 2. Comparison between experienced and novice surgeons with PSGs

	Experience group	Novice group	p-value	95% confidence interval
Breach (number)	2	0	-	
Corridor angle difference (degree)				
T12	5.95 ± 3.05	2.04 ± 1.59	< 0.05	
T13	5.46 ± 3.52	2.24 ± 2.11	< 0.05	
L1	4.72 ± 3.5	2.65 ± 2.19	< 0.05	
Corridor length (mm)				
T12	10.13 ± 0.62	10.45 ± 0.35	0.047	−0.63 to −0.04
T13	9.82 ± 0.79	10.21 ± 0.54	0.074	−0.81 to −0.04
L1	9.50 ± 0.88	10.08 ± 0.67	0.02	−1.07 to −0.1
Pedicle width (mm)				
T12	1.18 ± 0.56	1.49 ± 0.44	0.057	−0.61 to 0.01
T13	1.30 ± 0.58	1.59 ± 0.65	0.127	−0.68 to 0.09
L1	1.58 ± 0.53	1.7 ± 0.53	0.501	−0.44 to 0.22

The data were summerized as mean ± standard deviation (SD).
L, lumbar vertebra; T, thoracic vertebra.

mm breach). However, there was no perforation or breach in the novice group. Novice surgeons performed 63 guided surgeries, from which they encountered problems in seven pins. In two cases, the sleeve part of the guide was broken during manipulation, and in five cases, the issue was the contact between PSGs and the bone. These issues were due to soft tissue collision (one case), rib head interference (one case), PSGs slipping (two cases), and difficulties in the manipulation of PGS due to the small size of the body and PSGs (one case).

Discussion

This study showed that the use of 3D printed PSGs for pin insertion in the thoracolumbar region by novice surgeons is an accurate and safe alternative to freehand screw placement in toy, small and medium breed dogs. In the experienced group of this study, two pins breached the wall of the vertebral canal. In the novice group, all pins were inserted in concordance with the ideal surgical plan. The outcome of this study is better than the outcomes of previous studies which reported the incidence of vertebral canal breach, when using similar 3D printed PSGs in veterinary medicine, to be in a range between 3.3 and 21% (8,11,13,16,21). Although direct comparison with them is difficult due to surgical differences in the anatomies, using the PSGs allows to get favorable surgical outcomes. Therefore, even novice surgeons who have never operated before could achieve better surgical accuracy outcomes with the help of PSGs than experienced surgeons who used the freehand method.

The optimal angle by Watine et al is considered to be 60 degrees, however, it is recommended to modify the angle to 30.5° in T12, 44.5° in T13, and 60° in L1, considering the relationship with insertion points and the surrounding soft tissue (34). That's because the surgeon can only look at a limited surface during the insertion of the pin, since the soft tissue would obscure the surgical field (32,34). In addition, the presence of ribs would obscure the visual field of the surgeon and lead to irreversible damage to the chest cavity (32,34). If the pin is inserted correctly, the maximum length will be longer than that of the nonoptimal corridor, and the maximum width will also be larger (15,34,36). To procure maximum bone purchase, the ideal insertion angles of the thoracolumbar vertebrae in this study were planned to be 51.02° ± 2.23 for T12, 51.9° ± 3.16 for T13, and 52.52° ± 5.56 for L1. The differences between the planned and postoperative angle in novice groups were less than those of the experienced group in all vertebrae ($p < 0.05$). In addition, the average maximum length was longer, and the minimum width of the pedicle was wider in the novice group than those in the experienced group. There were no statistically significant differences between groups ($p > 0.05$). Therefore, it could be concluded that using PSGs has the advantage of inserting implants in an ideal location without any need for modification of the insertion angle or position.

Spine guides are different from other guides (4,8,9,12,13,21,23). There are distinct prominences and depressions in the spine structure, including spinous, articular, and transverse processes which could be used to position the guide accurately on the bone (4,8,13,21). It is common to use temporary K-wires in corrective surgery to ensure stability when combined with a guide and bone (14,17,22-24,28). However, it is impossible to apply a temporary pin in spinal surgery without soft tissue dissection around the spinous process (8,12). Therefore, the PSGs for spinal surgery should have relatively more bone contact than the corrective osteotomy guide in dogs, to provide easy manipulation and secure stability during surgery (8,12). In this study, PSGs were designed to contact the bone on three different anatomic regions, including spinous and articular processes and lamina and a few guide-related issues occurred during the operation (in total, seven occurrences) which included broken PSGs (two cases), soft tissue collision (one case), rib head interference (one case), PSGs slipping (two cases), and difficulties in the manipulation of PGS due to the small size of the body and PSGs (one case). Therefore, the collision parts of the PSGs were grounded and removed, and the experiments were carried on. Although there was no problem with the postoperative insertion angle and width because the residual part of the PSGs could contact the bone, further studies are needed for standard guide design production to prevent collision and improper contact (12).

This study has some limitations. First, this study designs included only one experienced and seven novice surgeons, which could not reflect the statistical average of experienced group (type II error). Second, since this study was conducted on cadavers, and it couldn't reflect the clinical circumstances including vertebrae malformation, bone changes, and bleeding during the surgeries. Moreover, all soft tissues were removed entirely to expose the space where guides and pins would be placed in this cadaver experiment. The procedures like removing surrounding muscles would require additional time and interfere with recovery in clinical cases. The PSGs would need to be modified for attaching the guide accurately and safely while keeping the soft tissue removal at a minimum. Moreover, the usage of 3D printing technique might not be appropriate for real patients and emergency cases. It would require time-consuming preparation including a CT scan, surgical planning on CAD software, and production time in a 3D printer. Furthermore, in small and toy breed dogs, slices <1 mm with a significant overlap should be obtained to increase the accuracy of CT images and 3D reconstructed volume rendering. All of these would cost the owner an additional fee. Therefore, further studies are needed to assess the clinical outcome of using PSGs in a large population and to evaluate the accuracy of PSGs with applicability such as surgical time and PSG making time.

Conclusions

The aim of this study was to compare experienced and novice surgeons when using PSGs. Even though they had never inserted a pin into the bone before, novice surgeons using the 3D printed PSGs can achieve better or similar results in terms of accurate placement of pin/screws than experienced surgeons. Furthermore, the use of PSGs resulted in minimal differences between the preoperative surgical plan and post-operative outcomes. Therefore, the application of 3D-PSGs may represent a promising and easy treatment for pin or screw insertion in thoracolumbar vertebrae of dogs. This study will improve outcomes of operation on the stability of the thoracolumbar joint in toy, small and medium breed dogs in the future.

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Author Contributions

Author 1: co-conceived study, data collection, performed surgical procedures, interpretation of the results, manuscript preparation, critical review of the article, and approval of the final manuscript; Author 2: interpretation of the results, manuscript preparation, critical review of the article, and approval of the final manuscript; Author 3: co-conceived study, data collection, interpretation of the results, manuscript preparation, critical review of the article, and approval of the final manuscript.

Ethics Approval

All procedures were approved by the Chungnam National University Animal Care and Use Committee. 21 thoracolumbar vertebrae from toy, small and medium breed dog cadavers were obtained for this study through donations after euthanasia for reasons unrelated to the study.

Conflicts of Interest

The authors have no conflicting interests.

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