Eur Spine J (1999) 8 : 458–467

ORIGINAL ARTICLE

B. Drerup
M. Granitzka
J. Assheuer
G. Zerlett

Assessment of disc injury in subjects exposed to long-term whole-body vibration

Received: 19 February 1998
Revised: 13 August 1999
Accepted: 21 August 1999

B. Drerup (✉) · M. Granitzka
Institut für experimentelle Biomechanik,
Domagkstrasse 11,
D-48129 Münster,
Germany
e-mail: drerup@uni-muenster.de
Fax: +49-251-8355 983

J. Assheuer
Institut für Kernspintomographie,
Cologne,
Germany

G. Zerlett
Rheinbraun AG,
Cologne,
Germany

Abstract Long-term exposure to whole-body vibration is known to increase the risk of low back problems. The chain of events leading from repeated loading of the lumbar spine to back complaints and the exact nature of the vibration-induced damage are, however, obscure. Fluid in- and outflow as well as viscoelastic deformation are important aspects of the physiological function of the lumbar disc. Precision measurement of stature, termed ‘stadiometry’, has previously been applied in healthy subjects to document changes in disc height in relation to the load on the lumbar spine. The purpose of this study was to explore the relation between spinal loading and stature in a cohort of 20 subjects with long-term exposure to whole-body vibration. If the change of stature (and thus the change of disc height) caused by changes in spinal loading differed between exposed and normal subjects, this would point to vibration-induced changes in structure and material properties of the discs. For this purpose, four hypotheses were tested: (1) the viscoelastic deformation and fluid exchange of intervertebral discs during phases of spinal loading and unloading differs from normal; (2) the water content of lumbar discs of subjects exposed to long-term whole-body vibration deviates from normal; (3) the mean disc height of the lumbar spine depends on the total time of vibration exposure; (4) repeated loading influences trabecular bone density of vertebrae in the lumbar spine. A cohort of 20 operators of heavy earth-moving machinery was enrolled. Back complaints suspected to be due to long-term exposure (mean 17.6 ± 2.1 years) to whole-body vibration and application for early retirement were the selection criteria used. Change of stature during a regular 8-h shift and change of stature in standing, carrying and sitting activities were measured. The stadiometric investigations were supplemented by magnetic resonance imaging (MRI) of the lumbar spine to assess whether the water content of the discs exhibited deviations from normal. In addition, quantitative computed tomography (QCT) was performed to assess whether the trabecular bone density of the third lumbar vertebra deviated from normal. The results showed no significant difference in change of stature while standing, carrying or sitting between exposed machine operators and non-exposed operators. Likewise, MRI examinations revealed no significant differences in the water content of the discs averaged over the lumbar spine. In addition, QCT examinations revealed no significant difference in the trabecular bone density of the third lumbar vertebra. The study thus revealed no significant difference between a cohort with long-term exposure and non-exposed controls with respect to viscoelastic properties of discs as determined by stadiometry, average water content of lumbar discs and trabecular bone density of L3.

Key words Whole-body vibration · Measurement of stature · Vertebral end-plate area · Compressive strength of vertebrae · Occupational disease

Introduction

Epidemiological data reveal interconnections between low back problems and long-term exposure to whole-body vibration. Reviews of the literature provide evidence of this connection, e.g. in operators of tractors and heavy earth-moving equipment [6, 11, 24, 25].

In ergonomic practice, conclusions have been drawn from this finding. Damped seats reducing whole-body vibration in heavy earth-moving equipment have led to significant improvements [5]. On the theoretical side, however, the mechanism of whole-body vibration acting on the spine and producing impairments to it needs better understanding. Various hypotheses on the relevant mechanisms have been put forward [6], yet few systematic investigations have been carried out. As a consequence, no objective criterion, apart from exposure time, has been established on the basis of which to decide in the individual case whether or not back problems may be attributed to vibration exposure.

This study focuses on the question of whether objective proof of disc injury caused by exposure to long-term vibration can be found. Disc injury, for example, might consist in tissue degeneration induced by a high number of alternating disc compressions and stretches, causing either mechanical damage or a change in the metabolism of the disc. This damage might be evident in various aspects:

1. The viscoelastic properties and the properties of fluid exchange might deviate from normal.
2. The water content of the disc might deviate from normal.
3. The disc height might be affected.

If repeated loading were an important factor in causing altered viscoelasticity together with altered mechanical properties, an influence on the bone density of the lumbar vertebrae would also be expected. Therefore, as a further aspect:

4. The trabecular bone density and compressive strength of the vertebra might deviate from normal.

The viscoelastic properties of the disc depend strongly on the tendency of proteoglycans to imbibe water and thus to create a high osmotic pressure [13, 27]. Under load, the disc disposes of liquid and loses height, and conversely it gains height by absorbing liquid. Height loss and height gain of the disc under load and unloading conditions is determined objectively by measuring stature. Diurnal height changes have long been observed [9, 17–19]. In 1987 it was suggested that changes in stature might be used for the measurement of spinal loading [8]. This method gained precision in the development of the stadiometric measurement procedure [1, 2], with an accuracy of 0.4 mm in measuring stature. At the same time, reference values were established for stature changes due to particular activities like carrying a 30-kg waistcoat or sitting comfortably. For a cohort of ten healthy males aged between 20 and 60 years, a height loss of 3.0 ± 1.0 mm when carrying a 30-kg load was found. During 30 min relaxed sitting, a cohort of five persons showed a height increase of 3.5 ± 0.6 mm. For another activity, namely sitting for 30 min on a vibrating seat, no net effect on stature was found.

