

High Cycle Fatigue Behaviour of Functional Spinal Units

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Received June 4, 2009 and accepted May 6, 2010

Abstract: Vibrations have been shown to be an important risk factor for spinal pathologies. The underlying mechanisms are poorly understood and *in vivo* data scarce and difficult to obtain. Consequently numerical models are used to estimate spinal loading; requiring fatigue strength information, which was obtained in this study for spinal specimens from young and old male donors of working age *in vitro*. Bone mineral density (*BMD*) and endplate area were determined using CT scans. Three groups were investigated: young specimens in neutral posture, young in flexed posture, and old in neutral posture. The loading consisted of 300,000 sinusoidal compression cycles of 2 kN, inducing a nucleus pressure peak of approximately 1.4 MPa. No failure of the young specimens in neutral posture was observed, but four specimens from older donors with low *BMD* failed. The product between endplate area and *BMD* was shown to be useful to predict fatigue strength for old donors and should therefore be considered with regard to whole body vibration injuries. In flexed posture, two specimens from young donors failed. One failure can be attributed to low *BMD* following the trend for the old specimens; the other failure could not be explained, leaving the influence of flexion yet unclear.

Key words: Lumbar spine, *in vitro*, Fatigue, Flexion, Prevention, Vibration

Introduction

Vibrations and impact loads are potential risk factors for spinal failure. In particular, the combination of long exposure durations and constrained sitting postures might accelerate disc degeneration or endplate failure^{1–3}). Vertical vibrations and impacts, as occurring when working for example with heavy haul trucks, were shown to be potentially harmful⁴). Large cohorts showed that long term exposure to whole body vibrations due to badly damped seats lead to significantly decreased disc heights⁵). The associated risks are addressed by regulations and recommendations aiming to limiting the permitted exposure to vibration (e.g. 2002/44/EG; ISO 2631-1, 1997; ISO 2631-5, 2004). Beside the personal burden, the economic cost of low back injuries is immense; exceeding those caused by cardiovascular diseases, cancer and AIDS combined⁶). For dorsopathy, excluding fractures and osteoporosis, 8.4 billion euro was spent in Germany alone in the year 2002, not taking into account the lost working time⁷). For compulsorily insured workers, about 3 working days are lost per year⁸).

The mechanisms and pathways by which external vibrations cause internal damage are not well understood - especially since *in vivo* studies with healthy subjects are nearly impossi-

ble. A better understanding of the mechanism involved could improve the appraisal of occupational diseases, enable the determination of duty cycles for implants and also improve the development of prevention systems. Numerical simulations can help in the estimation of spinal loading. Whole body models, validated with *in vivo* measurements, were used to predict spinal loading for humans exposed to whole body vibration^{9, 10}). Regardless the controversy if these kinds of models are already able to predict real behaviour, they are only made to determine loading of substructures. In order to interpret the findings of the models with regard to potential failure of the structure, spinal fatigue strength has to be known additionally.

Fatigue testing of spinal specimens has been rarely performed *in vitro*. A comprehensive work with 70 specimens of donors that had reached the second half of their working age (51 ± 18 yr) was done by Brinckmann *et al*¹¹). In this study, several protocols with peak loads up to 7.1 kN compression were applied. The number of load cycles was limited to 5,000, but already loading below 3 kN leads to failure rates of almost 50%.

Fatigue *in vitro* measurements with low numbers of cycles till failure (1,000–10,000 cycles, 0.33–1 Hz) were reported by other authors as well^{1, 11, 12}). These low cycle numbers are most likely caused by the high fatigue load used. These types of fatigue measurements with low numbers of cycles and very

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high loading peaks is not in the main focus with regard to health safety in the workplace, but they are indicating influencing factors on fatigue failure, which might be valid for high cycle fatigue failures as well. Lumbar motion segments from middle-aged donors (49.2 ± 17.3 yr) exhibited higher fatigue life than those of rather old donors (80.7 ± 7.8 yr) when exposed to different loading regimes with peak compressive forces ranging from 1.3 kN to 3.15 kN¹¹. This was associated with the superior bone mineral content of the middle-aged specimens. Furthermore, flexion and shear was observed to decrease the fatigue life¹¹. Fatigue loading with peak loads of 2 kN to 4 kN lead to spinal segment failure in less than 1,000 cycles. For the donors, advanced in years (63.0 ± 18.2 yr), these loads resembled 60 to 80% of the predicted ultimate compressive strength - calculated based on the bone mineral content¹².

