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Load-displacement properties of the thoracolumbar calf spine: experimental results and comparison to known human data

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Abstract The availability of human cadaveric spine specimens for in vitro tests is limited and the risk of infection is now of vital concern. As an alternative or supplement, calf spines have been used as models for human spines, in particular to evaluate spinal implants. However, neither qualitative nor quantitative biomechanical data on calf spines are available for comparison with data on human specimens. The purpose of this study was to determine the fundamental biomechanical properties of calf spines and to compare them with existing data from human specimens. Range of motion, neutral zone, and stiffness properties of thoracolumbar calf spines (T6–L6) were determined under pure moment load-

ing in flexion and extension, axial left/right rotation and right/left lateral bending. Biomechanical similarities were observed between the calf and reported human data, most notably in axial rotation and lateral bending. Range of motion in the lumbar spine in flexion and extension was somewhat less in the calf than that typically reported for the human, though still within the range. These results suggest that the calf spine can be considered on a limited basis as a model for the human spine in certain in vitro tests.

Key words Spinal biomechanics · Stiffness · Motion · Calf · In vitro testing

Introduction

Biomechanical in vitro testing is important for pre-clinical evaluation of new implants and new surgical procedures for stabilization. Results from these tests seem to be most reliable when these procedures are tested with specimens from humans. However, the availability of human cadaveric specimens for such tests is limited because of ethical, religious, safety, and other reasons.

Therefore, researchers in some studies have used spines from other species for such in vitro tests. Aside from calf spines, those of pigs [2, 3, 21, 28, 30], goats [5, 38, 64], sheep [1, 27, 46, 51], and canines [8, 22, 24, 25, 48, 52, 63, 66] have been used for biomechanical experiments. Calf spines are the most widely used specimens as

they appear to approximate most closely the properties of the human spine [7].

Most of the reported tests using calf spines concern the evaluation of implants in quasi static tests [9–13, 19, 20, 23, 26, 41, 44, 47, 53, 59, 65] or cyclic tests [4, 24, 40, 43, 45, 49, 54, 60, 61]. Calf spines have also been used for end-plate failure tests [2] and burst fracture investigations [6]. The bone density of calf vertebrae was compared with that of young human spines and it was found that the pedicles of the thoracic and lumbar spine show the greatest similarity in size and bone density [50]. Unmodified calf spines can therefore be considered for use in pull-out tests of pedicle screws to evaluate various screw profile parameters [60]. Also, the anatomy of the calf spine was described qualitatively and quantitatively and it was reported that spines from 6- to 8-week-

old calves approximate the human spine in several dimensions [7].

Despite these studies, there are no quantitative biomechanical data on calf spines reported in the literature for comparison with human specimens, although such a correlation is critical to the validation of the calf spine as a reasonable human spine model. Interpretation and application of results from earlier biomechanical tests, therefore, is limited.

The purpose of this study was to establish quantitative biomechanical properties of calf spines and to compare them with published data from human specimens. We tested intact calf spines under the same loading magnitudes as are commonly applied to human specimens for the evaluation of spinal implants. This study may help to decide when it may be appropriate to use spines from calves for biomechanical in vitro testing.

Materials and methods

Twelve spines of 12- to 16-week-old calves of the Rotflekkälber breed with a market-ready weight of 179.7 ± 3.8 kg were provided by a local butcher for this study. The thoracolumbar spine from T6 to L6 was dissected then stored at -20°C prior to preparation and testing. All musculature was carefully removed so that the ligamentous and bony structures were not damaged, and the specimens were cut into monosegmental functional spinal units (FSU) with intact ligaments and discs.

Six specimens were divided into the segments T6–T7, T8–T9, T10–T11, T12–T13, L1–L2, L3–L4, and L5–L6. (Note that the calf typically has 13 thoracic and 6 lumbar vertebrae, compared to 12 and 5, respectively, in the typical human spine.) The other six specimens were cut into the segments T7–T8, T9–T10, T11–T12, T13–L1, L2–L3 and L4–L5, yielding in all six specimens of each, or 78 in total.

The specimens were fixed in polymethylmethacrylate and tested in a spine tester [56] by applying continuous cycles of 7.5 Nm in flexion and extension ($\pm M_x$), axial left and right rotation ($\pm M_y$), and right and left lateral bending ($\pm M_z$) moments (Fig. 1). The pure moments were applied at a constant rate of $1.7^\circ/\text{sec}$ by stepper motors integrated with the cranial gimbal of the spine tester, starting and ending in a neutral position defined by zero load. The 7.5-Nm moment is less than the failure load for healthy specimens, thus allowing testing in multiple directions, and is in the range used for many in vitro experiments of the spine [29, 31, 36], making these results comparable with published data from human specimens. The spine tester allowed the specimen to move unconstrained in all other five degrees of freedom. Monosegmental motion was measured using a three-dimensional goniometric linkage system [57].