Stadiometric measurements are an appropriate method for investigating the above-mentioned properties of discs in subjects complaining of back problems after exposure to whole-body vibration for many years. Results must be compared with corresponding data of a healthy reference cohort as above. Note that stadiometry provides an overall measure: stature change comprises height changes summed over all disc levels. Therefore, impairment of an individual disc may be masked.

Stadiometry needs cooperation on the part of the subjects. Although workers may have more difficulties than students, for example, in reproducing their posture in the stadiometric device, they are found to cooperate willingly and thus to enable stadiometry to be used for examination in an industrial environment [19].

Some authors hypothesize a relation between viscoelastic properties of the disc and water content [13, 18]. If this is the case with the viscoelastic properties of the disc impaired, the water content is likely to differ from normal values. Measurement of water content is performed by magnetic resonance imaging (MRI) [3, 21, 22, 26, 28].

Altered trabecular bone density and calculated compressive strength of the vertebra is measured by quantitative computed tomography [4] (QCT). Preparatory to the QCT investigation, a lateral scout image was obtained, which served for evaluating disc height according to the method of Farfan (described by Pope and co-workers [23]).

Applying these methods in subjects exposed to long-term vibration reveals whether this population is subject to an increased prevalence of disc injury.

Materials and methods

Cohort

A cohort of 20 operators of heavy earth-moving machinery was selected for investigation. The mean age of the operators was 42.4 ± 9.4 years. All operators were working at the open-cast lignite mines of ‘Rheinische Braunkohlenwerke’, Cologne, Germany, and had been subjected to long-term whole-body vibration; the mean exposure was 17.6 ± 2.1 years.

Work history was documented by the employer. Mean vibration dose was: $a_{zw(8h)} = 1.2\ \mathrm{m/s^2}$ [14]. The operators were selected if:

1. They had back complaints and had applied for early retirement on account of these complaints, and
2. On clinical examination an impairment of one or more discs was suspected

Any radiological findings – be it their presence or absence – were of no relevance to the selection.

Fourteen operators volunteered for a radiological examination (QCT and MRI). Their mean age of 42.4 ± 9.8 years and their mean exposure time of 18.5 ± 2.2 years were in good agreement with those of the total cohort. While all QCT examinations were carried out successfully, the MRI examinations had to be broken off in two cases because of claustrophobia. Therefore 14 QCT and only 12 MRI measurements were available for evaluation.

Data acquisition and analysis

Anthropometric, stadiometric and radiologic surveys and examinations were carried out. The stadiometric measurements determined stature change.

1. While wearing a 30-kg waistcoat for 30 min (task 1)
2. While sitting comfortably for 30 min (task 2)
3. Before and after an 8-h morning shift

The radiologic examinations used MRI for determination of disc water content and morphological findings, and QCT for assessment of bone density and end-plate area of the 3rd lumbar vertebra and calculation of its compressive strength.

Anthropometry

The following data were collected: height, weight, age, duration of exposure to whole-body vibration at the workplace and external bone dimensions, i.e. diameter of the wrist, elbow joint, knee and ankle. These recordings were made on the day scheduled for practising the stadiometric measurement procedure.

Stadiometry

The stadiometer was set up at the health centre of the company to allow pre- and post-shift stature measurements to be performed immediately before (6.00 a.m.) and after (2.00 p.m.) the morning work shift. In the sitting and carrying activities, subjects had to interrupt their activity for each single stadiometric measurement and to position themselves in the apparatus until the measurement was released. Typically, the interruption lasted 25 s.

A detailed description of the system has previously been given [1]. It consists of a stable metal frame (see Fig. 1) supporting the subject in a tilted standing posture with a 10° backward inclination [8]. Support is given to the feet, knees, buttocks, back and head. Supports are adjusted individually for each subject. To allow for stature changes, back and head supports tolerate longitudinal movements. In addition, control of back profile is necessary as the subject moves in and out of the system for each measurement. Control is provided by three sagittal co-ordinate sensors (lumbar lordosis, kyphosis, cervical lordosis), which block release of a new measurement if the co-ordinates differ by more than ± 0.25 mm from their initial reference values. The range of head movements is limited to ± 1° by a laser targeting device that works together with a mirror attached to spectacles and a wall marker. Stature measurements were done by reference to a marker attached to the skin approximately 1.5 cm above vertebra prominens. This marker was observed by a telescopic sight with online co-ordinate readout to a personal computer.