In a recent study from the author's group the test design differed fundamentally. The numbers of cycles was clearly increased while the loading was reduced to a more physiological one. Exclusively motion segments from young donors ($n=30$, 33 ± 6 yr) were harvested and exposed to 100,000 cycles of loading in the physiological range. Five different loading protocols varying in amplitude and offset were applied. The weakest protocol went from 0 kN to 1 kN and the most harmful protocol went from 0 kN to 2 kN. However, it was shown that only two specimens in this age range failed within the enduring loading of 100,000 cycles. The two failed specimens had been assigned to the group with the highest loading exposure ($n=6$), but they coincidentally exhibited pure bone mineral density (BMD)¹³. Although only few failures could have been provoked the study showed, that the fatigue strength of young donor's specimens exposed to high numbers of loading cycles is high. It appears, that age or mechanically related factors as BMD have to be taken into account. An open question concerns the link of *in vitro* fatigue test to the *in vivo* situation of people in the workplace. If the force on the spine caused by whole body vibrations is predicted by e.g. numerical methods, it is not clear if the exposed numbers of cycles to failure are potentially harmful for different individuals.

An attempt can be made by relating the numbers of load cycles to failure (N_K) of a specimen exposed to cyclic loading (mean force: F_{mean} ; peak to peak force: F_{p2p}) to its ultimate strength (F_{max}) by using the equation suggested by Seidel *et al*¹⁴:

$$N_K = \left(\frac{F_{\text{max}} - F_{\text{mean}}}{0.5 \cdot F_{\text{p2p}}} \right)^6 \quad (1)$$

In combination with the prediction of the ultimate strength of specimens published by Brinckmann *et al*¹⁵.

$$F_{\text{max}} = 0.32 \text{ kN} + 0.00308 \cdot \text{BMD} \cdot \text{AREA} \cdot \frac{\text{kN}}{\frac{\text{mg K}_2\text{HPO}_4}{\text{ml}} \cdot \text{cm}^2} \quad (2)$$

a simple prediction for the fatigue behaviour would be available. This hypothesised relation only depends on the product of BMD and endplate area (AREA).

The aim of this study was to investigate the high cycle fatigue strength of spinal specimens from male donors of working age. Within this context it was especially analysed how specimen posture and spinal characteristics like age,

BMD and endplate size might be used to predetermine this.

Subjects and Methods

For the *in vitro* experiments lumbar functional spinal units (FSU) level L4/L5 from male donors were harvested after consent. The specimens were wrapped in saline-soaked gauze, double sealed in plastic bags and frozen at temperature below -20°C until testing. Computed tomography (CT) scans of both segment's vertebrae were performed in the frozen state. Specimens with pathologic deformities were eliminated prior to the *in vitro* experiments. A CT-phantom was additionally placed in the image area of the CT scanners (S5VA40A, Siemens, Munich, Germany & Mx8000 IDT 16, Philips Healthcare, DA Best, The Netherlands). This phantom consisted of three phials filled with an aqueous solution of dipotassium phosphate (K_2HPO_4) in different concentrations. The absorption of X-rays due to K_2HPO_4 is similar to that of the mineral fractions of the bone. The concentrations were 0, 100 and 500 mg $\text{K}_2\text{HPO}_4/\text{ml}$. With this, the Hounsfield Units received by the scanners could be converted to equivalents of dipotassium phosphate concentrations. Differences in scanners settings or x-ray beam hardening due to different amount of absorbing structures did consequently not influence the results. As a representative BMD value the mean was calculated for a defined rectangular volume ($30 \times 30 \times 15$ voxels, Amira 3.0, Avizio 5.0, Mercury Computer Systems, Merignac, France) placed manually at the centre of each vertebral body (Fig. 1). The positioning of the bounding box was performed by two investigators independently to account for subjective variability. If the values differed by more than 10% the measurements were repeated. If not, the mean value of both investigators was used for further analyses.

