



**HAL**  
open science

## A morphometric analysis of thoracolumbar vertebrae in goat by computed tomography

Josephine Roels, Roy Hassoun, M Massenzio, S Ronel, Y Lafon, Eric Viguiet, Thibaut Cachon

### ► To cite this version:

Josephine Roels, Roy Hassoun, M Massenzio, S Ronel, Y Lafon, et al.. A morphometric analysis of thoracolumbar vertebrae in goat by computed tomography. *Veterinary and Animal Science*, 2022, 15, pp.100233. 10.1016/j.vas.2022.100233 . hal-04395406

**HAL Id: hal-04395406**

**<https://vetagro-sup.hal.science/hal-04395406v1>**

Submitted on 22 Jul 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

1 **A morphometric analysis of thoracolumbar vertebrae in goat by**  
2 **computed tomography.**

3

4 Josephine Roels<sup>1-2</sup>, Roy Hassoun<sup>2-3</sup>, M. Massenzio<sup>3</sup>, S.Ronel<sup>3</sup>, Y. Lafon<sup>3</sup>, Eric Viguier<sup>1-2</sup>, Thibaut  
5 Cachon<sup>1-2</sup>

6 <sup>1</sup>Department of Small Animal Surgery, VetAgro-Sup, Campus Vétérinaire de Lyon, 69280 Marcy  
7 L'Etoile, France.

8 <sup>2</sup>Université de Lyon, VetAgro Sup, UPSP 2016 A104, Unité ICE, Marcy l'Etoile, France.

9 <sup>3</sup>Université de Lyon, Université Claude Bernard Lyon 1, Univ Gustave Eiffel, IFSTTAR, LBMC  
10 UMR\_T9406, F69622, Lyon, France

11

12

13 Corresponding author

14 E-mail: [josephine.roels@vetagro-sup.fr](mailto:josephine.roels@vetagro-sup.fr)

15

16 These authors contributed equally to this work.

17

## 18 **Abstract**

19 The goat spine is widely used as an animal model for preclinical research in human medicine to test  
20 new spinal implants and surgical procedures. Therefore, precise morphometric data are needed. This  
21 study aims to provide morphometric data of the goat thoracolumbar vertebrae and to define the  
22 parameters/characteristics of the optimum implantation corridors for pedicle screws in the  
23 thoracolumbar spine in goat. Eleven 36-month-old adult alpine goats were included in this study, and a  
24 sample of 198 vertebrae was measured. Subsequently, transverse and sagittal images were obtained  
25 using a multi-detector-row helical computed tomography (CT) scanner. Measurements of the vertebral  
26 bodies (ventral body width VBW, ventral body depth VBD, ventral body height ventral VBHv, ventral  
27 body high dorsal VBHd, spinal canal depth SCD, spinal canal width SCW), pedicles (pedicle length  
28 PDL, pedicle width PDW, pedicle angle PA and pedicle axis length PAL), intervertebral disc (DT)  
29 and transverse process length (TPL) were performed with dedicated software. The vertebral bodies  
30 and the spinal canal were wider than deep, mostly evident in the lumbar region. The intervertebral  
31 discs were as much as 65.7% thicker in the lumbar spine than in the thoracic spine. The pedicles were  
32 longer than wide over the thoracic and lumbar spines. The insertion angles in pedicle were  
33 approximately 30° for the T2-T4 segment, 25° for the T5-T6 segment, 23° for the T6 to T11 segment,  
34 20° for T11 to L3, 25° for L4 and 30° for L5 and L6. In conclusion, the generated data can serve as a  
35 CT reference for the caprine thoracolumbar spine and may be helpful in using the goat spine as an  
36 animal model for human spinal research.

37

38 **Key-words:** goat, morphometric, spine, computed tomography, pedicular screw

39

## 40 **Introduction**

41 Spinal abnormalities in humans have major effects on skeletal growth and the development of  
42 various organs. Several studies are interested in developing new surgical techniques to correct these  
43 abnormalities.

44 The use of human specimens is the best way to mimic the physiological situation, but many  
45 difficulties are associated with their use, such as the restricted number of fresh healthy cadavers.  
46 Several healthy cadavers are needed to eliminate the wide scattering effect associated with biological  
47 variability (3). Thus, an appropriate animal model should be used to mimic the human spine with  
48 chosen biomechanical characteristics and anatomical dimensions that are as similar as possible to  
49 those in humans. In addition, precise geometrical data of animal models are needed for mathematical  
50 models (11,26). The similarity of the anatomical characteristics of the goat spine to the human spine  
51 and the rapid growth observed in goats between the ages of 6 weeks and 8 months and between  
52 childhood and maturity in humans make caprine models an interesting replacement (4,6,10,20).  
53 Moreover, several in vitro and in vivo studies have used the caprine model as an animal model for  
54 orthopedic and neurological research. However, in those studies, neurological trauma and loss of  
55 animals due to poor implant positioning because of an under/over estimation of pedicle angulation  
56 caused time and cost losses. These facts highlight the importance of spinal monitoring and  
57 morphometrical analysis of the goat spine (15,19-20,27).