Each subject was measured on seven consecutive working days:

Day 1: practice day
Days 2–5: task 1 and 2, both carried out on each of the days
Days 6 and 7: pre- and post-shift measurements carried out on both days

On the practice day the sagittal co-ordinate sensors were set and the subjects were shown how to position themselves. Measurement on days 2–5 was performed by measurement cycles comprising three phases of 30 min each:

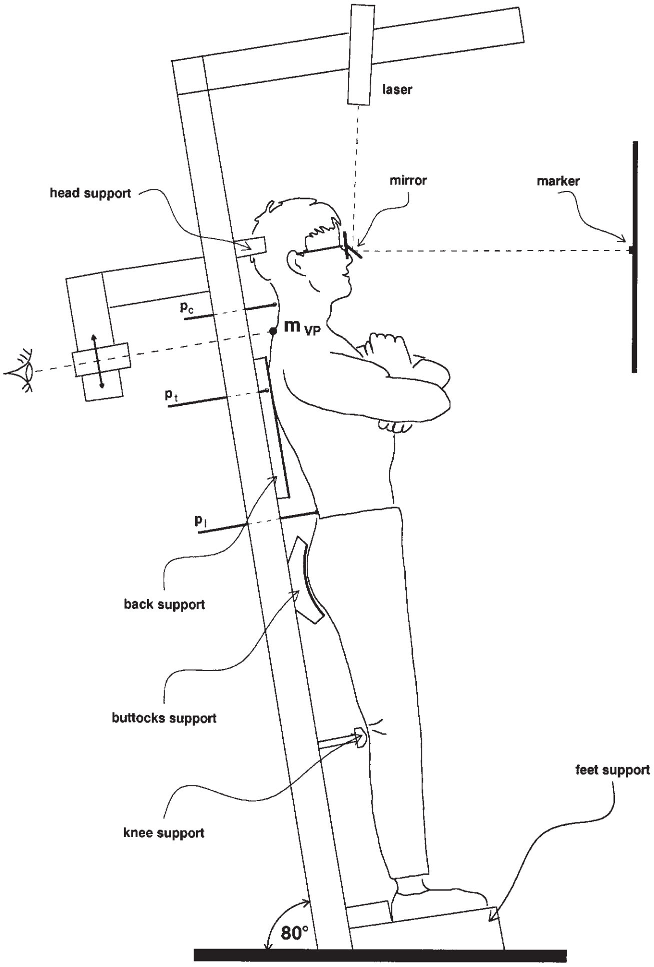

Fig. 1 Device for high-precision stadiometric measurement ($\boldsymbol{p}_c$, $\boldsymbol{p}_t$, $\boldsymbol{p}_l$ co-ordinate sensors to control cervical, thoracic and lumbar back contour respectively; $\boldsymbol{m}_{vp}$ reference marker above vertebra prominens)

1. 'Pre-test' phase: the subjects stood free or moved slowly
2. 'Test' phase: the subject either wore a 30-kg waistcoat (task 1) or sat comfortably on a chair with a back rest and arm supports (task 2)
3. 'Post-test' phase: as in the pre-test phase

The pre-test phase was designed to provide homogeneous conditioning of the subjects. The data collected during this phase allowed body height to be extrapolated as if this phase were continued. During the test phase of task 1, spinal load was created by the subject wearing a waistcoat with a mass of 30 kg distributed symmetrically around the trunk. During the same phase of task 2 the subject sat comfortably on a chair with a back rest. In the post-test phase the subject behaved as in the pre-test phase. Height measurements were performed at regular intervals: during the test phase every 5 min; otherwise every 3 min.

Biomechanically the disc is modelled as a viscoelastic system, with the time behaviour in elongation/compression being described by an exponential (Kelvin model) [12, 20]. According to this model, height change, Δh, is given by:

$$\Delta h = a_0 + a_1 \exp(-t/\tau) \tag{1}$$

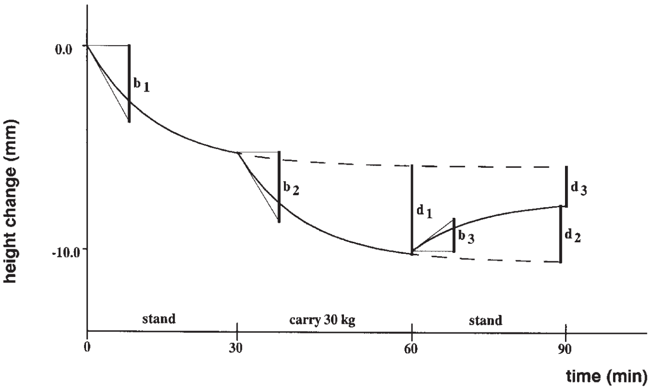

Fig. 2 Measurement cycle (carrying) characterised by six parameters [$\boldsymbol{b}_1$, $\boldsymbol{b}_2$, $\boldsymbol{b}_3$ initial slope of the exponential fit for pre-test, test and post-test phase respectively; $\boldsymbol{d}_1$, $\boldsymbol{d}_2$, $\boldsymbol{d}_3$ end-of-phase height differences between exponential fit (solid) and extrapolated exponential (dashed)]

a_0 is the final height approached asymptotically; a_1 is the magnitude of height change; τ is the time constant of the height change, τ was fixed at a constant value $\tau = 12$ min for all subjects and all phases. Previously it has been shown [10] that this confinement causes a minor reduction only to the accuracy of the fit. This loss was more than offset by the simplified interpretation and comparison of the results.

