Biomechanical in vitro evaluation of the complete porcine spine in comparison with data of the human spine

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Abstract The purpose of this study was to provide quantitative biomechanical properties of the whole porcine spine and compare them with data from the literature on the human spine. Complete spines were sectioned into single joint segments and tested in a spine tester with pure moments in the three main anatomical planes. Range of motion, neutral zone and stiffness parameters of the spine were determined in flexion/extension, right/left lateral bending and left/right axial rotation. Comparison with data of the human spine reported in the literature showed that certain regions of the porcine spine exhibit greater similarities than others. The cervical area of C1–C2 and the upper and middle thoracic sections exhibited the most similarities. The lower thoracic and the lumbar area are qualitatively similar to the human spine. The remaining cervical section from C3 to C7 appears to be less suitable as a model. Based on the biomechanical similarities of certain regions of the porcine and human spines demonstrated by this study results, it appears that the use of the porcine spine could be an alternative to human specimens in the field of in vitro research. However, it has to be emphasized that the porcine spine is not a suitable biomechanics surrogate for all regions of the human spinal column, and it should be carefully considered whether other specimens, for example from the calf or sheep spine, represent a better alternative for a specific scientific question. It should be noted that compared with human

specimens each animal model always only represents a compromise.

Keywords Biomechanics · Porcine · Animal model · Range of motion · Stiffness

Introduction

In the area of spinal research, biomechanical in vitro testing is necessary for the pre-clinical evaluation of new surgical the procedures and implants. Human cadaver specimens would be the best option for a biomechanical test, but these are difficult to obtain. Furthermore, the homogeneity related to age, weight and condition of the human spines cannot be assured.

Porcine, calf and sheep spinal columns are often used as a compromise for human spine specimens for the biomechanical tests. Several breeds at a certain age have similarities to the adult human spine in anatomy, size and material characteristics [4, 7, 16, 23, 42, 47]. The use of these animals as a model for the human spine is increasing [1, 2, 8, 13, 18, 24, 34, 41, 43]. Many studies were carried out with porcine spines. Most of these studies with the porcine model were in vitro experiments mainly concerning injury mechanisms [3, 11, 21, 22, 33–35] and in a few cases implant systems [9, 12, 31, 32]. Also in vivo experiments were carried out [6, 14, 15, 17, 25, 27] and some of these were subsequently tested in vitro [6, 25, 27].

The results of these studies should be interpreted with care as the porcine is a quadruped in contrast to the human biped. The anatomy of the porcine spine is described qualitatively [26] and for several parts of the spine also quantitatively [4, 7, 23, 47]. Limited quantitative data on the biomechanical behaviour of the porcine spine are

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Fig. 1 ROM and NZ of the motion segments of porcine spines from C1–C2 to L6–L7 (mean and standard deviation) for pure flexion/extension moments of $My = \pm 7.5$ N m in the lumbar and thoracic

region, $My = \pm 2.5$ N m in the cervical region and $My = \pm 1.0$ N m in the segment C1–C2

available. Specific segments in the thoracolumbar region were studied by Busscher et al. [5] and compared with the human spine. Schmidt et al. [31] tested the cervical region of both porcine and human spines in a comparative implant test. Both studies applied polysegmental specimens. Kettler et al. [19] determined the biomechanical segmental motion behaviour of monosegmental and polysegmental specimens in a sheep model and showed that the results should not be compared quantitatively, but only qualitatively.

To our knowledge, quantitative data on the biomechanical behaviour of each segment including the thoracic region of the whole porcine spine measured with monosegmental specimens are not available.

In order to complete our existing database, in which biomechanical data from calf and sheep already exist, the porcine spines were tested in the same way [41, 43].

The purpose of this study is to provide quantitative biomechanical parameters of the whole porcine spine and compare them with our own human in vitro data and with human data in the literature [37]. These data could be used to plan biomechanical in vitro and in vivo experiments with porcine spines.