58 Computed tomography (CT), a noninvasive imaging technique, has been used worldwide in  
59 humans and in animals as a gold standard to perform in vivo morphometric analysis of the spine and  
60 to determine variations in the vertebrae size and shape (1,12,18). Morphometric studies have many  
61 limiting factors, such as measurement accuracy and viewer control settings, factors that should be  
62 assessed.

63 Morphometry of the goat thoracolumbar spine is important for studies that contemplate its use.  
64 Design strategies, surgical techniques and interpretation of results derived from such studies require  
65 morphometry. The aim of this study is to provide quantitative reference values and a complete  
66 comprehension of the pedicle morphology and angulation in healthy adult caprine spine models using  
67 computed tomography.

68

## 69 **Materials and methods**

### 70 **Animals**

71 This study was approved by the institutional animal care and use committee at the School of VetAgro-  
72 Sup. Eleven adult alpine goats without any history or clinical signs related to spinal diseases were  
73 included in this study. All goats came from the same batch. The mean body weight of goats was 42.5  
74 kg.

75

## 76 **Computed tomography (CT) Examination**

77 The goats were euthanized for other experimental studies unrelated to this study. The goats  
78 were positioned in dorsal recumbency in a perpendicular position of the spine relative to the  
79 radiographic beam. CT scans were performed from the cranial aspect of T2 to the caudal aspect of L6  
80 with a multidetector-row helical CT unit General Electric's, Brightspeed 16 elite (GE Healthcare,  
81 Buckinghamshire, England, Great Britain).

82 The technical settings were 120 kV, 150 mA, 1-second tube rotation and 0.625 pitch. The data  
83 were reconstructed to a transverse, sagittal and frontal image series with slice thickness ranging  
84 between 0.2 and 0.8 mm using a high-frequency image reconstruction algorithm (Osirix Imaging  
85 Software). Transverse images were reconstructed parallel to the third level of the cranial endplate of  
86 the vertebral body, whereas sagittal images were reconstructed at the midsagittal plane of the vertebra  
87 to measure the vertebral body and intervertebral disc dimensions.

88 Three parameters were measured from the sagittal images, and eight parameters were  
89 measured from the transverse images for each spinal level. These parameters were measured as  
90 described in the human and veterinary literature (14,28). In addition, the parameters of the  
91 implantation corridor for pedicular screws were measured from the transverse images as described by  
92 McLain (16).

93 The morphometrical parameters obtained from transverse images included vertebral body  
94 width (VBW), which is the distance between the lateral border measured at the third cranial endplate  
95 of the vertebral body, and vertebral body depth (VBD), reflecting the distance between the dorsal and  
96 ventral borders of the vertebral body. Spinal canal width (SCW) and depth (SCD) were obtained by  
97 measuring the distance between the axial pedicle cortical and the dorsal border of the vertebral body to

98 the lamina at the midline, respectively. Transverse process length (TPL) was assessed by measuring  
99 the distance between the two tips of the transverse process (Figure 1).

100

101 The morphometric parameters obtained from sagittal images included the distance between the  
102 cranial and caudal endplates of the vertebral body at the dorsal margin, termed the vertebral body  
103 height dorsal (VBHd); the same distance at the ventral margin was termed the vertebral body height  
104 ventral (VBHv). Disc thickness (DT) was measured at the mid-level of the intervertebral disc (Figure  
105 2).

106

107 Parameters concerning the implantation corridor for the pedicular screw were assessed by  
108 measuring the pedicle width (PDW), pedicle length (PDL), pedicle angle (PA) and pedicle axis length  
109 (PAL) on transverse images (Figures 3 and 4). PDW was defined as the narrowest part of the pedicle.  
110 In the thoracic vertebrae, PDL reflects the distance between the dorsal pedicle cortex and the line  
111 perpendicular to the vertebral midline (tangent to the ventral border of the spinal canal). In the lumbar  
112 vertebrae, PDL reflects the distance between the dorsal pedicular cortex and the junction of the ventral  
113 border of the transverse process. PAL was measured from the dorsal cortex of the articular facet to the  
114 midpoint of the ventral vertebral body cortex. Finally, PA was the angle between the PAL and the  
115 vertebral sagittal midline.

116

### 117 **Statistical analysis**

118 Descriptive data are presented as means and standard deviations (SDs). Assessment of intraobserver  
119 reliability was calculated by randomly selecting three goats in which measurements were performed  
120 four times by the same operator. A coefficient of variation (CV) was used to assess reliability. The  
121 Mann-Whitney/Two-tailed test was used to determine differences between the vertebral levels for each  
122 parameter. Statistical analysis was performed with dedicated available software (Microsoft Excel  
123 2010, XLSTAT ®). The level of significance was set at  $p < 0.05$ , and  $CV < 5\%$  was considered  
124 acceptable.

