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

3

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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.

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296
297
298
299
300
301
302
303
304
305
306
307
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309
310
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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
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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

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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

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

PAL	25.9±1.0	31.2±1.0
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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).