Materials and methods

Fifteen spines from a 6-month-old porcine with a weight of 94.7 kg (± 6.9 kg) were tested in the present in vitro study. The breed was a cross of Piétrain boar with hybrid porcine. The complete spines from C1 to L6 were freshly dissected and frozen at -20°C until testing. Before testing, the specimens were thawed and the muscle tissue was carefully removed, and all ligaments, bony structures and discs were preserved. In the thoracic region, the costovertebral junctions were maintained and the ribs were shortened to a length of 5 cm. The specimens were cut into monosegmental functional spinal units (FSU) with six specimens for each FSU (note that the porcine typically has 14 thoracic and 7 lumbar vertebrae, compared to 12 and 5 in the human spine, respectively).

Then, the upper half of the cranial vertebra and the lower half of the caudal vertebra were embedded in polymethylmethacrylate (PMMA, Technovit 3040, Heraeus Kulzer, Wehrheim, Germany) ensuring that the middle disc was aligned horizontally. Before the embedding process, several screws were fixed in the upper and

Table 1 Biomechanical properties of porcine FSU from C1–C2 to L5–L6 with a pure flexion moment of $M_y = 7.5$ N m in the lumbar and thoracic region, $M_y = 2.5$ N m in the cervical spine and $M_y = 1.0$ N m in segment C1–C2

	ROM (°)	NZ (°)	S1 (N m/°)	S2 (N m/°)	S1/S2
C1–C2	7.0 ± 1.6	5.6 ± 0.9	0.0 ± 0.0	0.1 ± 0.0	0.0
C2–C3	3.2 ± 0.2	1.3 ± 0.1	0.1 ± 0.1	1.7 ± 0.3	0.1
C3–C4	8.3 ± 1.1	1.8 ± 0.4	0.2 ± 0.1	1.8 ± 1.3	0.1
C4–C5	7.6 ± 2.7	1.2 ± 0.9	0.2 ± 0.1	1.1 ± 0.2	0.2
C5–C6	10.2 ± 2.0	2.5 ± 0.4	0.1 ± 0.0	0.9 ± 0.3	0.1
C6–C7	9.9 ± 3.6	2.7 ± 1.0	0.1 ± 0.0	1.5 ± 0.3	0.1
C7–T1	6.2 ± 1.5	1.7 ± 0.4	0.2 ± 0.1	1.7 ± 0.9	0.1
T1–T2	2.3 ± 1.0	0.9 ± 0.2	0.9 ± 0.2	5.9 ± 3.1	0.2
T2–T3	5.0 ± 2.9	2.2 ± 1.5	1.8 ± 0.3	8.8 ± 4.2	0.2
T3–T4	3.4 ± 0.7	1.5 ± 1.0	0.9 ± 0.2	9.0 ± 3.9	0.1
T4–T5	4.0 ± 0.9	1.5 ± 0.5	1.5 ± 0.4	8.1 ± 2.9	0.2
T5–T6	4.0 ± 1.1	1.5 ± 1.0	1.4 ± 0.3	10.0 ± 4.6	0.1
T6–T7	4.2 ± 1.0	1.6 ± 1.0	0.7 ± 0.2	5.1 ± 2.4	0.1
T7–T8	4.2 ± 2.6	1.5 ± 1.2	1.3 ± 0.4	6.1 ± 1.0	0.2
T8–T9	3.9 ± 0.9	1.7 ± 0.7	0.9 ± 0.2	7.1 ± 4.0	0.1
T9–T10	2.8 ± 0.6	1.2 ± 0.2	1.0 ± 0.4	5.9 ± 2.9	0.2
T10–T11	4.3 ± 0.7	1.8 ± 0.2	1.0 ± 0.4	5.8 ± 1.2	0.2
T11–T12	5.3 ± 0.4	1.8 ± 0.6	0.9 ± 0.2	5.2 ± 1.0	0.2
T12–T13	5.3 ± 0.8	2.1 ± 0.6	0.7 ± 0.1	5.0 ± 2.2	0.1
T13–T14	5.1 ± 1.7	2.0 ± 0.6	0.7 ± 0.0	5.9 ± 1.4	0.1
T14–L1	5.0 ± 0.7	1.8 ± 0.4	0.8 ± 0.2	6.3 ± 1.0	0.1
L1–L2	4.5 ± 1.2	1.4 ± 0.5	0.9 ± 0.3	5.2 ± 1.8	0.2
L2–L3	4.0 ± 1.0	1.6 ± 0.5	0.8 ± 0.2	5.8 ± 1.4	0.1
L3–L4	3.6 ± 0.4	1.1 ± 0.4	0.7 ± 0.1	6.3 ± 1.9	0.1
L4–L5	4.0 ± 1.2	1.5 ± 0.9	1.1 ± 0.2	6.7 ± 1.7	0.2
L5–L6	5.5 ± 1.3	2.3 ± 1.0	0.9 ± 0.3	5.2 ± 1.8	0.2