125

## 126 **Results**

127 A total of 198 vertebrae (132 thoracic vertebrae and 66 lumbar vertebrae) from 11 mature  
128 goats' thoracolumbar vertebral columns were measured. CT images revealed that all the goats had 6  
129 lumbar vertebrae and 13 thoracic vertebrae (the first thoracic vertebra was not measured in this study).  
130 Assessment of intraobserver reliability revealed a high level of reliability (Table 1), with values  
131 ranging between 0.06% and 3.13%. Tables 2, 3, and 4 present the means and standard deviations of  
132 the CT measurements in the thoracolumbar spines of the 11 goats.

133

### 134 *Vertebral body measurements (transverse and sagittal view)*

135 Values and variation of the ventral body width (VBW) are summarized in Table 2 and Figure  
136 5. The value of VBW was greater for T2, T3 and for L5 and L6. VBW was significantly higher in the  
137 lumbar segment compared to the thoracic segment ( $p=0.02$ ). The value of the ventral body depth  
138 (VBD) was fairly constant around 12 mm in the thoracic and lumbar segment (Table 2 and Figure 5).

139 In the thoracic region, VBHd was constant, at approximately 22 mm, and then increased  
140 steadily from T9 until T13 to reach 29 mm. In the lumbar region, VBHd was fairly constant at  
141 approximately 34 mm, except at L6, where it was smaller at 29.6 mm. Similar to VBHd, VBHv was  
142 smaller at the level of L6 (26.7 mm). VBHv was constant at approximately 21 mm from T2 to T9 and  
143 then increased from T10 to T13. VBHd was always larger than VBHv in both the lumbar and thoracic  
144 regions (Table 2 and Figure 6).

145 DT ranged between 1.71 and 2.83 mm in the thoracic region, while in the lumbar region, it  
146 showed greater values ranging between 2.67 and 3.32 mm (Table 2). The largest point of DT was  
147 between the fifth and the sixth lumbar vertebrae. In the lumbar segment, DT was 1 mm thicker than in  
148 the thoracic spine.

149

### 150 *Spinal canal and transverse process measurements (transverse view)*

151 Table 3 and Figure 7 show that T2, T3, T4 and L4, L5, L6 vertebrae share the maximal spinal  
152 canal width (SCW) and depth (SCD). Concerning transverse process length, it was constant at

153 approximately 41 mm in the thoracic region. In the lumbar region, the value measured twice the length  
154 (around 90mm). The maximum TPL was observed in L4 and L5 (Table 3).

155

156 *Pedicle parameters (transverse view)*

157 The pedicle parameters are listed in Table 4; interesting variations are reported in Figure 8.  
158 Pedicle width (PDW) was significantly greater in the lumbar vertebrae, ranging from 5.20 to 8.10 mm,  
159 than PDW in the thoracic vertebrae, which ranged from 4.49 to 6.04 mm ( $p=0.002$ ). PDW reached its  
160 maximum at the sixth lumbar vertebra (8.10) and its minimum at T13 (4.49).

161 Pedicle length (PDL) showed a significant difference ( $p=0.0001$ ) between the thoracic and  
162 lumbar vertebrae, reaching its maximum at L3 and its minimum at T11. In the thoracic segment, the  
163 PDL values ranged from 8.43 to 11.11 mm, and in lumbar segment, the PDL values ranged from 11.37  
164 to 12.28 mm. Pedicle axis length (PAL) showed a significant difference ( $p=0.0008$ ) between the  
165 thoracic and lumbar vertebrae, reaching its maximum at the L6 level and its minimum at T2. PAL  
166 ranged between 29.1 and 32.5 for the lumbar vertebrae and between 24.3 and 27.7 for the thoracic  
167 vertebrae. Pedicle angle (PA) showed higher value between T2 and T3 (around 30 degrees) and  
168 between the L5-L6 segment (around 30 degrees to reach its maximum point of 33.4 degrees at L6).  
169 T12 and T13 showed the lowest pedicular angulation (around 20 degrees). PA value was around 25  
170 degrees for T4-T5, 23 degrees between T6 and T11, 22 degrees between L1 and L3 and at 24 degrees  
171 for L4.

172 In Table 5, mean values and standard deviation for each parameter are summarized for the  
173 thoracic and lumbar segment.

174

## 175 **Discussion**

176 Several in vitro studies have used the goat as an animal model for orthopedic spinal research.  
177 The goat is particularly interesting because of the similarity of its spine to the human spine and the  
178 rapid growth observed in goats between the ages of 6 weeks and 8 months, which mimics human  
179 growth. Moreover, goats are readily available, inexpensive, easy to handle and well accepted as an



180 ethical animal model. Therefore, precise morphometric data of the goat spine are mandatory to  
181 improve the quality of implant fixation and implantation and, thus, to avoid loss of the animal (5-6). In  
182 a previous study, eleven goats were used to develop a Shilla-like growth stem (15). During the  
183 experiment, one goat became paraplegic after the insertion of a pedicular screw. In another study  
184 about development of a scoliosis model by Zhang *et al.*, 28% (4/14) of goats were excluded from the  
185 results due to a failure in pedicular screw implantation (15,27). In this last study, pedicular screws  
186 were inserted between T6-T7, with an angulation of 30 degrees in the sagittal plane and an angulation  
187 of 40 degrees at the lumbar level. In the current study, the implantation corridor for the pedicle screws  
188 at the level of T6-T7 was 23 degrees and did not exceed 30 degrees in the lumbar region. These facts  
189 explain the needed CT reference values to establish safe implantation corridors for pedicular screws in  
190 the caprine thoracolumbar spine.