To determine AREA, three-dimensional models of the bony structure were created from the CT data (Amira 3.0, Avizio 5.0, Mercury Computer Systems, Merignac, France). Firstly, the soft tissue was separated from the bone by threshold segmentation. Cutting planes were chosen at the inferior side of L4 and the superior side of the L5 vertebra. The cutting plane was oriented with respect to the vertebral body such that a closed contour was formed around the circumference of the endplate (other structures, such as the dorsal process or pedicles were eliminated). The three-dimensional coordinates of these line sets were rotated (Matlab, MathWorks Inc., Natick, MA) to account for the non-planar orientation

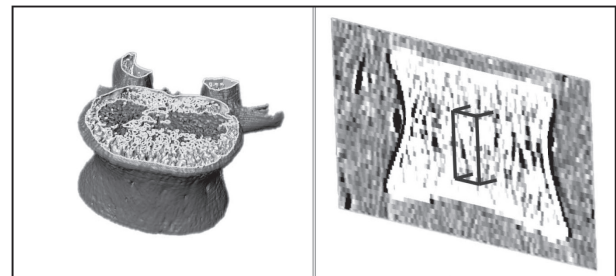


Fig. 1. Endplate area (left) and bone mineral density (right) were determined based on CT data. The plane of the endplate area (AREA) and the rectangular volume used for BMD calculation is indicated.

with respect to the CT planes. The area enclosed by the contours (Fig. 1) was determined by piecewise linearization of the kidney shaped cross-sectional area of the endplates (hullfit.m, public domain Matlab function by Peter Wasmeier, p.wasmeier@bv.tum.de). For analysis the mean value of both specimens' vertebral characteristics (*AREA*, *BMD*) was used. The *VERTEBRAL CAPACITY* was calculated as product of *AREA* and *BMD*.

The specimens were harvested from younger male adult donors (*YOUNG*: 20–40 yr) and from donors in the second half of their working age (*OLD*: 50–60 yr). The former were tested in neutral and flexed posture, the latter only in neutral posture. Thus, three groups with 6 specimens each were investigated: *YOUNG NEUTRAL*, *YOUNG FLEXED* and *OLD NEUTRAL*.

On the day of testing, the spinal muscles were removed, while ligaments (anterior and posterior longitudinal ligaments and the ligamentum flava) were left intact. Care was taken not to damage the disc. The FSUs were potted unconstrained in metal holders using a Polyurethane resin (RenCast FC53, Huntsman, Switzerland). For the neutral posture, the mid-plane of the segment's disc was potted parallel to the flange of the holders. For the flexed posture, both holders were angled 5° each in extension during potting, resulting in 10° flexion after mounting in the hydraulic test machine with its two parallel flanges (Bionix, MTS, MN). The flexion value was chosen based on Andersson *et al.* who showed that the L4/L5 segment angle changes approximately 10° during change of posture from standing to unsupported sitting¹⁶.

In addition to the hydraulic test machine's axial actuator an additional horizontal actuator was attached to the cross head of the machine to enable force controlled anterior/posterior loading or unrestricted movements in this direction respectively (Fig. 2). The two hydraulic axes were coupled to the moveable flange by means of leaf springs to prevent slip stick or friction within the controller chain. A six degree of freedom load cell (model 30031, Huppert, Herrenberg, Germany) was placed below the specimen. The specimens were immersed in Ringer solution maintained at 37°C for testing since the test environment strongly influences the mechanical properties¹³. Biological degeneration was minimised by adding Penicillin/Streptomycin (final concentration: 10 ml/l, PAA Laboratories

GmbH, Pasching, Austria).

First the dynamic and quasistatic stiffness of the specimens in the axial and anterior-posterior directions were measured in a non-destructive manner. The maximal axial force was 2 kN and the maximal anterior-posterior force was 0.4 kN. These measurements served as pre-conditioning, to diminish the effects of non-uniform starting conditions (such as different swelling status caused by variations in harvesting).