A complete measurement cycle with three phases is therefore described by a total of six parameters (a_0^i, a_1^i), with $i = 1, 2, 3$. For biomechanical interpretation another set of six parameters was found to be more adequate, providing the initial velocity and final result of height change for each phase (see Fig. 2). The parameters $\mathbf{b}_1$, $\mathbf{b}_2$, $\mathbf{b}_3$ give the velocity (in mm/min) of height change in the initial instant of phases 1, 2 and 3 respectively. The parameters $\mathbf{d}_1$, $\mathbf{d}_2$ and $\mathbf{d}_3$ give particular height differences (in mm) at distinct instants: $\mathbf{d}_1$ gives the height difference between the phase-2 curve and the extrapolated phase-1 curve at the end of phase 2. $\mathbf{d}_3$ gives the 'net height deficit' of the phase-3 curve to the extrapolated curve of phase 1 at the end of phase 3. For the same instant, $\mathbf{d}_2$ gives the difference between the phase-3 curve and the extrapolated curve of phase 2.

In pre- and post-shift measurements no time series are recorded. Instead, three measurements are taken at 5-min intervals and the mean value is calculated.

Radiology

MR images were obtained to quantify the water content of the discs and for morphological diagnosis of the lumbar spine. The water content of the disc was measured on T2-weighted images with a special inversion-recovery sequence (Ir 1400/400/23) [3]. In these images desiccation and degeneration of the discs are associated with a loss of signal. Fig. 3 shows a typical sagittal section. The calibration units (on the left) were used for quantification. They were filled with H_2O/D_2O in different concentrations. This composition was selected because D_2O has no spin echo, and thus the concentration of H_2O was measured alone. The comparison of disc signal intensity with that of the calibration units then yielded the 'water-equivalent' parameter of the disc (%H_2O). At least five, at most seven, discs were measured and the mean water-equivalent value was obtained by averaging over all levels. Errors in determining the 'water-equivalent' parameter may result from field inhomogeneities, as well as from certain chemical effects. By simultaneous measurement of pure water samples at different locations the error due to field inhomogeneities was found to amount to 4.2%. Error due to chemical effects may be due, for instance, to variations in the chemical composition of the disc: for example, in the calibration unit with a concentration of 300 mg/ml of K_2HPO_4 the signal intensity was found to be increased by more than 50% compared with pure water. This increase is caused mainly by the strong echo of phosphorus (P^{31}). Unfortunately, this error could not be quantified exactly. Presumably it is higher than that due to field inhomogeneities.

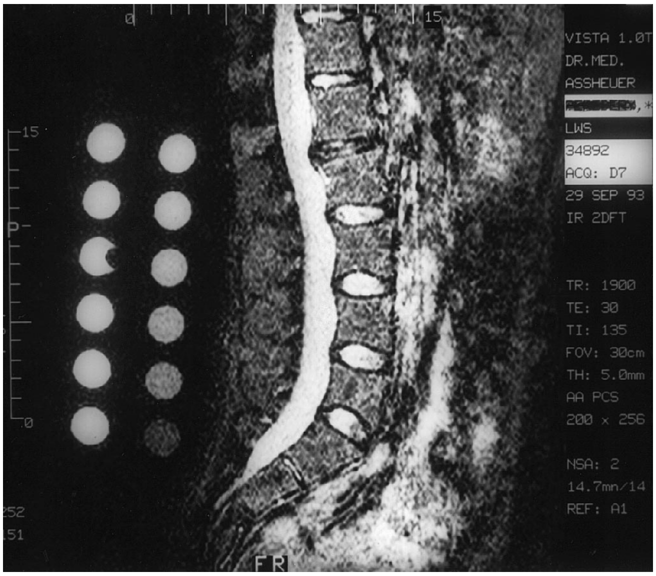

Fig. 3 T2-weighted magnetic resonance (MR) image of the lumbar spine. The two calibration devices on the *left* contain K_2HPO_4 in six concentrations and H_2O/D_2O in five concentrations

In addition to the T2-weighted MR images, T1-weighted images were obtained for diagnosing morphological changes.

QCT was performed:

1. To measure bone density and calculate the compressive strength of the vertebrae
2. To measure end-plate area as a contributing factor to compressive strength and to eliminate its influence on height measurements

In measuring the compressive strengths of vertebrae a scout view and two transversal CT sections of the third lumbar vertebra (L3) were recorded (Fig. 4). The first section, delivering bone density, was positioned straight through the centre between the end-plates; the width was 10 mm. Quantification of bone density was enabled by a calibration device positioned under the patient and incorporated into the CT scan. It consisted of six units of K_2HPO_4 solution in different concentrations. Quantitative comparison of bone signals with calibration signals then allowed trabecular bone density to be expressed in K_2HPO_4-equivalent units.

The second CT section had a width of 5 mm and was positioned through the caudal end-plate of the 3rd lumbar vertebra. It provided the area of the lower end-plate of L3 (in cm^2). Together with bone density, it allowed the compressive strength (in kN) to be predicted with an error of ± 1.06 kN [4].