191 In humans, Roy-Camille *et al.* recommended that the pedicle screw should be inserted in a  
192 straight (vertical) direction (22). It is interesting to note that the pedicle angulation in goats is more  
193 oblique than in humans. Therefore, using a straight screw insertion technique could lead to a high  
194 misplacement rate in goats. Thus, an oblique trajectory should be used. This conclusion was also  
195 reported in sheep (10).

196 The results of the present study show that the spinal canal and vertebral bodies in goats are  
197 wider than deep, especially in the lumbar region. However, the spinal canal tends to have a  
198 comparable width and depth in the caudal thoracic region. The intervertebral discs are the thickest in  
199 the lumbar region. Pedicles are higher and longer than wide throughout the entire thoracic and lumbar  
200 spine. The disc thickness is 65.7% thicker in the lumbar vertebrae than in the thoracic vertebrae. A  
201 thicker disc offers better mobility than a thinner disc (8). Conversely, transverse processes are longer  
202 in the thoracic region than in the lumbar region. The latter findings may explain the limited lateral  
203 flexion and axial rotation of the lumbar region (25).

204 In humans, spinal canal dimensions have an influence on movement upon the coronal axis of  
205 the spine; for instance, larger dimensions facilitate bending movement (9,23). In the current study, the  
206 dimensions of the spinal canal were maximal at two points: L6 and T8. Based on these results, we  
207 expect the maximum flexion point to be at L6 and the minimal flexion point to be at T9. No

208 biomechanical study of this nature has been carried out on the goat spine. To our knowledge, this is  
209 the first report of this value in the goat spine.

210 In a study conducted by Qui *et al.*, eleven goats with an average weight of 28 kg underwent  
211 magnetic resonance imaging for the caudal thoracic spine (T9-T13), and morphometrics data were  
212 measured (19). As an example, the T10 body height value was 23.7 mm vs 23 mm in the current  
213 study, which confirms the reliability of the results obtained. Moreover, the age of the goats used in the  
214 study of Qui *et al.* ranged between 26 and 32 months, while in our study, the age average was 48  
215 months. These results support the fact that the vertebral column of goats reaches its maximum growth  
216 size between 26 and 32 months (19).

217 In humans, pedicles represent a maximum resistance site for the placement of screws. The  
218 trabeculae in the pedicles seem to be thicker and stronger than in the vertebral body. In addition, the  
219 pedicular cortex is thicker, allowing an effective holding of screws (12); thus, the pedicular  
220 morphometry plays an important role in vertebral fixation. The screw diameter should be 80% of the  
221 pedicle diameter (28). Therefore, the current study provides the precise morphometric data needed for  
222 the use of goats as a research model for pedicular fixation.

223 To our knowledge, this is the first report of the pedicular implantation corridors of the entire  
224 thoracolumbar goat spine (except for the first thoracic vertebra T1). However, the majority of cases  
225 concern the segment T3-L5 due to the complexity of the surgical approaches for T1, T2, T3 and L6.  
226 Their description has little relevance for pedicle attachment but is provided to fill in the lack of the  
227 morphometric data for goats in the literature. Plus, our study provides the first reports of certain  
228 parameters, such as PDL, PDW, PAL and PA, for the goat's thoracolumbar spine.

229 It is interesting to highlight that the pedicle width was thicker in the lumbar region than in the  
230 thoracic region. It is known that the widest pedicles allow thicker screws to be inserted, thus providing  
231 better stability and avoiding implant failure, as seen in the studies performed by Zhang *et al.* and  
232 Braun *et al.* (5,27). In our study, PAL was longer in the lumbar vertebrae than in the thoracic  
233 vertebrae. Longer pedicles allow longer screw insertion in the lumbar vertebrae and could provide  
234 better stability.

235

236 Variation of pedicle angle has been evaluated. These data correspond to the "optimum"  
237 insertion angle, which means that the insertion angle can vary around this "optimal" value by four  
238 degrees without incurring a major risk. We can therefore simplify the results by estimating insertion  
239 angles of approximately 30 ° for the T2-T3 segments, 25 ° for the T4-T5 segments, 23 ° for the T6-  
240 T11 segments, 20 ° for the T12-T13 segments, 22 ° for the L1-L3 segments, 24° for the L4 segment  
241 and 30° for the L5-L6 segments.

242 Jahng *et al.* reported a significant difference between the insertion angle of the thoracic region  
243 and the lumbar region in a study performed in sheep; those findings correlate with the results obtained  
244 in the current study (10). This significant difference between the lumbar and thoracic spine could be  
245 secondary to the type of vertebra (thoracic type I/ lumbar type II).