After preconditioning (~90 min) the segments were exposed to 300,000 cycles of sinusoidal compression (~18 h). A peak to peak load of 0 kN to 2 kN was applied at a frequency of 5 Hz. The anterior-posterior loading direction was maintained force controlled at 0 kN. All other degrees of freedom were restricted. Based on the *VERTEBRAL CAPACITY* of the harvested specimens and the relations given in equation 1 and 2, almost all specimens were expected to fail with this peak force and this high numbers of cycles. Pilot measurements showed that this loading regime induced nucleus pressures of up to 1.4 MPa. This is about the pressure that was measured during lifting 20 kg *in vivo*¹⁶. Therefore it can be considered as pressures of a high physiological range for repeated loading with a huge number of loading cycles. Specimen height loss was continuously recorded in order to determine cycles to failure based on unsteadiness in the characteristic physiological creep curve.

After mechanical testing, the specimens were deep frozen and then sectioned along the mid-sagittal plane using a diamond saw (EXAKT 310, EXAKT Apparatebau GmbH, Norderstedt, Germany). Photographs of the unloaded sectioned segments were taken and morphologically graded according to the scheme of Thompson *et al.*¹⁸ (Table 1).

Variance analyses to examine the differences between the characteristics of the specimens were accomplished for the three groups. Linear regression analyses were performed for failed specimens. The independent variables were the age or the *VERTEBRAL CAPACITY* and the dependent variables were linear or logarithmically scaled numbers of cycles to failure. Type II error level for all statistical analyses was chosen to be $\alpha=0.05$.

Results

The characteristics of the specimens in each group show a wide variation (Table 2). The standard deviations ranged from 10 to 25% of the corresponding mean values. The mean *BMD* values between the *OLD NEUTRAL* and *YOUNG FLEXED* groups were significantly different ($p=0.041$), but the mean endplate areas between groups were not significantly different. A significant decrease of *BMD* with donor's age was observed for the specimens ($r^2=0.38$; $p=0.007$).

The indication of the numbers of load cycles till fatigue failures of specimens based on the creep curve was successful. In most cases the discontinuity in the creep behaviour was quite distinct (Fig. 3). None of the *YOUNG NEUTRAL* specimens failed during the test period, whereas four of the *OLD NEUTRAL* specimens with the lowest *BMD* failed (Table 3). Two of the *YOUNG FLEXED* group also showed unsteadiness in the characteristic creep curve used to indicate fatigue failure (Table 3). However, for one of them (#3) this was not very distinct.

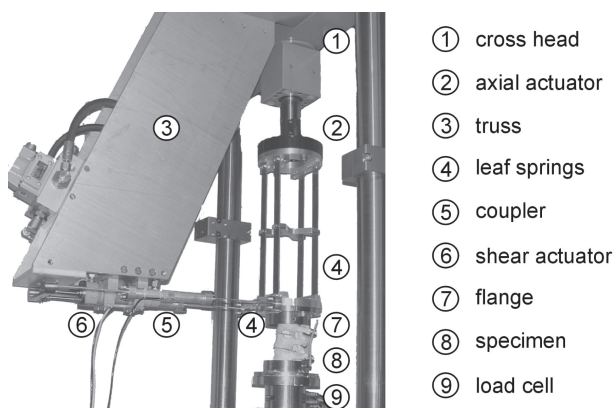


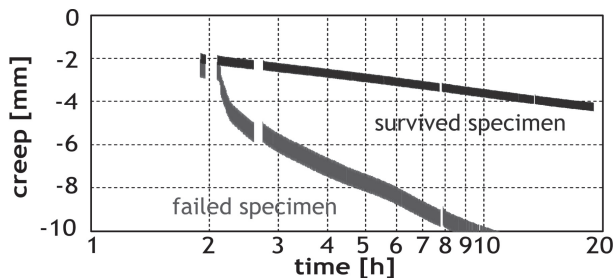
Fig. 2. Modified hydraulic test rig build to enable dynamic loading in axial and anterior-posterior direction.