To reduce the data to the parameters of greatest interest, only the planar motions associated with the loading direction were analyzed, using the third cycle. From these curves, range of motion (ROM), neutral zone (NZ), and two stiffness properties (S_1 , S_2) were determined (Fig. 2). ROM was determined separately in each direction to indicate the degree of symmetry of the motion. NZ was defined as half the total laxity at zero load in the complementary directions. S_1 was defined as the inverse of the slope in the steep initial part of the curve, S_2 was defined as the inverse of the slope at maximum load. The quotient, S_1/S_2 , was used to describe the non-linearity of the elastic behavior: a small number represents strong sigmoidity, a number close to 1.0 represents an almost linear curve. These seven properties grossly describe the load-deformation properties of the motion segment.

Fig. 1 Monosegmental calf motion segment L4–L5 fixed in the spine tester

Fig. 2 Characteristic hysteresis curve with the definition of the properties – range of motion (ROM), neutral zone (NZ), stiffness (S_1 , S_2) – that were determined in this study for the moments, $M_i = M_x$, M_y , M_z (flexion/extension, axial rotation left/right, lateral bending right/left)

Results

The thoracic, thoracolumbar, and lumbar segments of the calf spines exhibited characteristic hysteresis curves in each load direction (Fig. 3). Thoracic and lumbar segments were similar in lateral bending but different in flexion/extension and axial rotation.

In flexion the thoracic spine was about 50% more flexible (2.3° – 3.2° ROM; Fig. 4, Table 1) than in extension (1.5° – 2.0° ROM; Fig. 4, Table 2). However, the lumbar spine showed almost the same flexibility for flexion and

Fig. 3 Typical hysteresis curves of thoracic (T9–T10), thoracolumbar (T12–T13, T13–L1), and lumbar segments (L3–L4) from calf spines

Fig. 4 ROM of the motion segments of calf spines from T6 to L6 (mean and standard deviation) for flexion ($M_x = 7.5$) and extension ($M_x = -7.5$ Nm) moments. ROM in degrees is the sum of neutral zone (NZ, dark area) and elastic zone (EZ, light area)

extension, increasing respectively from 2.3° and 2.5° at L1–L2 to 5.0° and 5.4° at L5–L6. NZ was about 15–20% of ROM except for segment L5–L6, where it was more than 50%.

Axial rotation was nearly identical left and right, with NZ about 15% of ROM. In the thoracic spine total ROM generally was about 4.5° (Fig. 5, Table 3). The lumbar spine and the neighboring thoracic segments, however, were very stiff against axial rotation, with a nearly constant ROM of about 1.1°.

Lateral bending produced the largest ROM and highest proportional NZ and was also nearly symmetric left and right (Fig. 6, Table 4). ROM had two regional maxima and minima, respectively 5.2° and 6.7° at T9–T10 and L2–L3 and 4.4° and 4.2° at T7–T8 and T12–T13. NZ was between 75% ROM (3.7°) in the thoracic spine and 40% ROM (2.8°) in the lumbar spine.

Discussion

This study provides quantitative data on the biomechanical properties of the calf spine that may help determine whether we can use this quadruped as a supplemental model for the human spine in *in vitro* tests. We determined range of motion (ROM), neutral zone (NZ), and stiffness, which are commonly used to describe the motion characteristics of spinal segments [14, 32, 56]. These properties were characteristically different for each region and each loading direction. The calf spine was most flexible in lateral bending. Axial rotation was greatest in the thoracic region and flexion and extension in the lumbar region. The thoracic region was especially stiff in flexion and extension and the lumbar region in axial rotation. These trends are similar to those of the human spine [15, 31, 37, 59, 62].