Table 2 Biomechanical properties of porcine FSU from C1–C2 to L5–L6 with a pure extension moment of $M_y = -7.5$ N m in the lumbar and thoracic region, $M_y = -2.5$ N m in the cervical spine and $M_y = -1.0$ N m in segment C1–C2

	ROM (°)	NZ (°)	S1 (N m/°)	S2 (N m/°)	S1/S2
C1–C2	8.1 ± 2.2	5.6 ± 0.9	0.0 ± 0.0	0.2 ± 0.1	0.0
C2–C3	2.3 ± 0.4	1.3 ± 0.1	0.2 ± 0.1	2.4 ± 0.3	0.1
C3–C4	5.6 ± 0.9	1.8 ± 0.4	0.3 ± 0.1	2.3 ± 0.6	0.1
C4–C5	4.5 ± 1.5	1.2 ± 0.9	0.4 ± 0.1	1.8 ± 0.3	0.2
C5–C6	5.3 ± 0.6	2.5 ± 0.5	0.2 ± 0.0	1.3 ± 0.2	0.2
C6–C7	5.7 ± 0.9	2.7 ± 1.0	0.2 ± 0.0	1.9 ± 0.1	0.1
C7–T1	4.3 ± 1.5	1.7 ± 0.4	0.3 ± 0.0	2.1 ± 0.5	0.1
T1–T2	2.8 ± 0.2	0.9 ± 0.2	1.0 ± 0.3	6.2 ± 2.9	0.2
T2–T3	4.8 ± 1.5	2.2 ± 1.5	1.6 ± 0.1	6.2 ± 2.5	0.3
T3–T4	3.7 ± 0.9	1.5 ± 1.0	0.8 ± 0.3	8.0 ± 2.9	0.1
T4–T5	4.4 ± 0.5	1.5 ± 0.5	1.2 ± 0.3	6.9 ± 3.0	0.2
T5–T6	4.0 ± 1.4	1.5 ± 1.0	1.2 ± 0.4	9.0 ± 3.2	0.1
T6–T7	4.2 ± 1.3	1.6 ± 1.0	0.7 ± 0.2	9.2 ± 1.9	0.1
T7–T8	4.0 ± 1.1	1.5 ± 1.2	0.8 ± 0.1	8.1 ± 2.0	0.1
T8–T9	4.7 ± 0.7	1.7 ± 0.7	1.5 ± 0.4	5.8 ± 2.5	0.3
T9–T10	3.4 ± 0.9	1.2 ± 0.2	0.9 ± 0.4	4.5 ± 1.8	0.2
T10–T11	4.5 ± 0.7	1.8 ± 0.2	1.3 ± 0.4	6.0 ± 1.4	0.2
T11–T12	3.7 ± 0.9	1.8 ± 0.6	0.9 ± 0.3	4.8 ± 1.9	0.2
T12–T13	5.0 ± 1.1	2.1 ± 0.6	0.7 ± 0.1	4.7 ± 2.1	0.1
T13–T14	4.1 ± 1.3	2.0 ± 0.6	0.7 ± 0.2	5.8 ± 2.4	0.1
T14–L1	4.8 ± 1.0	1.8 ± 0.4	0.9 ± 0.3	7.1 ± 2.0	0.1
L1–L2	3.7 ± 0.9	1.4 ± 0.5	0.7 ± 0.0	4.5 ± 1.3	0.2
L2–L3	4.4 ± 1.0	1.6 ± 0.5	0.8 ± 0.3	6.1 ± 1.0	0.1
L3–L4	3.3 ± 1.1	1.1 ± 0.4	1.0 ± 0.3	4.2 ± 2.0	0.2
L4–L5	4.4 ± 2.1	1.5 ± 0.9	0.9 ± 0.3	4.5 ± 1.9	0.2
L5–L6	5.1 ± 1.8	2.3 ± 1.0	0.8 ± 0.4	5.1 ± 0.9	0.2

lower vertebra in order to improve the fixation between vertebra and PMMA. Flanges were fixed to the cranial and caudal PMMA blocks to mount the specimens in a spine tester.