There was a second reason for measuring end-plate area: according to physical principles disc pressure, under a given axial load of the segment, varies with the inverse of cross-sectional area. Therefore the cross-sectional area has an effect on the change in spinal height. This effect can be compensated for if disc area is normalised across the whole cohort [1], for which it is sufficient to perform this measurement for one specific level, e.g. L3. As six

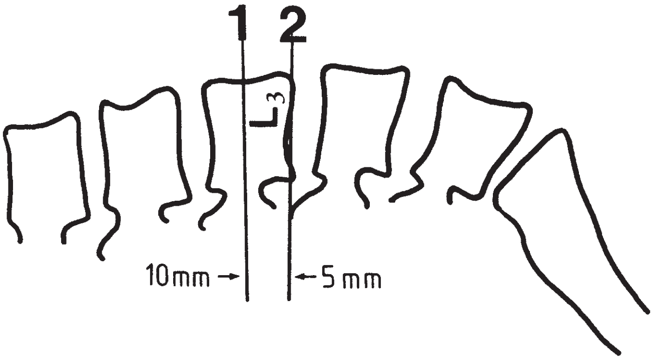

Fig. 4 Location of computed tomographic (CT)-sections in the scout view

subjects did not agree to radiological examination, their disc area had to be determined in the following way. There is a linear relation [7] between vertebral end-plate area and the square sum of the joint diameters. By a least squares analysis, this relation was established numerically for the end-plate area A_{L3} of L3 in the 14 subjects who underwent a CT scan:

$$A_{L3} = k \cdot (D_w^2 + D_e^2 + D_k^2 + D_a^2) \qquad (2)$$

where $k = 0.0616 \pm 0.0043$ and D_w, D_e, D_k and D_a are the joint diameters of wrist, elbow, knee and ankle respectively. A_{L3} is given in cm^2, the diameters in cm. As an additional parameter in these subjects, the mean height of intervertebral discs was determined from the digitised lateral scout CT by averaging the height of discs L5/L4, L4/L3 and L3/L2. In essence, the following parameters were obtained from QCT measurement:

1. Area of the caudal end-plate of L3 in square centimetres
2. Mean height of intervertebral discs in millimetres
3. Trabecular bone density in K_2HPO_4-equivalent value
4. Compressive strength in kilonewtons

Results

Anthropometry

Relevant anthropometric data are listed in Table 1: age, duration of occupation under vibration exposure, height, weight and external bone dimensions, and predicted area of the lower end-plate of the third lumbar vertebra.

Stadiometry

Figure 5 shows a typical time series for a carrying cycle. Pre-test and post-test measurement points are represented by open circles, test-phase points by closed circles. A closed circle together with an open circle marks transition between two phases. Separately for each phase an exponential (Eq.1) is fitted to the respective points. The root mean square deviation of the data points from the fit function is indicated by error bars.

The height changes in Fig. 5 are typical of the carrying cycle. During the pre-test phase a moderate height decrease is observed. During the test phase, when a load is carried, an additional decrease occurs. During the post-test phase the height recovers due to relaxation, with a final height approximately equal to the extrapolated pre-test height. In contrast, the sitting cycle exhibits partially different height changes: a height decrease during the pre-test phase as in the carrying cycle, a height increase during the test phase and a height decrease during the post-test phase.

Table 2 presents for all phases of both cycles the mean values and standard deviations of the velocity and differ-

Table 1 Anthropometric data of investigated operators (n = 20). *L3* lists the area of the lower L3 end-plate either measured on computed tomographic (CT) scans or estimated from wrist, elbow, knee and ankle diameters (in parentheses)

Subject	Age (years)	Exposure (years)	Height (cm)	Weight (kg)	Wrist (cm)	Elbow (cm)	Knee (cm)	Ankle (cm)	L3 (cm^2)
1	52.0	31.0	170.0	80.0	5.7	7.8	9.7	7.2	14.8
2	52.0	28.0	182.0	105.0	6.6	8.0	11.0	8.4	18.4
3	53.0	35.0	186.0	104.0	6.4	7.8	10.8	8.0	17.4
4	37.0	18.0	176.0	88.0	6.0	7.0	9.5	7.7	(14.5)
5	52.0	10.0	165.0	65.0	6.0	7.2	10.0	7.5	15.7
6	29.0	12.0	186.0	78.0	6.1	7.5	10.5	8.2	16.7
7	38.0	12.0	177.0	87.0	6.4	7.1	10.5	6.8	15.3
8	26.0	6.5	186.0	92.0	6.4	7.6	10.1	8.0	16.3
9	37.0	13.0	182.0	70.0	6.8	7.6	10.1	7.8	16.5
10	37.0	14.0	183.0	105.0	6.8	8.3	11.8	7.8	(19.4)
11	29.0	13.0	171.0	68.0	5.8	7.2	9.8	7.7	14.9
12	35.0	11.0	182.0	92.0	6.4	7.8	11.0	8.4	18.1
13	49.0	30.0	170.0	89.0	5.9	7.6	10.3	7.6	15.8
14	31.0	6.5	180.0	80.0	6.5	7.3	9.6	7.3	(14.9)
15	51.0	25.0	179.0	85.0	6.0	7.3	10.0	7.9	15.9
16	53.0	32.0	173.0	75.0	6.2	8.1	10.1	7.7	(16.4)
17	53.0	12.0	173.0	80.5	6.3	7.3	10.5	7.9	(16.4)
18	46.0	11.0	178.0	110.0	6.3	8.0	11.3	8.4	(18.6)
19	44.0	12.0	182.0	65.0	5.8	7.1	9.9	7.6	14.8
20	44.0	20.0	168.0	60.0	5.0	7.0	9.7	7.1	13.5

