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Why cervical vertebrae do not fracture – a biomechanical approach using loading tests on human vertebrae of a 79-year-old body donor

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1. Abstract

Purpose: Bone structure alters with increasing age. Material and structural properties are both important for bone strength. Despite having an ageing society, there is a paucity of data from elderly subjects in terms of these parameters.

The aim of the present study was to conduct comparative examinations of the structure and material properties of the cervical spine (CS), the thoracic spine (TS) and the lumbar spine (LS), in order to identify both structural and biomechanical differences between the segments of the spine.

Methods: We examined central bone cylinders of vertebral bodies C1 to L5 from a 79-year-old body donor in regards to their bone volume fraction (BVF), trabecular thickness (Tb.Th.), separation (Tb.Sp.), trabecular orientation (SMI) and degree of anisotropy (DA). Samples were obtained from all vertebrae with a Jamshidi needle®, and were prepared with a damp cloth in an Eppendorf reaction vessel (1.5 ml). The investigations were performed with a micro-CT device (SKYSCAN 1172, RJL Micro & Analytic GmbH, Germany). Existing deformities and fractures were registered with quantitative computed tomography (QCT). The load tests of the vertebral bodies C1 to L5 were performed on a servo-hydraulic testing machine (MTS 858, MTS Systems Cooperation, Eden Prairie, USA).

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Results: Regarding BVF (p=0.003), Tb.Th. (p=0.041) and SMI (p=0.012) statistically significant differences were found in the different spinal column sections. The force per area was significantly higher in the CS than in the TS and LS (CS *vs.* TS, p=0.022; CS *vs.* LS, p<0.001; TS *vs.* LS, p=0.012).

Conclusion: Due to their unique microarchitecture cervical vertebrae are less prone to fractures than thoracic and lumbar vertebrae. Among the reasons are the higher BVF and Tb.Th. of the cervical vertebrae compared to other vertebrae. Furthermore, the SMI of the CS has more plates than rods. Thus, the CS is characterized by specific features, whose causes must be determined in further investigations.

2. Keywords: Biomechanics; Osteoporosis; Fracture; Micro-CT; QCT

3. Introduction

Fragility fractures of the cervical spine are not found, even in the presence of clinically manifest osteoporosis. An earlier histomorphometric study reported a higher bone mass and greater trabecular interconnectivity in the cervical spine [1]. The biomechanical competence of vertebrae is determined by cortical bone and cancellous bone as in a two-spring model [2]. The loss of trabecular structure of the vertebrae with age is significantly greater than that of cortical bone [3].

4. Methods

Recruitment and Ethics

The subject originated from the body donor program of the University Medical Centre of Rostock and had given voluntary consent, to donate his body after death for scientific research, during his lifetime. Furthermore, the study was also assessed and approved by the responsible Ethics Committee of the University of Rostock (No. A 2017-0072).

Processing

Data regarding the case history of the body donor are shown in Table 1. The entire spine was assessed for any existing fractures or significant bone disease through high-resolution computed tomography imaging (GE Revolution EVO 64-slice computed tomography/slice thickness <1 mm). In order to simulate a homogenous and anatomically analogous surrounding soft-tissue, the spinal specimen was embedded in a Plexiglas water phantom with a 25 cm diameter, which was as free of air as possible [5] (Figure 1A).

Table 1: Case data.

Parameters	
Age (years)	79
Sex m/f	m
Height (cm)	168
Weight (kg)	52.3
Body mass index (kg/m^2)	18.5

Figure 1A: Scanogram of the spine placed in a water bath.

Figure 1b: 3D-reconstruction for visualization of the spinal anatomy as a whole.

3D-reconstruction (Figure 1B) was performed at an external workstation (GE AW-Server® Version 2.0. Measurement of the spine in GE Centricity RIS-i® Version 5.0) to visualize the spinal anatomy. Surface quantification of the individual vertebrae was conducted using axial CT cross-sectional imaging.

Trabecular bone density was calculated for the levels L1, L2 and L3 using QCT (GE Revolution EVO / 64-sline CT, Mindwaays Software 3D Volumetric QCT

Spine) in the usual way using volume block.

In addition, the cancellous bone from all 24 vertebrae from the cervical, thoracic and lumbar spines were examined on their bone mineral content (BMC), trabecular thickness (Tb.Th.) and trabecular separation (Tb.Sp.). Samples were taken from all vertebrae using a Jamshidi® needle and were prepared with a wet gauze in a 1.5 ml Eppendorf reaction vessel. The examinations were conducted using a µ-CT (SKYSCAN 1172, RJL Micro & Analytic GmbH, Germany). For this purpose, a flat-field correction and a comparison with phantoms (reference) with a density of 0.25 g/cm^3 and 0.75 g/cm^3 was performed. The cancellous region of interest was defined manually to exclude any cortical components of the vertebrum. The following parameters relevant to cancellous bone microarchitecture were measured: bone volume fraction (BVF, %), bone density (BMC, mg/cm^3), trabecular thickness (Tb.Th., mm), trabecular separation (Tb.Sp.), degree of anisotropy (DA, 0 = isotropic; 1 = anisotropic) and structure model index (SMI, 0 = plate-like; 3 = rod-like).