A comparison with reported human data, taken from White and Panjabi's literature review, is shown in Fig. 7 [55]. ROM is useful as a global parameter as it incorporates both joint laxity (relating to NZ) and, when the loading magnitude is known, elasticity (relating to S1 and S2), although indistinguishably. The mechanics of the calf spine generally correspond well with those of the human spine loaded to various degrees. ROM is very similar for the two species between T6 and L5 in axial rotation and lateral bending, and in flexion/extension in the thoracic region. Flexion/extension in the calf lumbar region generally is less than that reported for the human, although it is

Table 1 Biomechanical properties of calf specimens from T6 to L6 for a flexion moment of 7.5 Nm (ROM range of motion; NZ neutral zone; S1, S2 stiffness properties)

Flexion	ROM (°)	NZ (°)	S1 (Nm/°) ^a	S2 (Nm/°) ^b	S1/S2
T6–T7	2.3 ± 0.24	0.5 ± 0.07	1.8 ± 0.40	2.5 ± 0.26	0.72 ± 0.14
T7–T8	2.5 ± 0.49	0.4 ± 0.09	2.3 ± 0.50	2.5 ± 0.44	0.94 ± 0.07
T8–T9	3.2 ± 0.72	0.4 ± 0.12	1.5 ± 0.44	2.3 ± 0.36	0.65 ± 0.17
T9–T10	3.2 ± 1.25	0.4 ± 0.10	1.6 ± 0.62	2.8 ± 0.55	0.56 ± 0.18
T10–T11	2.6 ± 0.41	0.3 ± 0.07	1.7 ± 0.39	2.8 ± 0.34	0.61 ± 0.15
T11–T12	2.7 ± 0.43	0.4 ± 0.06	1.5 ± 0.20	2.6 ± 0.41	0.60 ± 0.15
T12–T13	2.5 ± 0.68	0.3 ± 0.12	1.5 ± 0.44	3.1 ± 0.32	0.47 ± 0.16
T13–L1	2.9 ± 0.52	0.4 ± 0.15	1.5 ± 0.57	2.4 ± 0.52	0.61 ± 0.15
L1–L2	2.8 ± 0.66	0.4 ± 0.15	1.0 ± 0.53	2.9 ± 0.58	0.33 ± 0.20
L2–L3	3.1 ± 0.51	0.5 ± 0.15	0.9 ± 0.23	2.4 ± 0.38	0.38 ± 0.12
L3–L4	3.2 ± 0.39	0.8 ± 0.22	0.4 ± 0.21	2.7 ± 0.54	0.18 ± 0.09
L4–L5	3.2 ± 0.71	1.0 ± 0.42	0.5 ± 0.21	2.9 ± 0.46	0.16 ± 0.05
L5–L6	5.0 ± 0.79	2.8 ± 0.73	0.2 ± 0.08	2.4 ± 0.42	0.07 ± 0.04

^aS1 was defined as the inverse of the slope in the steep initial part of the curve

^bS2 was defined as the inverse of the slope at maximum load

Table 2 Biomechanical properties of calf specimens from T6 to L6 for an extension moment of -7.5 Nm

Extension	ROM ($^{\circ}$)	NZ ($^{\circ}$)	S1 (Nm/ $^{\circ}$)	S2 (Nm/ $^{\circ}$)	S1/S2
T6-T7	1.5 ± 0.45	0.5 ± 0.07	1.9 ± 0.39	3.3 ± 0.73	0.56 ± 0.06
T7-T8	1.6 ± 0.49	0.4 ± 0.09	1.7 ± 0.40	3.1 ± 0.52	0.54 ± 0.13
T8-T9	1.6 ± 0.24	0.4 ± 0.12	1.6 ± 0.42	3.1 ± 0.52	0.53 ± 0.13
T9-T10	1.7 ± 0.50	0.4 ± 0.10	1.6 ± 0.55	3.5 ± 0.74	0.47 ± 0.17
T10-T11	1.7 ± 0.31	0.3 ± 0.07	1.8 ± 0.48	3.5 ± 0.69	0.52 ± 0.14
T11-T12	2.0 ± 0.47	0.4 ± 0.06	1.7 ± 0.33	2.9 ± 0.46	0.60 ± 0.09
T12-T13	1.7 ± 0.39	0.3 ± 0.12	1.5 ± 0.48	3.7 ± 0.77	0.42 ± 0.17
T13-L1	2.0 ± 0.61	0.4 ± 0.15	1.3 ± 0.53	3.4 ± 0.90	0.39 ± 0.09
L1-L2	2.5 ± 0.97	0.4 ± 0.15	0.8 ± 0.36	2.7 ± 0.75	0.30 ± 0.12
L2-L3	2.7 ± 0.57	0.5 ± 0.15	0.8 ± 0.19	2.2 ± 0.35	0.37 ± 0.06
L3-L4	3.0 ± 0.65	0.8 ± 0.22	0.5 ± 0.22	2.9 ± 0.91	0.21 ± 0.16
L4-L5	3.5 ± 1.00	1.0 ± 0.42	0.5 ± 0.22	2.6 ± 0.38	0.17 ± 0.06
L5-L6	5.4 ± 0.77	2.8 ± 0.73	0.3 ± 0.08	1.9 ± 0.45	0.14 ± 0.05

quite close to the particular lumbar human data produced with this spine tester and protocol in a related study [58]. Further agreement is found with other authors [15, 42], and in more recent investigations by Panjabi et al. [37], when extrapolating the results to 7.5 Nm.