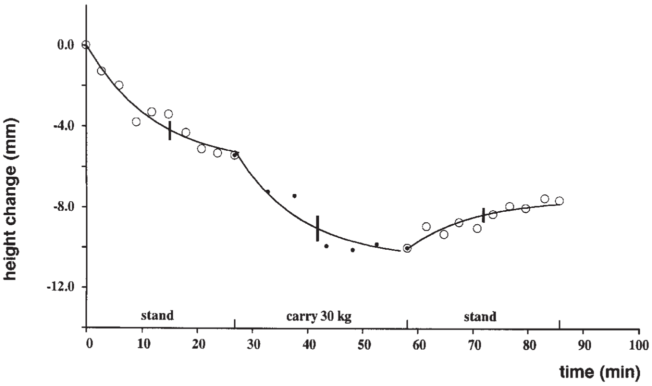

Fig. 5 Example of a measurement cycle (carrying). Height measurement is plotted against time. The cycle consists of three phases: pre-test (‘stand’), test (‘carry 30 kg’), post-test (‘stand’). Pre-test and post-test measurements are indicated by *open circles*, test measurement by *closed circles*; curves show fitted exponential; error bars indicate root mean square deviation of measurement points from exponential fit

ence parameters of the carrying and sitting cycle $\mathbf{b}_i$, $\mathbf{d}_i$ and $\mathbf{B}_i$, $\mathbf{D}_i$, where $\mathbf{B}_i$, $\mathbf{D}_i$ refer to the sitting cycle in analogy to $\mathbf{b}_i$, $\mathbf{d}_i$ in the carrying cycle. Additionally, in the bottom row, the mean stature change during the morning shift is listed. Each entry relates to 40 measurements (i.e. 20 subjects on 2 days). More detailed tables, providing these parameters for each subject, are given elsewhere [10].

The range of stature changes is well illustrated by Fig. 6, where stature change during phase 2 (carrying, sitting) is plotted against relaxation in phase 3. Each measurement cycle (days 2 through 5) of each subject is represented by one point, totalling 80 points. As stature change in the relaxation phase is generally in an opposite direction to stature change during the test phase, data points are mainly in quadrants II and IV. No subject increased height in both phase 2 and 3; therefore no data point is found in quadrant I. While a stature decrease in both phases is observed in three cases only (quadrant III). The carrying task exhibits a negative height change in the second phase and a positive relaxation in the third phase. The pertinent points are prevailingly in quadrant II. As relaxation gain is less than the previous height loss, the points are shifted by the net height deficit $\mathbf{d}_3$ towards negative y-values. Similar considerations hold for the sitting cycle.

The height loss during the morning shift (days 6 and 7) is highly significant ($P \leq 0.00001$). The minimum height loss was 1.5 mm, and the maximum loss 13.1 mm.

Since the pre-test phase was carried out under identical conditions on all 4 days, as criterion for reliability, the slope of the height loss curves may not vary significantly on different days. This is confirmed with $P \leq 0.00001$.

Radiological findings

Parameters derived from CT, QCT and MRI examinations are listed in Table 3. Fourteen subjects underwent CT and QCT examination, 12 of them also underwent MRI. Clinical examination of both T1- and T2-weighted images of the lumbar spine revealed two negative findings, three minor findings and seven severe findings, including complete degeneration of one or more discs, disc prolapse and protrusion.

In Fig. 7, bone density obtained from QCT measurements is plotted as a function of age. The pertinent regression line shows a clear reduction of bone density with increasing age. For comparison purposes, range data from literature [16] (mean ± SD) in different age groups are visualised by rectangles.

Correlations

Relations between measurements were studied by calculating Pearson’s correlation coefficients. Parameters tested were all anthropometric data including exposure time (Table 1), all stadiometric data (Table 2) and all radio-

Table 2 Mean values and standard deviations of stadiometric measurement parameters ($n = 20$). For notations refer to Fig. 2 and to the text

Parameter	Mean ± SD
$\mathbf{d}_1$: height loss after 30 min carrying	–3.68 ± 1.57 mm
$\mathbf{d}_2$: height gain when standing, 30 min after carrying	1.78 ± 1.42 mm
$\mathbf{d}_3$: remaining height loss 30 min after carrying	–2.22 ± 1.26 mm
$\mathbf{D}_1$: height gain after 30 min sitting	4.16 ± 1.39 mm
$\mathbf{D}_2$: height loss when standing, 30 min after sitting	–4.61 ± 1.34 mm
$\mathbf{D}_3$: remaining height gain 30 min after sitting	–0.12 ± 1.16 mm
$\mathbf{b}_1$: initial slope pre-test phase carrying	–0.21 ± 0.16 mm/min
$\mathbf{b}_2$: initial slope test phase carrying	–0.37 ± 0.12 mm/min
$\mathbf{b}_3$: initial slope post test phase carrying	0.13 ± 0.11 mm/min
$\mathbf{B}_1$: initial slope pre-test phase sitting	–0.23 ± 0.13 mm/min
$\mathbf{B}_2$: initial slope test phase sitting	0.35 ± 0.11 mm/min
$\mathbf{B}_3$: initial slope post-test phase sitting	–0.38 ± 0.12 mm/min
height change shift (post-shift height – pre-shift height)	–6.77 ± 2.81 mm