246 CT scan is the gold standard for the evaluation of the spine bony structures as seen in the  
247 current study. The quality of the perceived image depends on the calibration of the imaging  
248 parameters, the reconstruction algorithm of the reformatting parameters and the display mode (24).  
249 Dorsal recumbency is the position of choice for spinal computed tomography evaluation. This position  
250 reduces motion artifacts resulting from respiratory movements occurring during image acquisition  
251 (24). In the current study, goats were placed in sternal decubitus because it is the natural position of  
252 the spine and can mimic the same abnormalities, especially kyphosis in the lumbar spine. Goats were  
253 also euthanized before the study and CT scan; thus, breathing did not influence the image quality.

254 There are several limitations of our study. First, a data limitation is noted due to the limited  
255 number of available goat spines. To overcome this problem, the significance of the analysis was set  
256 using a low p value ( $P < 0.05$ ); in addition, each goat has 19 thoracolumbar vertebrae, ultimately  
257 constituting a sample size of 198 thoracolumbar vertebrae. However, the animals were of the same  
258 age, weight, sex and breed. Furthermore, the measurements obtained in this study had a small variance  
259 around the mean, indicating that a larger sample was not necessary. In addition, a comparable sample  
260 number has been used in similar studies (13-14). Second, the positioning of goats, particularly  
261 regarding the alignment of the spine in a single plane, can lead to measurement errors of the segment's  
262 length; however, we did not measure the length of the segments. Third, this study is not a direct  
263 anatomic study. Measurements were performed on CT scans, which may lead to some approximation

264 in the measurements. This technique was selected because CT is a noninvasive imaging modality and  
265 is a well-accepted method to assess spinal and vertebral morphometry in vivo. CT has been widely  
266 used in both humans and animal models (2,21,25). The CT scan parameters (i.e., slice thickness, pitch,  
267 and window width) used in this study follow the recommendations for orthopedics studies and are  
268 consistent with published spinal CT imaging protocols. The validation of the results obtained would  
269 have required an anatomical comparison. Since goats were sacrificed for further studies, it was  
270 unfortunately not possible to make this comparison.

271

## 272 **Conclusion**

273 In conclusion, this study provides a quantitative database of pedicle screw implantation  
274 corridors and morphometric dimensions of the normal thoracolumbar goat spine. These results should  
275 be considered when using pedicle screws on goat spines in experimental studies (i.e., when testing  
276 new implants or surgical techniques) to provide correct and safer screw positions. Thus, these results  
277 may limit postoperative complications and thereby limit the use of live animals.

278

## 279 **References**

- 280 1. Abuzayed, B, B Tutunculer, B Kucukyuruk, and S Tuzgen. "Anatomic basis of anterior and  
281 posterior instrumentation of the spine: morphometric study." *Surg Radiol Anat* 32, no. 1  
282 (2010): 75-85
- 283
- 284 2. Bergmann G, Graichen F, Rohlmann A. Hip joint forces in sheep. *J Biomech* 1999; 32(8):  
285 Bland, J M, and D G Altman. "Statistical methods for assessing agreement between two  
286 methods of clinical measurement." *Lancet* 1, no. 8476 (1986): 307-310.
- 287
- 288 3. Bland J M, and D G Altman. "Statistical methods for assessing agreement between two  
289 methods of clinical measurement." *Lancet* 1, no. 8476 (1986): 307-310.

290  
291  
292  
293  
294  
295  
296  
297  
298  
299  
300  
301  
302  
303  
304  
305  
306  
307  
308  
309  
310  
311  
312  
313  
314

4. Braun, J T, M Hoffman, E Akyuz, J W Ogivie, D S Brodke, and K N Bachus. "Mechanical modulation of vertebral growth in the fusionless treatment of progressive scoliosis in an experimental model." *Spine* 31, no. 12 (2006): 1314-1320.
5. Braun, JT, JW Oglivie, E Akyuz, D Brodke, KN Bachus, and RM Stefko. "Experimental scoliosis in an immature goat model: a method that creates idiopathic-type deformity with minimal violation of the spinal elements along the curve." *Spine* 28 (2003): 2198-2203.
6. Braun, JT, and E Akyuz. "Prediction of curve progression in a goat scoliosis model." *Spinal Disord Tech* 18 (2005): 272-276.
7. Cachon, T. Validation pré-clinique d'un dispositif innovant de correction de la scoliose. Biomécanique [physics.med-ph]. Université de Lyon, 2018. Available from : <https://www.theses.fr/2018LYSE1355>.
8. Haussler, KK. "Anatomy of the thoracolumbar vertebral region." *Vet Clin North Am Equine Pract* 15, no. 1 (1999): 13-26.
9. Inufusa , A, H S An, T H Lim , T Hasegawa, and V Haughton. "Anatomic changes of the spinal canal and intervertebral foramen associated with flexion-extension movement." *Spine* 21, no. 21 (1996): 2412-2420.
10. Jahng, TA, TS Fu, and DH Kim. "Open versus endoscopic lumbar pedicle screw fixation and posterolateral fusion in a sheep model: a feasibility study." *Spine J* 4, no. 5 (2004): 519-526
11. Kiefer, A, A Shirazi-Adl, et M Parnianpour. "Stability of the human spine in neutral postures." *Eur Spine J* 6, n° 1 (1997): 45-53.