It is difficult to compare the reported data on human spines directly with these results, as earlier data vary substantially due to different loading conditions and apparatus. Even results of different studies from the same group may vary two-fold [33, 35, 37, 62]. These calf spines were tested under the conditions suggested by Panjabi et al. [32, 34], and accepted by many research groups [16, 17, 29], for testing human specimens in the evaluation of spinal implants.

As the data in the cited work [55] were combined for flexion and extension, we also combined our data to provide a comparison (Fig. 7). For the same reason we combined the values for axial rotation to the right and left, as well as those for lateral bending to the right and the left.

Fig. 5 ROM of the motion segments of calf spines from T6 to L6 (mean and standard deviation) for axial rotation to the left ($M_y = 7.5$) and the right ($M_y = -7.5$ Nm)

Table 3 Biomechanical properties of calf specimens for all segments from T6 to L6 for an axial rotation moment to the right of -7.5 Nm. Data for axial rotation to the left were equivalent

Axial rotation	ROM ($^{\circ}$)	NZ ($^{\circ}$)	S1 (Nm/ $^{\circ}$)	S2 (Nm/ $^{\circ}$)	S1/S2
T6-T7	4.5 ± 0.32	1.3 ± 0.24	0.1 ± 0.03	2.5 ± 0.49	0.05 ± 0.01
T7-T8	4.7 ± 0.68	1.2 ± 0.36	0.1 ± 0.01	2.5 ± 0.43	0.05 ± 0.01
T8-T9	4.9 ± 0.48	0.8 ± 0.32	0.1 ± 0.03	2.4 ± 0.19	0.05 ± 0.01
T9-T10	4.7 ± 0.49	1.0 ± 0.39	0.1 ± 0.02	2.5 ± 0.39	0.05 ± 0.01
T10-T11	4.3 ± 0.47	0.6 ± 0.26	0.2 ± 0.03	2.6 ± 0.38	0.06 ± 0.01
T11-T12	3.1 ± 0.91	0.3 ± 0.08	0.3 ± 0.09	3.2 ± 0.29	0.08 ± 0.03
T12-T13	1.2 ± 0.32	0.2 ± 0.09	0.7 ± 0.34	4.8 ± 0.66	0.16 ± 0.07
T13-L1	1.1 ± 0.09	0.1 ± 0.02	1.2 ± 0.41	5.0 ± 0.57	0.24 ± 0.11
L1-L2	1.1 ± 0.29	0.2 ± 0.08	0.9 ± 0.39	5.6 ± 0.80	0.17 ± 0.07
L2-L3	1.4 ± 0.24	0.2 ± 0.07	1.0 ± 0.63	5.4 ± 0.43	0.19 ± 0.11
L3-L4	1.1 ± 0.16	0.2 ± 0.05	0.9 ± 0.21	5.6 ± 0.80	0.16 ± 0.05
L4-L5	1.3 ± 0.31	0.2 ± 0.10	0.8 ± 0.36	5.9 ± 0.98	0.14 ± 0.06
L5-L6	1.7 ± 0.31	0.3 ± 0.10	0.4 ± 0.19	6.0 ± 0.86	0.06 ± 0.03

Fig. 6 ROM of the motion segments of calf spines from T6 to L6 (mean and standard deviation) for lateral bending to the left ($M_z = 7.5$) and the right ($M_z = -7.5$ Nm)

Means and ranges are reported similarly. This comparison shows that spines from calves with the same age and weight vary relatively little compared with variations among human cadaveric spines.

The load-deformation characteristics established by this study build on the results of previous studies that have shown similar bone mineral density and screw pull-out strength for calf and human specimens. There is now a substantial body of evidence supporting the use of calf spines for limited thoracolumbar implant testing. The next

step is to compare directly the effects of a wide range of systems on the motion and stiffness characteristics of the two species. This comparison will depend partly on the accuracy and flexibility of purchase into and around the calf spine. A thorough investigation of its morphology beyond its gross dimensions [7] is still needed.