Each FSU was tested in the spine tester without preload in an alternating sequence of flexion/extension ($\pm M_y$), lateral bending right/left ($\pm M_x$) and axial rotation left/right ($\pm M_z$) with pure moments [40, 44, 45]. The load was applied continuously at a constant rate of 1.7°/s by stepper motors integrated into the gimbal of the spine tester. During loading, the specimens were allowed to move unconstrained in the five uncontrolled degrees of freedom. The applied bending moments and the resulting rotations of the specimens were recorded continuously. Two loading cycles were applied for preconditioning; the third cycle was evaluated. The C1–C2 segments were tested with ± 1.0 N m, the rest of the cervical spine was tested with ± 2.5 N m the thoracic and lumbar spine with ± 7.5 N m. These moments were chosen to avoid damaging the FSU

and to remain within the viscoelastic range. A three-dimensional goniometric linkage system was used to measure the monosegmental motion.

Range of motion (ROM), neutral zone (NZ) and two stiffness parameters (S1, S2) were determined from the resulting load-deformation curve of the third cycle [41, 43].

Range of motion was defined as the deformation at the maximum load in the positive and negative loading direction of each test.

Neutral zone was defined as half of the total laxity in the combined positive and negative loading directions, as indicated by the range over which practically no load was required to flex, bend or rotate the specimen [40].

S1 was defined as the inverse of the slope in the steep initial part of the curve; S2 was defined as the inverse of the slope at maximum load. The quotient, S1/S2, was used to describe the nonlinearity of the elastic behaviour: a small value represents strong sigmoidicity; a value close to 1.0 represents an almost linear curve.

Fig. 2 ROM and NZ of the motion segments of porcine spines from C1–C2 to L6–L7 (mean and standard deviation) for pure right/left lateral bending moments of $M_x = \pm 7.5$ N m in the lumbar and

thoracic region, $M_x = \pm 2.5$ N m in the cervical region and $M_x = \pm 1.0$ N m in the segment C1–C2

Table 3 Biomechanical properties of porcine FSU from C1–C2 to L5–L6 with a pure lateral bending moment to the right of $M_x = 7.5$ N m in the lumbar and thoracic region, $M_x = 2.5$ N m in the cervical spine and $M_x = 1.0$ N m in segment C1–C2

	ROM (°)	NZ (°)	S1 (N m/°)	S2 (N m/°)	S1/S2
C1–C2	4.5 ± 1.4	2.0 ± 0.5	0.1 ± 0.0	0.7 ± 0.1	0.1
C2–C3	7.5 ± 1.5	3.4 ± 1.3	0.1 ± 0.0	0.8 ± 0.2	0.1
C3–C4	8.4 ± 0.4	4.3 ± 1.9	0.0 ± 0.0	0.9 ± 0.1	0.0
C4–C5	6.9 ± 1.3	3.1 ± 1.2	0.1 ± 0.0	1.1 ± 0.4	0.1
C5–C6	8.0 ± 0.7	4.8 ± 1.4	0.0 ± 0.0	0.9 ± 0.3	0.0
C6–C7	6.8 ± 0.5	3.2 ± 1.4	0.1 ± 0.0	0.7 ± 0.1	0.1
C7–T1	4.7 ± 1.7	2.2 ± 1.5	0.2 ± 0.1	1.0 ± 0.3	0.2
T1–T2	4.4 ± 1.2	2.3 ± 1.0	0.2 ± 0.0	1.5 ± 0.2	0.1
T2–T3	6.2 ± 1.1	2.8 ± 0.9	0.1 ± 0.0	1.8 ± 0.3	0.1
T3–T4	4.3 ± 0.9	2.5 ± 2.3	0.1 ± 0.0	1.4 ± 0.3	0.1
T4–T5	5.5 ± 1.0	1.8 ± 0.5	0.3 ± 0.0	2.1 ± 0.6	0.1
T5–T6	5.2 ± 0.9	2.0 ± 0.7	0.2 ± 0.1	1.6 ± 0.5	0.1
T6–T7	5.8 ± 1.5	2.8 ± 1.2	0.1 ± 0.0	2.1 ± 0.6	0.0
T7–T8	6.5 ± 3.1	3.1 ± 2.5	0.1 ± 0.0	3.0 ± 0.4	0.0
T8–T9	6.2 ± 1.9	2.4 ± 1.3	0.1 ± 0.0	2.6 ± 0.2	0.0
T9–T10	4.3 ± 0.6	2.2 ± 0.8	0.3 ± 0.1	1.7 ± 0.5	0.2