- 315 12. Krag, M H, D L Weaver, B D Beynnon , et L D Haugh. "Morphometry of the thoracic and  
316 lumbar spine related to transpedicular screw placement for surgical spinal fixation." *Spine* 13,  
317 n° 1 (1988): 27-32.
- 318
- 319 13. Kumar, N, S Kukreti, M Ishaque, and R Mulholland. "Anatomy of deer spine and its  
320 comparison to the human spine." *Anat Rec* 260, no. 2 (2000): 189-203.
- 321
- 322 14. Mageed, M, D Berner, C Hohaus, W Brehm, and K Gerlach. "Morphometrical dimensions of  
323 the sheep thoracolumbar vertebrae as seen on digitised CT images." *Lab Anim Res* 29, no. 3  
324 (2013): 138-147.
- 325
- 326 15. McCarthy, RE, D Sucato, JL Turner, H Zhang, M Henson, and K McCarthy. "Shilla Growing  
327 Rods in a Caprine Animal Model: A Pilot Study." *Clin Orthop Relat Res* 468 (2010): 705-710.
- 328
- 329 16. McLain, R F, S A Yerby , and T A Moseley . "Comparative morphometry of L4 vertebrae:  
330 comparison of large animal models for the human lumbar spine." *Spine* 27 (2002): 200-206.
- 331 17. Newton, PO, DR Wenger, and B Yaszay. "Idiopathic Scoliosis." In *Lovell and Winter's*  
332 *Pediatric Orthopaedics*, by Weinstein SL and Flynn JM, edited by Weinstein SL and Flynn  
333 JM., 629-697. Philadelphia: Lippincott Williams and Wilkins, Wolters Kluwer Health, 2013.
- 334
- 335 18. Olsweski, J M, E H Simmons, F C Kallen, F C Mendel, C M Severin, et D L Berens.  
336 "Morphometry of the lumbar spine: anatomical perspectives related to transpedicular  
337 fixation." *J Bone Joint Surg Am* 72, n° 4 (1990): 541-549.
- 338
- 339 19. Qui, F, et al. "Influence of vertebral column distraction on spinal cord volume: an  
340 experimental study in a goat model." *Arch Orthop Trauma Surg* 135 (2015): 1201-1210.

- 341
- 342 20. Quin, J, et al. "Artificial cervical vertebra and intervertebral complex replacement through the
- 343 anterior approach in animal model: a biomechanical and in vivo evaluation of a successful
- 344 goat model." *PLos One* 7, no. 12 (2012): e52910.
- 345
- 346 21. Riley LH 3rd, Eck JC, Yoshida H, Koh YD, You JW, Lim TH. "A biomechanical comparison
- 347 of calf versus cadaver lumbar spine models". *Spine* 2004; 29(11): E217-220.
- 348
- 349 22. Roy-Camille, R, G Saillant, and C Mazel. "Internal fixation of the lumbar spine with pedicle
- 350 screw plating." *Clin Orthop Relat Res* 203 (1986): 7-17.
- 351
- 352 23. Schönström, N, S Lindahl, J Willén, and T Hansson. "Dynamic changes in the dimensions of
- 353 the lumbar spinal canal: an experimental study in vitro." *J Orthop Res* 7, no. 1 (1989): 115-
- 354 121.
- 355
- 356 24. Tins, B. "Technical aspects of CT imaging of the spine." *Insights imaging* 1, no. 5 (2010):
- 357 349-359.
- 358
- 359 25. Wilke HJ, Kettler A, Claes LE. "Are sheep spines a valid biomechanical model for human
- 360 spines?" *Spine* 1997; 22(20): 2365-2374.
- 361
- 362 26. Yoganandan, N, S Kumaresan, L Voo, and FA Pintar. "Finite element applications in human
- 363 cervical Spine modeling." *Spine* 21, no. 15 (1996): 1824-1834.
- 364

365 27. Zhang, YG, GQ Zheng, XS Zhang, and Yan Wang. "Scoliosis Model Created by Pedicle  
 366 Screw Tethring in Immature Goats: The Feasibility, Reliability, and Complications." *Spine* 34,  
 367 no. 21 (2009): 2305-2310.

368  
 369 28. Zhou, S H, I D McCarthy, A H McCregor, R R Coombs, and S P Hughes. "Geometrical  
 370 dimensions of the lower lumbar vertebrae--analysis of data from digitized CT images." *Eur*  
 371 *Spine J* 9, no. 3 (2000): 242-248.