Furthermore, the breaking forces and tensions required to produce a grade 1 fracture in the loading test were also calculated [4]. Compression of the vertebrae C3 to L5 were conducted on a servo hydraulic testing system (MTS 858, MTS Systems Cooperation, Eden Prairie, USA) (Figure 2).

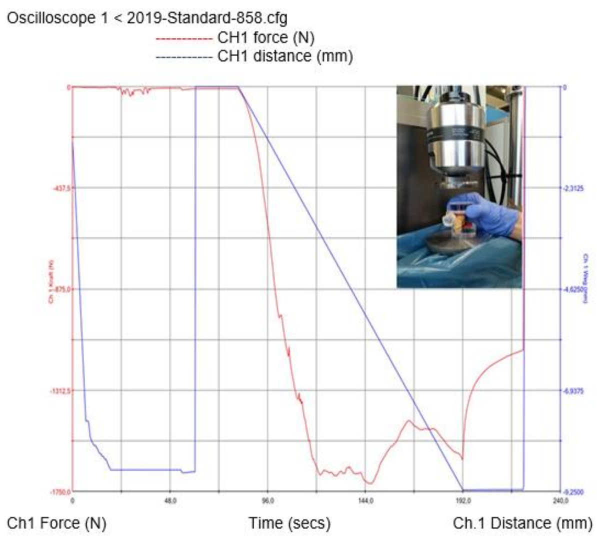

Figure 2: Force-distance diagram of the compressed vertebral (grade 1 fracture); baseline height determined by CT; test speed 5 mm/min; transmission of force via circular blanks made of acrylic glass.

Statistics

All data collected were analyzed using the statistical software package SPSS, Version 23.0 (SPSS Inc., Chicago, USA). The quantitative characteristics were reported as mean value (M), standard deviation (SD) and number (n) of available observations and presented using the interval mean value ± standard deviation (M±SD). The Kruskal-Wallis test was used for comparisons between the groups. The selection was made on the basis of the result of the Shapiro-Wilk test for normal distribution. We conducted pairwise comparisons for statistically significant results. All p-values are the results of two-tailed statistical tests and $p \leq 0.05$ is regarded as statistically significant.

5. Results

QCT

The QCT assessment revealed an osteoporotic axial skeleton with an average bone mineral content of 69.4 mg/cm^3 (Table 2).

Table 2: Bone mineral content results for the lumbar spine, as measured by QCT. The threshold to osteoporosis is reached with an average BMC of below 80 mg/cm^3.

Lumbar spine	BMC (mg/ cm^3)
L1	65.6
L2	71.7
L3	70.8
Ø (L1-L3)	69.4

Micro-CT

The µCT assessment showed that the BVF of the cervical spine is significantly higher than that of the thoracic spine ($p = 0.002$), but not higher than that of the lumbar spine ($p > 0.05$). The Tb.Th. of the cervical spine is significantly higher than that of the lumbar spine ($p = 0.042$). No statistical meaningful difference was discovered between the segments of the spine with regard to Tb.Sp. and DA ($p > 0.05$). The differences in SMI were also highly significant in the various sections of the spine ($p<0.001$).

Table 3: Descriptive statistics for Micro-CT parameters.

		Spinal sections				Group comparison		
Architectural	**Total**	**CS**	**TS**	**LS**	**General**	**CS *vs.* TS**	**CS *vs.* LS**	**TS *vs.* LS**
Measure	M ± SD	M ± SD	M ± SD	M ± SD	differences			
	(Min. - Max.)	(Min. - Max.)	(Min. - Max.)	(Min. - Max.)	p-value	p-value	p-value	p-value
BVF (%)	23.11 ± 7.25	30.76 ± 9.02	19.29 ± 2.88	21.59 ± 2.84	0.003^{K}	0.002^{P}	0.384^{P}	0.532^{P}
	(14.63 - 45.23)	(23.39-45.23)	(14.63 - 25.48)	(17.55 - 24.74)				
Tb.Th. (µm)	215 ± 43	245 ± 48	209 ± 37	185 ± 21	0.041^{K}	0.237^{P}	0.042^{P}	0.771^{P}
	(151 - 324)	(188 - 324)	(171 - 304)	(151 - 204)				
Tb.Sp. (µm)	850 ± 213	732 ± 203	938 ± 133	803 ± 316	0.104^{A}	----------	----------	----------
	(427 - 1338)	(427 - 1057)	(585 - 1073)	(559 - 1338)				
DA (n)	0.29 ± 0.06	0.27 ± 0.07	0.31 ± 0.06	0.26 ± 0.05	0.235^{A}	----------	----------	----------
	(0.19 - 0.41)	(0.19 - 0.37)	(0.19 - 0.41)	(0.23 - 0.34)				
SMI (n)	1.64 ± 0.27	1.34 ± 0.27	1.75 ± 0.16	1.78 ± 0.14	0.012^{K}	0.020^{P}	0.049^{P}	1.000^{P}
	(1.01 - 2.00)	(1.01 - 1.84)	(1.39 - 2.00)	(1.58 - 1.92)				