Table 3 continued

	ROM (°)	NZ (°)	S1 (N m/°)	S2 (N m/°)	S1/S2
T10–T11	5.4 ± 0.7	1.6 ± 0.4	0.2 ± 0.1	2.0 ± 0.4	0.1
T11–T12	5.5 ± 0.3	2.5 ± 0.8	0.1 ± 0.0	2.7 ± 0.5	0.1
T12–T13	5.4 ± 0.9	2.0 ± 0.8	0.2 ± 0.1	2.3 ± 0.3	0.1
T13–T14	5.5 ± 0.8	1.9 ± 1.3	0.2 ± 0.4	2.9 ± 0.4	0.1
T14–L1	5.5 ± 0.9	2.7 ± 0.4	0.2 ± 0.1	2.8 ± 0.3	0.1
L1–L2	5.8 ± 1.3	1.7 ± 0.6	0.2 ± 0.1	2.4 ± 0.2	0.1
L2–L3	5.6 ± 0.6	2.1 ± 0.8	0.1 ± 0.0	2.2 ± 0.4	0.0
L3–L4	5.3 ± 0.8	1.9 ± 0.6	0.2 ± 0.0	2.5 ± 0.5	0.1
L4–L5	5.5 ± 1.0	1.7 ± 0.6	0.2 ± 0.1	2.7 ± 0.3	0.1
L5–L6	5.7 ± 1.4	1.3 ± 0.3	0.2 ± 0.1	2.1 ± 0.3	0.1

Data for lateral bending to the left were equivalent

Results

In flexion and extension, the C1–C2 segment showed a ROM from 7° to 8° (Fig. 1; Tables 1, 2). From C2 to C7, the largest ROM was noticed in segment C5–C6 in flexion with approximately 10°. In general the ROM in flexion was

Fig. 3 ROM and NZ of the motion segments of porcine spines from C1–C2 to L6–L7 (mean and standard deviation) for pure left/right axial rotation moments of $M_z = \pm 7.5$ N m in the lumbar and

thoracic region, $M_z = \pm 2.5$ N m in the cervical region and $M_z = \pm 1.0$ N m in the segment C1–C2

Table 4 Biomechanical properties of porcine FSU from C1–C2 to L5–L6 with a pure axial rotation moment to the left of $M_z = 7.5$ N m in the lumbar and thoracic region, $M_z = 2.5$ N m in the cervical spine and $M_z = 1.0$ N m in segment C1–C2