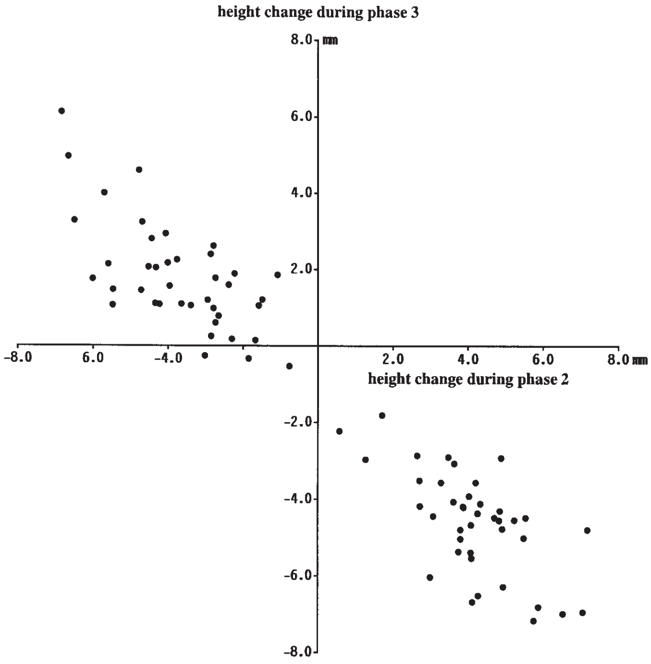

Fig. 6 Phase 3 height change as a function of phase 2 height change. Combined display of carrying and seated measurements ($n = 80$)

logical data including mean disc height and mean water content (Table 3). Table 4 gives the non-trivial relations between stadiometric parameters with a significance level $P \leq 0.01$. The first line of Table 4, for example, shows a correlation between the initial slope $\mathbf{b}_2$ of height loss (carrying) and subsequent height gain $\mathbf{d}_2$ (relaxation phase). The sign is negative, as movements are in opposite directions.

Note that correlations were found solely between parameters of the same task – i.e. no significant correlations were found between carrying and seated parameters. Furthermore, no correlation was found between pre-test and post-test phase parameters.

Correlations between anthropometric and stadiometric parameters are given in Table 5. Stadiometric data are normalised to the end-plate area of L3. Figure 8 illustrates one finding: the correlation between age and the net height deficit $\mathbf{d}_3$ after a carrying cycle. It is evident that, for subjects up to 35 years, a 30-min recovery period is not sufficient to re-establish former height: instead a height deficit is observed. For older subjects the results are divergent: in some, complete recovery is observed, while others exhibit a deficit like the younger ones. Although the correlation proves to be significant, it is not evident whether a simple relationship between age and recovery after spinal loading exists.

Among anthropometric parameters, age correlates with radiological parameters (Table 6). This finding is in agreement with the literature [4, 15, 16]. No significant correlation was found between length of exposure and radiological findings including mean disc height and mean water equivalent. Furthermore, a *t*-test was used to compare the mean exposure time of subjects with no or only one minor finding of disc degeneration ($n = 5$) with that of subjects with at least one severe finding of disc degeneration. The difference was not significant ($P > 0.2$). Likewise, no significant correlation was found between stadiometric and radiological measurements.

Table 3 Radiological parameters from quantative (Q)CT ($n = 14$) and magnetic resonance imaging (MRI) ($n = 12$) examinations

Subject	Lumbar discs with radiological findings	Area of L3 (cm^2)	Bone density of L3 (mg K_2HPO_4/ml)	Predicted compressive strength of L3 (kN)	Mean disc height averaged over all lumbar discs (mm)	Water equivalent averaged over all lumbar discs (% H_2O)
1	1 minor	14.9	181.1	5.76	7.99	84.9
2	1 severe	16.4	128.5	6.86	10.37	79.0
3	1 minor	18.0	108.3	6.34	9.71	77.7
5	–	15.7	109.5	5.61	8.49	–
6	1 minor	16.0	146.8	7.64	10.71	83.8
7	3 severe	15.3	140.9	7.00	9.14	73.7
8	0	14.7	211.2	10.02	9.27	82.5
9	1 severe	16.2	140.9	7.42	8.96	74.1
11	1 severe	15.4	147.4	7.37	8.96	89.8
12	1 severe	17.2	164.2	9.12	9.57	84.6
13	0	16.0	143.7	7.46	9.57	77.8
15	–	15.9	67.3	3.55	9.85	–
19	2 severe	17.4	152.7	8.60	8.54	81.5
20	1 severe	13.5	124.0	5.47	9.22	81.5