Table 1. Description of the morphologic grade according to Thompson *et al*¹⁸⁾

Grade	Nucleus	Annulus	End-plate	Vertebral body
I	Bulging gel	Discrete fibrous lamellas	Hyaline, uniformly thick	Margins rounded
II	White fibrous tissue peripherally	Mucinous material between lamellas	Thickness irregular	Margins pointed
III	Consolidated fibrous tissue	Extensive mucinous infiltration; loss of annular-nucleus demarcation	Focal defects in cartilage	Early chondrophytes or osteophytes at margins
IV	Horizontal clefts parallel to end-plate	Focal disruptions	Fibrocartilage extending from subchondral bone; irregularity and focal sclerosis in subchondral bone	Osteophytes less than 2 mm
V	Clefts extended through nucleus and annulus		Diffuse sclerosis	Osteophytes greater than 2 mm

Table 2. Group characteristics (n=6 per group, mean $\pm$ SD)

		OLD NEUTRAL	YOUNG FLEXED	YOUNG NEUTRAL
age	[yr]	53.5 $\pm$ 3.8	30.5 $\pm$ 8.3	29.0 $\pm$ 7.1
BMD	[mg K ₂ HPO ₄ /ml]	117.0 $\pm$ 28.8	161.8 $\pm$ 29.2	152.8 $\pm$ 15.4
AREA	[cm ²]	17.8 $\pm$ 3.1	16.7 $\pm$ 3.7	15.6 $\pm$ 2.1

**Fig. 3.** Examples for the creep curves of a failed and a survived specimen.

The failures that could be detected afterwards were observed exclusively within the vertebral body. This was seen by comparing the pre-testing x-ray image to the post testing section plane (Fig. 4). The Thompson grading based on this section planes exhibited a distinct difference of degeneration grades (Table 4). The *YOUNG NEUTRAL* specimens appear to be unaffected from the 300,000 load cycles. The mean degeneration grade of these specimens was 1.9 ± 0.4 while those of *OLD NEUTRAL* were clearly higher (3.6 ± 0.7). *YOUNG FLEXED* mean Thompson grading was 2.9 ± 1.3 .

Age alone was not a good predictor of failure. Two specimens of the *OLD NEUTRAL* group (aged 52 and 50 yr) did not fail during the 300,000 load cycles (Fig. 5), which can be explained considering the *VERTEBRAL CAPACITY* (Fig. 6). The two specimens that survived the fatigue testing had *BMD* values that exceeded those of the others in the group by 50% and 67%, respectively and for *AREA* the mean was exceeded by 47% and 7%, respectively. The hypothesised failure load based on the *VERTEBRAL CAPACITY* is conservative in most of the cases but not for specimens from older donors with low *BMD*. Regression analyses were only performed based on the data of the four failed specimens in *OLD NEUTRAL*.

The coefficient of determination between the *VERTEBRAL CAPACITY* and the logarithmical scaled numbers of cycles was higher (adjusted $r^2=0.75$, $p=0.088$) than for the interrelation between age and the numbers of cycles to failure (adjusted $r^2=0.62$, $p=0.153$). Neither for age nor for *VERTEBRAL CAPACITY* it was possible to detect significant relations; probably due to the small numbers of failed specimens.

Discussion

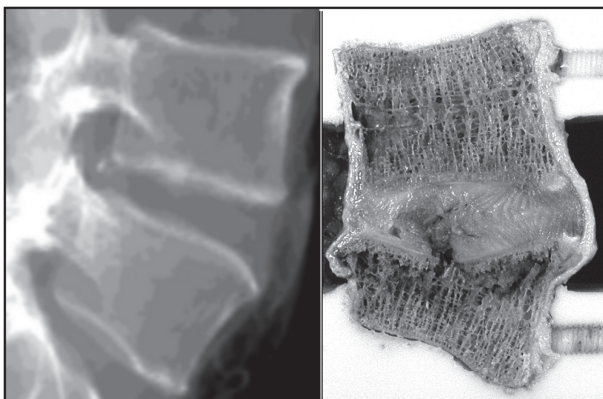
The resistance of young donors' specimens, tested in neutral posture, against cyclic fatigue loading was unexpectedly high. The hypothesised acceptable numbers of cycles were clearly exceeded by most of those specimens from young donors without failure. Specimens from donors in the second half of working age with low *VERTEBRAL CAPACITY* failed if exposed to fatigue loading with high numbers of cycles as used in this study. The *VERTEBRAL CAPACITY* calculated out of *AREA* and *BMD* tend to be more appropriate to predict fatigue strength than age. This agrees with measurements of the ultimate compressive strength¹⁵⁾. The initially hypothesised equation underestimates the strength of specimens in most cases.