	ROM (°)	NZ (°)	S1 (N m/°)	S2 (N m/°)	S1/S2
C1–C2	29.1 ± 2.3	17.9 ± 6.2	0.0 ± 0.0	0.0 ± 0.0	0.0
C2–C3	1.1 ± 0.3	0.2 ± 0.1	0.2 ± 0.1	1.0 ± 0.3	0.2
C3–C4	2.5 ± 1.1	0.6 ± 0.3	0.3 ± 0.1	0.8 ± 0.2	0.4
C4–C5	2.4 ± 1.1	0.4 ± 0.3	0.3 ± 0.1	0.7 ± 0.2	0.4
C5–C6	2.2 ± 0.7	0.5 ± 0.3	0.1 ± 0.0	0.6 ± 0.1	0.2
C6–C7	2.3 ± 0.7	0.5 ± 0.1	0.2 ± 0.1	0.5 ± 0.1	0.4
C7–T1	1.6 ± 0.1	0.3 ± 0.1	0.1 ± 0.0	0.6 ± 0.3	0.2
T1–T2	4.8 ± 1.7	0.6 ± 0.2	0.1 ± 0.0	1.4 ± 0.2	0.1
T2–T3	5.4 ± 1.6	1.0 ± 0.5	0.0 ± 0.0	1.2 ± 0.3	0.0
T3–T4	5.3 ± 0.8	0.7 ± 0.2	0.0 ± 0.0	1.7 ± 0.3	0.0
T4–T5	6.1 ± 0.9	0.7 ± 0.3	0.1 ± 0.0	2.0 ± 0.6	0.1
T5–T6	6.2 ± 0.5	0.9 ± 0.7	0.0 ± 0.0	1.9 ± 0.5	0.0
T6–T7	6.2 ± 0.7	1.0 ± 0.3	0.1 ± 0.0	2.1 ± 0.6	0.0
T7–T8	6.4 ± 0.6	1.0 ± 0.5	0.2 ± 0.0	2.5 ± 0.4	0.1
T8–T9	6.1 ± 0.5	0.1 ± 0.4	0.1 ± 0.0	2.0 ± 0.2	0.1
T9–T10	5.4 ± 0.9	0.7 ± 0.5	0.3 ± 0.1	1.9 ± 0.5	0.2

Table 4 continued

	ROM (°)	NZ (°)	S1 (N m/°)	S2 (N m/°)	S1/S2
T10–T11	2.5 ± 1.2	0.5 ± 0.3	0.5 ± 0.1	1.9 ± 0.4	0.3
T11–T12	2.5 ± 2.0	0.3 ± 0.2	0.9 ± 0.2	2.7 ± 0.5	0.3
T12–T13	1.9 ± 0.4	0.3 ± 0.1	0.9 ± 0.4	2.4 ± 0.3	0.4
T13–T14	1.6 ± 0.4	0.2 ± 0.1	0.8 ± 0.4	3.0 ± 0.4	0.3
T14–L1	1.2 ± 0.1	0.2 ± 0.1	1.4 ± 0.3	3.0 ± 0.3	0.5
L1–L2	2.2 ± 0.1	0.6 ± 0.8	2.4 ± 0.5	3.4 ± 0.5	0.7
L2–L3	1.2 ± 0.2	0.2 ± 0.1	3.2 ± 0.9	4.0 ± 1.1	0.8
L3–L4	1.2 ± 0.2	0.1 ± 0.1	3.9 ± 1.2	4.9 ± 2.1	0.8
L4–L5	1.2 ± 0.1	0.2 ± 0.1	4.9 ± 2.0	6.8 ± 2.0	0.7
L5–L6	1.5 ± 0.3	0.3 ± 0.2	5.8 ± 2.9	7.7 ± 1.6	0.8

Data for axial rotation to the right were equivalent

larger than in extension in the cervical segments with the exception of C1–C2. The ROM in the upper thoracic spine ranged from approximately 4° in extension to 4° in flexion. In the lower thoracic spine, the ROM increased minimally from 4° to 5.5°. In the lumbar segments the ROM ranged from 3° to 5.5° in both directions.

Fig. 4 Comparison of the ROM (mean and standard deviation) of porcine and human spines from C1–C2 to L5–L6 for flexion plus extension. Porcine data were determinate in this study, and human data were adapted from White and Panjabi [37] and compared with data from other pure in vitro studies

In lateral bending, the ROM was symmetrical and the greatest in the cervical spine: 4.5° in segment C1–C2 and 7°–8.5° in the cervical segments C2–C7 (Fig. 2; Table 3). An exception exhibited by the transition segment C7–T1 with a value of 5°. The ROM in the thoracic and lumbar spine ranged from approximately 4.5° to 6.5°.