^{K} Kruskal Wallis test, ^{P} Pairwise comparison, ^{A} One-way analysis of variance (ANOVA), F-test significance, ^{L} Post-hoc LSD test.

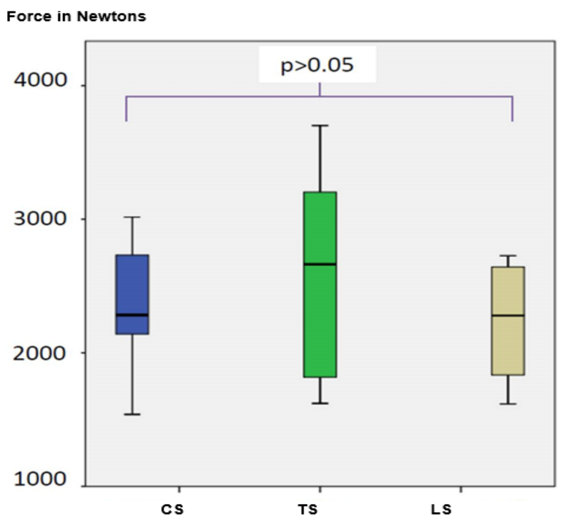

Figure 3: Force required to produce a grade 1 fracture in various segments of the spine.

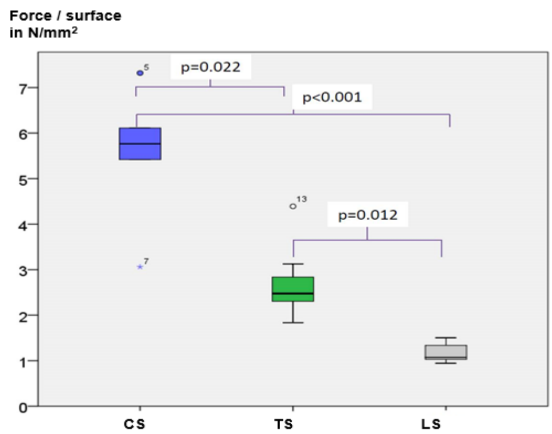

Figure 4: Force per surface in the various segments of the spine.

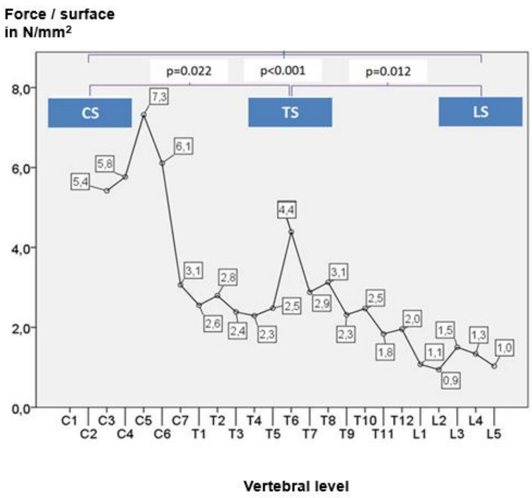

Figure 5: Force per surface as a function of the vertebral level and presentation of the results of the group comparison of the segments of the spine. Force per surface depending on the vertebral level and presentation of the group comparison results of the spine segments.

6. Discussion

Cervical vertebrae have a significantly greater loading capacity than thoracic and lumbar vertebrae due to their denser trabecular structure and stronger mineralization. The "smaller vertebrae" of the cervical spine are capable of bearing the same overall load as the vertebrae of the thoracic and lumbar spine. Age, hormone-related bone degradation and reduced mobility of elderly patients are reflected in a reduction of trabecular architecture in the region of the thoracic and lumbar spines. Whereas a high degree of stability and mobility is still demanded of the cervical spine for everyday situations and the weight of the head, as an axial force of between 4 kg to 6 kg, remains unchanged lifelong. An additional effect on preventing fragility fractures arising from the cortical structure has been reported [2]; possible differences in the cervical, thoracic and lumbar spines are currently the subject of further studies.

7. Conclusion

BVF and Tb.Th. are different in the individual portions of the spine. The differences are especially pronounced between the CS and TS, and the CS and LS. BVF reduces from the CS to the LS.

The microarchitecture of the cervical vertebrae is plate like, whereas the lumbar vertebrae are rod like.

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