A linear relationship between logarithmical scaled cycles to failure and the *VERTEBRAL CAPACITY* appears appropriate. However, this curve can hardly be extrapolated to higher *BMD* or higher *VERTEBRAL CAPACITY*, respectively, as it is only supported by four measurements from old donors' specimens.

Based on the post testing morphological Thompson grading it is not possible to distinguish if the higher degeneration grades of the older specimens were caused by the cyclic loading or by age related normal degeneration. For *YOUNG NEUTRAL* lower degeneration grades were assigned to all components of the spinal segments, meaning that the numbers of cycles applied in this study hardly caused damages.

Table 3. Spinal characteristics and cycles to failure for the 18 specimens. The six failed specimens are indicated by the respective number in the column 'Fx'

	Fx	age	BMD	AREA	BMD *AREA	Cycles
	[#]	[yr]	[mg K ₂ HPO ₄ /ml]	[cm ²]	[cm*mg K ₂ HPO ₄ /ml]	[*1,000]
OLD NEUTRAL	#1	48	99.9	17.2	1718.7	28.9
		50	163.5	17.5	2868.6	
		52	147.1	24.2	3554.0	
	#2	56	114.7	15.1	1733.4	18.0
	#5	56	88.3	17.4	1539.1	1.6
	#6	59	88.8	15.8	1404.7	1.8
YOUNG NEUTRAL		21	163.0	18.9	3085.8	
		22	171.2	14.1	2411.2	
		23	167.0	13.1	2184.9	
		34	138.7	15.3	2116.8	
		36	129.1	14.1	1824.5	
		38	147.8	18.0	2663.6	
YOUNG FLEXED	#1	20	136.4	13.6	1857.8	140.0
		21	199.5	13.3	2656.3	
		27	138.1	18.0	2491.7	
		35	148.4	23.5	3491.7	
	#3	39	205.8	14.0	2887.8	215.6
		41	142.8	18.0	2569.9	

**Fig. 4.** Pre-testing x-ray image (left) and post-testing section (right) of a failed specimen from the OLD NEUTRAL group (#5) is shown. The middle part of the L5 endplate, which was initially well shaped, failed during loading and the disc tissue was heavily damaged.

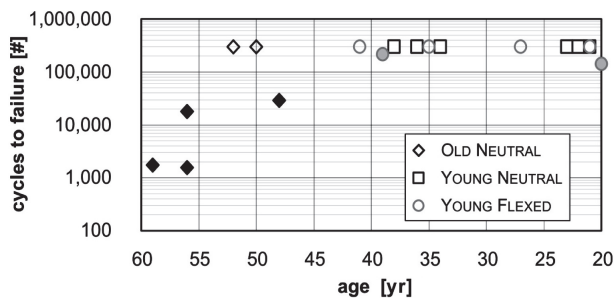
Two of the young specimens in the flexed posture failed. One of those (#1) with low VERTEBRAL CAPACITY fits into the relationship derived for the older specimens whereas the second (#3) did not. For the former it is therefore not possible to state additional damaging effects due to flexion. The failure can solely be explained by the VERTEBRAL CAPACITY. For the latter it is doubtful if the small unsteadiness in the characteristic creep curve really exhibited a fatigue failure. Only for this single specimen the detection of unsteadiness in the creep curve was doubtful. Morphological

investigations after the testing did not exhibit any disruption of the spinal structures. Therefore, it is likely that in this case the identification of fatigue failure based on the creep curve was not meaningful. Consequently the influence of flexion still remains unclear.