In axial rotation, the largest ROM was noticed in the segment C1–C2 with 29° in each direction (Fig. 3; Table 4). In the other cervical regions, the ROM for rotation ranged from 1.1° to 2.5°. Larger motions were found in the upper and middle thoracic spine with values of 4.8°–6.4°. The lower thoracic and lumbar region of the spine showed similar behaviour: the ROM was between 1.2° and 2.5°.

Neutral zone was the highest in the lateral bending mode up to 60% of the ROM. Axial rotation showed the lowest NZ, which was approximately 15%. In extension/flexion

the NZ ranged from 26° to 56°. An exception to this trend was the C1–C2 segment in the extension/flexion with 68% and the axial rotation with 58% of the ROM.

The stiffness quotient, S1/S2, was the highest in axial rotation in the lower thoracic and lumbar spine from T14–L1 to L5–L6 (0.5–0.8), and moderate for the whole spine in flexion and extension (0.1–0.3) and for the cervical spine in axial rotation (up to 0.4). S1/S2 was low for the whole spine in lateral bending (0.0–0.2) and for the upper thoracic spine in axial rotation (0.0–0.1).

Discussion

Many in vivo and in vitro experiments, as described in the introduction, have relied on the porcine model with the assumption that it resembles the biomechanics of the

Fig. 5 Comparison of the ROM (mean and standard deviation) of porcine and human spines from C1–C2 to L5–L6 for lateral bending right/left. Porcine data were determined in this study, and human data were adapted from White and Panjabi [37] and compared with data from other pure in vitro studies

human spine. This study presents the biomechanical properties of each single motion segment of the porcine spine and compares them with published results for the human spine (Figs. 4, 5, 6). We found that the ROM of porcine spines for the different loading directions is qualitatively similar to data of the human specimens. In the cervical and lumbar spine for both species the ROM is typically small for axial rotation. A large ROM was noticed in axial rotation in the upper thoracic region. For lateral bending we found a large ROM over the entire length of the spines for both species. This study also revealed that certain regions of the spinal column exhibit greater similarities than others. In summary, the cervical area of C1–C2 and the upper and middle thoracic sections show good similarities. The lower thoracic and the lumbar regions show only moderate similarities to the human spine. The remaining cervical section from C3 to C7 appears to be different.

This is the first study to characterize monosegmental ROM, NZ and stiffness parameters for each segment of the whole porcine spine. ROM and NZ are parameters that are commonly used to describe the motion characteristics of the spinal segments. The stiffness parameters contain information about the sigmoidicity of the nonlinear load-deformation curves. Other parameters might be useful if complex loading becomes more relevant. However, the goal of this study was to provide a database, which is consistent with the previous papers on other species [41, 43]. These data may be very useful for deciding when to use the porcine spine as a model for spinal research.

The data for comparison with the human spine were taken from a literature review by White and Panjabi [37], which reflects a mixture of both in vivo and in vitro data. Additionally, our data were compared to published data from in vitro studies, which applied pure moments in the same way as in the present study [28–30, 36, 45, 46]. These

Fig. 6 Comparison of the ROM (mean and standard deviation) of porcine and human spines from C1–C2 to L5–L6 for axial rotation left/right. Porcine data were determined in this study, and human data were adapted from White and Panjabi [37] and compared with data from other pure in vitro studies

loading conditions are recommended and accepted by many research groups for investigating biomechanical properties of human spines [8, 10, 20, 28–30, 36, 46]. A previous study comparing loads in an internal fixator measured both in vivo and in vitro has proven that pure moments represent an acceptable loading case [39].

Furthermore, it should be noted that no axial preload was applied in order to avoid buckling or tilting of the spinal segment, which could result in artefacts. This also complies with the recommendations for the spinal implant testing [44].

Conclusion

The presented results not only showed similarities between the human and the porcine spine, but also

revealed limitations of the porcine spine as a model. The data may help the spine researchers to better decide whether a certain region of the porcine spine may serve as an appropriate model for their specific scientific question [18].

This comparison with the human spine shows that the porcine spine like the spines of other animal species can only be regarded as a compromise. Depending on the exact question of the planned in vitro or in vivo study, the appropriate animal model should be selected with care [38].

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Conflict of interest None.

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