372

373

374 **Tables**

375 *Table 1. Means and standard deviations of the coefficient of variation (CV) values of the*  
 376 *thoracolumbar spine measurements of the three goats.*

377 *DT= Disc Thickness, VBW= Vertebral body width, VBD= Vertebral Body Depth, VBHd= Vertebral*  
 378 *Body Height dorsal, VBHv= Vertebral Body Height ventral, SCW= Spinal Canal Width, SCD= Spinal*  
 379 *Canal Length, TPL= Transverse Process Length, PDL= Pedicle Length, PDW= Pedicle Width, PA=*  
 380 *Pedicle Angle, PAL = Pedicle Axis Length.*

Dimension	Mean CV %
VBHd	0.3686±0.273
VBHv	0.5734±0.393
DT	1.7505±0.852
VBW	0.8735±0.312
VBD	0.9694±0.558
SCW	0.7073±0.755
SCD	1.4508±1.076
TPL	0.3319±0.25
PDL	0.5324±0.211
PDW	1.1618±0.999
PAL	2.46 ±0.7204



PA	0.326±0.173
----	-------------

381

382

383 **Table 2.** Means and standard deviations of the CT measurement dimensions related to intervertebral  
384 disc and vertebral bodies of 11 healthy goat thoracolumbar spines.

385 *DT= Disc Thickness, VBW= Vertebral Body Width, VBD= Vertebral Body Depth, VBHd= Vertebral*  
386 *Body Height dorsal, VBHv= Vertebral Body Height ventral.*

Vertebrae	Transverse view		Sagittal view		
	VBW (mm)	VBD (mm)	DT (mm)	VBHd (mm)	VBHv (mm)
T2	18.37±2.7	12.10±0.4	2.83±0.4	20.71±0.7	20.55±0.7
T3	16.76±1.5	12.30±0.8	2.19±0.2	21.33±0.8	22.45±3.2
T4	15.17±2.0	12.16±0.6	1.93±0.2	21.12±1.2	21.77±0.9
T5	13.78±1.2	12.09±0.8	2.00±0.4	21.14±0.9	21.38±0.8
T6	13.71±1.0	11.84±0.9	1.77±0.2	20.90±0.9	20.78±0.9
T7	13.41±0.9	12.39±0.6	1.71±0.2	20.87±0.8	20.99±1.0
T8	13.12±0.8	12.24±0.5	1.79±0.2	21.85±1.4	21.65±1.0
T9	13.14±1.0	12.19±0.7	1.76±0.3	23.00±1.1	22.40±1.2
T10	13.41±1.4	11.66±0.6	1.74±0.4	24.06±1.3	23.22±1.3
T11	13.96±1.2	12.00±1.0	1.77±0.2	25.48±1.5	24.49±1.2
T12	14.36±1.2	12.03±0.8	1.90±0.2	27.79±1.2	25.15±1.8
T13	14.58±1.9	12.70±0.7	1.99±0.4	29.83±1.7	28.63±1.3
L1	15.43±1.5	12.96±0.5	2.67±0.6	33.01±1.3	31.15±1.3
L2	15.25±1.1	13.21±0.9	2.89±0.7	34.26±1.4	32.25±1.4
L3	14.75±1.4	12.63±0.9	2.84±0.7	34.69±1.2	32.26±1.2
L4	15.08±1.2	12.17±0.8	2.73±0.5	34.94±1.3	33.25±1.3
L5	17.16±1.5	11.66±0.7	2.91±0.6	34.52±1.8	32.01±2.1
L6	18.71±2.4	11.40±0.8	3.32±0.8	29.63±2.1	26.67±1.8

387

388

389 **Table 3.** Means and standard deviations of the CT measurement dimensions related to the spinal  
 390 canal and transverse processes of 11 healthy goat thoracolumbar spines.  
 391 SCW= Spinal Canal Width, SCD= Spinal Canal Depth, TPL= Transverse Process Length.

	SCW (mm)	SCD (mm)	TPL (mm)
T2	12.60±1.4	9.57±0.2	42.69±3.0
T3	12.13±1.0	9.38±0.3	42.56±2.5
T4	11.02±1.2	9.16±0.6	40.77±2.4
T5	10.25±0.5	8.53±0.6	41.22±1.8
T6	9.53±0.4	8.34±0.5	38.97±1.7
T7	9.27±0.4	8.20±0.4	38.38±2.4
T8	9.07±0.4	7.94±0.4	39.53±2.2
T9	9.13±0.3	8.12±0.3	40.24±2.3
T10	9.19±0.5	7.84±1.0	40.21±2.0
T11	9.26±0.4	8.12±0.4	39.67±2.8
T12	10.07±0.5	8.70±0.7	42.03±3.2
T13	9.88±0.4	8.38±0.6	45.64±2.3
L1	10.24±0.4	8.81±0.7	92.63±8.1
L2	10.63±0.3	9.01±0.6	101.86±5.7
L3	11.25±0.4	9.38±0.8	105.48±6.9
L4	12.12±0.8	10.06±0.8	108±8.6
L5	14.35±1.2	11.14±0.8	108.65±8.7
L6	16.68±0.7	10.53±0.9	89.53±7.8

392

393

394 **Table 4.** Means and standard deviations of the CT measurement dimensions and angles related to the  
 395 pedicles of 11 healthy goat thoracolumbar spines.