The observed exclusive failure within the vertebral body was in good agreement with other *in vitro* studies, in which high loads, resulting in considerably less cycles to failure, were applied^{11, 12, 19}. Adams *et al.*²⁰ observed disc failure in few cases, but this was an effect of combined high loads and close to limit flexion angles, clearly exceeding the 10° used in this study. The results are inconsistent with the findings presented by Kumar³ who announced disc failure rather than failure of the bony structures and also contradicts the findings of an *in vivo* cross sectional study of highly exposed cohorts²¹. In that study it was shown, that high load exposure influenced the disc height rather than the vertebral bodies. Two issues might be responsible for this. First, the morphological disc grading of the Thompson classification is done with photographs of the section view of unloaded specimens. Clefts in the disc tissue may be not revealed in this method of investigation. Second, the *in vitro* test design does not account for bone healing during rest between the periods of vibration exposure. It might be possible, that the damage accumulation of the vertebrae is masked by the remodelling while that of the disc is progressing. The former will imply, that failure of the spinal structure occurred earlier than shown in this study, while the latter will suppose, that the fatigue strength *in vivo* is even higher.

Table 4. Received Thompson grading scores for the specimens after testing

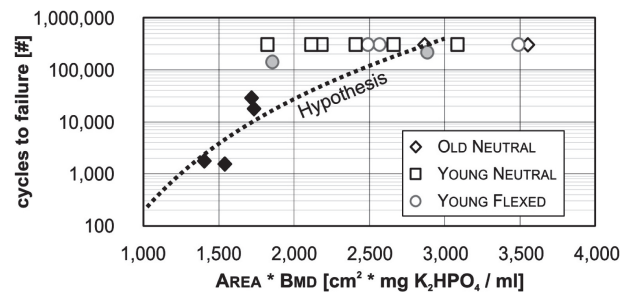
	Fx	age	mean local grade				
		[yr]	nucleus	annulus	endplate	vertebrae	max
OLD NEUTRAL	#1	48	4.5	4.0	3.0	3.5	4.5
		50	2.5	2.5	3.0	3.5	3.5
		52	2.5	2.5	3.0	3.0	3.0
	#2	56	4.0	3.5	4.0	3.0	4.0
	#5	56	4.5	4.5	4.5	4.5	4.5
	#6	59	4.0	4.0	4.5	3.5	4.5
YOUNG NEUTRAL		21	1.5	1.5	3.5	1.0	3.5
		22	1.5	1.5	2.0	1.0	2.0
		23	1.0	1.5	2.0	2.0	2.5
		34	1.5	1.5	3.0	1.0	3.0
		36	2.0	2.0	3.5	2.5	3.5
		38	2.0	2.0	2.0	1.0	2.0
YOUNG FLEXED	#1	20	3.5	3.5	3.0	5.0	5.0
		21	1.5	1.5	2.0	1.0	2.0
		27	2.0	2.5	2.5	1.5	2.5
		35	5.0	5.0	5.0	5.0	5.0
	#3	39	2.0	2.0	2.0	1.0	2.0
		41	2.5	3.0	2.5	3.0	3.0

**Fig. 5.** Fatigue behaviour of the spinal segments versus donor's age. The filled markers represent failed specimens, open markers represent specimens that survived 300,000 cycles.

Conclusion

Neither the threefold increase of load cycles compared to the former project of the authors¹³⁾ nor the inclusion of specimens of older donors and the additional flexion led to the expected high numbers of failure. Only five to six specimens out of 18 failed after exposure to 300,000 cycles of high physiological fatigue loading. From the authors' point of view, further studies with higher numbers to failures, higher loading and different postures are required to deepen the knowledge about fatigue strength especially for young subjects.

It is well understood, that *in vitro* testing is only an approximation of the *in vivo* situation. The results can not directly be transferred to the *in vivo* situation, but trends can be indicated. The influence of artificial load application and constraints as the potting or the reduced degrees of freedom (rotation and lateral translation) could affect the numbers of

**Fig. 6.** Fatigue behaviour of the spinal segments against VERTEBRAL CAPACITY. The filled markers represent failed specimens, open markers represent specimens that survived 300,000 cycles.

cycles to failure. However, the transfer to the more complex *in vivo* situation might be possible using numerical dynamic whole body vibration models.

With regard to fatigue strength and consequently with regard to whole body vibration injuries it has been shown that VERTEBRAL CAPACITY is a crucial factor in predicting spinal compressive fatigue strength.

Acknowledgments

Institutional support by the German Federal Institute for Occupational Safety and Health (FIOSH) through the Projects F1899 and F2069 was received. The kind support of Dr. Seidel, Dr. Hinz, B. Pöplau, N. Wilke and A. Matthaei is deeply appreciated.

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