A limitation of this and most related studies is that the method of applying pure moments does not truly represent physiological loads, as compressive and shear forces are neglected. However, in vivo motion patterns are well reproduced and loading is consistent and thus known at every point in the specimen. This has the advantage of reproducible loading from one specimen or one study to the next, thus providing uniform conditions within a given study and allowing comparisons between different investigations.

These 3- to 4-month-old calf spines had a length about one and a half to two times the height of an average adult human spine. Cotterill recommended for in vitro testing 6- to 8-week-old calf spines as they have a thoracolumbar length similar to that of the adult male. Spines of such young calves, however, are often difficult to obtain as calf spine availability is determined most economically by the age at which the calves are sent to market. Therefore, many of the studies described in the literature used spines from 10- to 16-week-old calves, with a weight of 125 kg or more [12, 13, 26, 41]. In this study we also used spines from calves this size, with a weight of around 170 kg.

Segments above T6–T7 were not tested in this study, because the anatomical differences are too great.

Conclusions

This study may help to decide whether the use of calf specimens is appropriate for a particular in vitro test. We found biomechanical similarities between human and calf spines in both the thoracic and lumbar regions in all load

Table 4 Biomechanical properties of calf specimens from T6 to L6 for a lateral bending moment to the right of 7.5 Nm. Data for lateral bending to the left were equivalent

Lateral bending	ROM (°)	NZ (°)	S1 (Nm/°)	S2 (Nm/°)	S1/S2
T6–T7	4.8 ± 0.58	2.9 ± 0.61	0.1 ± 0.02	2.4 ± 0.19	0.04 ± 0.01
T7–T8	4.4 ± 0.90	2.9 ± 1.07	0.1 ± 0.03	2.6 ± 0.51	0.04 ± 0.01
T8–T9	4.9 ± 0.90	3.3 ± 1.32	0.1 ± 0.03	2.3 ± 0.45	0.04 ± 0.01
T9–T10	5.2 ± 0.60	3.5 ± 1.23	0.1 ± 0.03	2.2 ± 0.25	0.03 ± 0.02
T10–T11	4.8 ± 0.47	3.7 ± 0.67	0.1 ± 0.03	2.1 ± 0.50	0.04 ± 0.01
T11–T12	4.4 ± 0.78	3.4 ± 0.99	0.1 ± 0.01	2.4 ± 0.58	0.03 ± 0.01
T12–T13	4.2 ± 0.64	2.0 ± 0.89	0.2 ± 0.11	2.1 ± 0.27	0.08 ± 0.05
T13–L1	5.2 ± 1.04	2.4 ± 0.94	0.1 ± 0.07	2.3 ± 0.87	0.06 ± 0.04
L1–L2	6.3 ± 0.70	3.0 ± 1.17	0.1 ± 0.07	2.1 ± 0.45	0.06 ± 0.05
L2–L3	6.7 ± 0.84	2.8 ± 1.16	0.1 ± 0.04	2.7 ± 0.33	0.03 ± 0.02
L3–L4	5.9 ± 0.36	2.7 ± 0.99	0.1 ± 0.04	2.3 ± 0.46	0.05 ± 0.02
L4–L5	5.8 ± 0.94	2.6 ± 0.97	0.1 ± 0.05	2.8 ± 0.39	0.03 ± 0.02
L5–L6	5.0 ± 1.09	2.6 ± 0.80	0.1 ± 0.05	2.9 ± 0.70	0.03 ± 0.01

Fig. 7 Comparison of the range of motion of calf spines (for ± 7.5 Nm moment loading) with that of human spines from T6–T7 to L4–L5 for all load directions, using the results of this study and the review data of White and Panjabi [55], which present a mean of all relevant in vivo and in vitro results of tests on the human spine. We also included newer data from in vitro studies also using pure moments – $\circ$ Oxland et al. (7.5 Nm) [31], $\triangle$ Panjabi et al. [37], $\diamond$ Yamamoto et al. (10 Nm) [62], $\square$ Goel et al. (3.0 Nm) [15], ∇ Wilke et al. (3.75 Nm) [58] – and from in vivo studies – $\blacklozenge$ Gregersen and Lukas [18], $\bullet$ Plamondon et al. [39]

directions – axial rotation, lateral bending, and to a lesser degree flexion/extension. This lends support to the suggestion that calf spines can be used as a supplement to human cadaver spines for in vitro evaluation of spinal implants. The two principal advantages of calf spines are their availability and low variability. The relatively small standard deviation in calf spine data suggests that potential differences in implant performance and operative effi-

cacy, which can be misleadingly subtle, may be borne out statistically more readily and with fewer specimens in tests on calf spines than has been realized using human cadaver spines.

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