396 PDL= Pedicle Length, PDW= Pedicle Width, PA= Pedicle Angle, PAL = Pedicle Axis Length

	PDL (mm)	PDW (mm)	PA (°)	PAL (mm)
T2	9.54±0.6	6.04±0.4	30.334±0.62	24.3±1.5

T3	9.44±0.3	5.87±0.3	30.457±0.55	25.3±1.5
T4	9.60±0.3	5.38±0.2	26.359±0.77	26.2±1.4
T5	10.30±1.0	5.18±0.4	24.465±0.45	26.8±1.3
T6	9.82±0.7	4.88±0.4	23.214±0.46	27.2±1.3
T7	9.72±0.8	4.97±0.4	22.663±0.63	27.2±1.2
T8	9.24±0.7	4.91±0.3	23.059±0.73	26.3±1.1
T9	8.84±0.4	5.07±0.4	22.944±0.58	25.2±1.0
T10	8.52±1.0	5.23±0.4	23.388±0.50	24.8±0.9
T11	8.43±1.0	5.61±0.5	23.957±0.80	24.3±1.3
T12	10.56±0.5	4.77±0.6	20.960±0.51	25.1±1.7
T13	11.11±0.5	4.49±0.3	20.050±0.49	27.7±1.3
L1	12.06±1.4	5.20±0.5	21.771±0.83	29.1±1.1
L2	12.24±1.5	6.24±0.8	22.596±0.91	30.6±1.1
L3	12.28±1.0	6.28±0.4	23.035±0.91	31.6±1.4
L4	12.14±0.9	6.39±0.5	24.061±1.12	31.6±2.3
L5	12.08±1.6	6.66±0.8	29.519±0.49	31.6±2.1
L6	11.37±1.2	8.10±1.0	33.440±1.23	32.5±2.2

397 **Table 5.** Means and standard deviations of the CT measurement dimensions and angles related to the  
398 pedicles of 11 healthy goat thoracolumbar spines.

Dimension (mm)	MEAN	
	Lumbar	Thoracic
VBHd	<b>33.51±2.5</b>	<b>23.39±3.2</b>
VBHv	<b>31.27±2.6</b>	<b>22.91±2.6</b>
DT	<b>2.89±0.7</b>	<b>1.90±0.4</b>
VBW	<b>16.06±2.3</b>	<b>14.22±1.9</b>
VBD	<b>12.34±1.0</b>	<b>12.14±0.8</b>
SCW	<b>12.54±2.4</b>	<b>9.92±1.2</b>
SCD	<b>9.82±1.1</b>	<b>8.44±0.7</b>
TPL	<b>101.03±10.7</b>	<b>40.86±3.1</b>
PDL	<b>12.03±1.3</b>	<b>9.60±1.1</b>
PDW	<b>6.48±1.1</b>	<b>5.13±0.5</b>
PA	<b>25.737±4.37</b>	<b>23.796±2.76</b>

PAL	25.9±1.0	31.2±1.0
-----	----------	----------

399  
400  
401  
402  
403  
404  
405  
406  
407  
408  
409  
410  
411  
412  
413  
414  
415  
416  
417  
418  
419  
420  
421  
422  
423

**Figure legends**

**Figure 1.** Transverse CT images obtained at the cranial aspect of L4 of a goat illustrating the measurements obtained for T2 through L6. Left is right. The measurements of interest obtained for each of the thoracolumbar vertebrae are vertebral body width (VBW), vertebral body depth (VBD), spinal canal width (SCW), spinal canal depth (SCD) and transverse process length (TPL).

**Figure 2.** Sagittal CT images with measurements at T10 in a goat illustrating the vertebral body height at the dorsal border (VBHd), at the ventral border (VBHv) and disc thickness (DT). Cranial is to the left.

**Figure 3.** Sagittal CT images with measurements at T10 in a goat illustrating the vertebral body height at the dorsal border (VBHd), at the ventral border (VBHv) and disc thickness (DT). Cranial is to the left.

**Figure 4.** Transverse CT images obtained at the cranial aspect of L4 of a goat. Left is right. The measurements of interest obtained were pedicle length (PDL), referring to pedicle type II (lumbar vertebrae); pedicle width (PDW); pedicle axis length (PAL); pedicle axis angle (PAA); and sagittal midline (ML) for each vertebra.

**Figure 5.** Variation of the ventral body width (VBW) and ventral body depth (VBD) (mean values).

**Figure 6.** Variation of the ventral body height dorsal (VBHd) and ventral body height ventral (VBHv) (mean values).

**Figure 7.** Variation of the spinal canal width (SCW) and spinal canal depth (SCD) (mean values).

**Figure 8.** Variation of the pedicle length (PDL), pedicle axis length (PAL) and pedicle angle (PA) (mean values).

