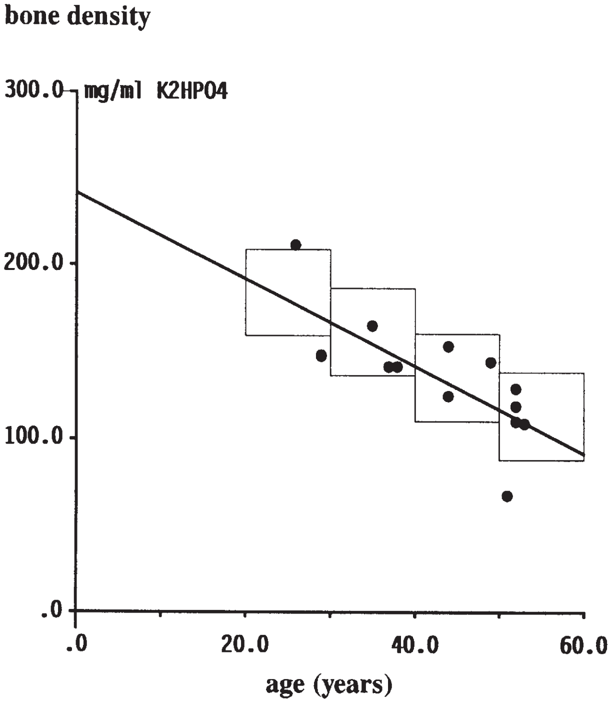

Fig. 7 Relation between age and bone density ($n = 14$). Standard ranges from the literature [16] are indicated by rectangles

Discussion

Analysis of the measurements shows that time-dependent behaviour of stature can be described very well by exponential functions. This applies even in cases where the subject has to change their activity and attitude in order to perform height measurements. According to the Kelvin model, three parameters must be fitted. The size of the measurement error and the limited number of measurement points cause a large uncertainty of one parameter – the time constant τ. Under these conditions the time constant is of little use in interpreting the measurements. Conversely, only a small error is introduced if a uniform time constant (here 12 min) is chosen. The advantage of this restriction is a relevant simplification of the analysis.

The accuracy of measurements is found to be in good agreement with the standard error of 0.40 ± 0.15 mm given in literature [1], where the mean standard deviation of the measurement points from the fitted exponential is considered. For reasons of simplicity and uniformity, the analysis was restricted to the pre-test phase only. This approach was adopted here, and all pre-test measurements (days 2–5 of all 20 subjects) were averaged. The standard error found here is 0.46 ± 0.25 mm. If one outlier subject is ignored, this figure is reduced to 0.42 ± 0.16 mm. This is in agreement with the published data, i.e. no significant difference is found.

On the other hand, remarkable inter-day variations were observed: measurements made on the same subject on successive days sometimes exceeded this error by up to four times. This cannot be due to measurement errors, but must have other causes – either stadiometric, anthropometric or radiological – which cannot be investigated from the measurements carried out here. Instead, 24-h observation of the subjects would be necessary.

Analysis of the measurements provides consistent results that agree with results for a healthy control group: whilst carrying a shoulder load the subjects shrink by 3.68 ± 1.57 mm; conversely, they gain height (4.16 ± 1.39 mm) when seated. As a peculiarity, no correlation was found between height measurements in different tasks (i.e. sitting, carrying, morning shift). As measurements for different tasks were recorded on separate days, the lack of correlations may well be ascribed to effects of inter-day variations obscuring the correlations. This is all the more probable as the inter-day variation exceeds the statistical measurement error. Parameters observed in the carrying task prove to be correlated with anthropometric data. In particular, height recovery depends on age: a return to the extrapolated pre-test height is not complete (‘height deficit’) 30 min after the end of the carrying task in the younger age group, while this is frequently the case for older subjects. The absolute gain in height is height dependent: it is larger for smaller persons. No significant relationship was found between stadiometric results and average intervertebral disc thickness. One possible explanation is that this relationship would be difficult to observe in our cohort, which exhibited a relatively uniform disc height (see Table 3).

Table 4 Coefficients of the significant ($P < 0.01$) correlations between stadiometric parameters ($n = 20$)

Stadiometric	vs	stadiometric parameters	*r*
b2: initial slope test phase carrying	vs	**d**2: height gain 30 min after carrying	–0.65
d1: height loss after 30 min carrying	vs	**d**2: height gain 30 min after carrying	–0.66
d1: height loss after 30 min carrying	vs	**d**3: height deficit 30 min after carrying	0.57
B2: initial slope test phase sitting	vs	**B**3: initial slope post-test phase sitting	–0.71
B1: initial slope pre-test phase sitting	vs	**D**1: height gain after 30 min sitting	–0.61
B3: initial slope post-test phase sitting	vs	**D**1: height gain after 30 min sitting	–0.61
B2: initial slope test phase sitting	vs	**D**2: height loss 30 min after sitting	–0.73
D1: height gain after 30 min sitting	vs	**D**2: height loss 30 min after sitting	–0.69

Table 5 Coefficients of the significant ($P < 0.01$) correlations between anthropometric and stadiometric parameters ($n = 20$)

Anthropometric vs stadiometric parameters			r
Age	vs	**d**3: height deficit 30 min after carrying	0.63
Height	vs	**d**2: height gain 30 min after carrying	–0.59
Weight	vs	**B**3: initial slope post-test phase sitting	–0.56

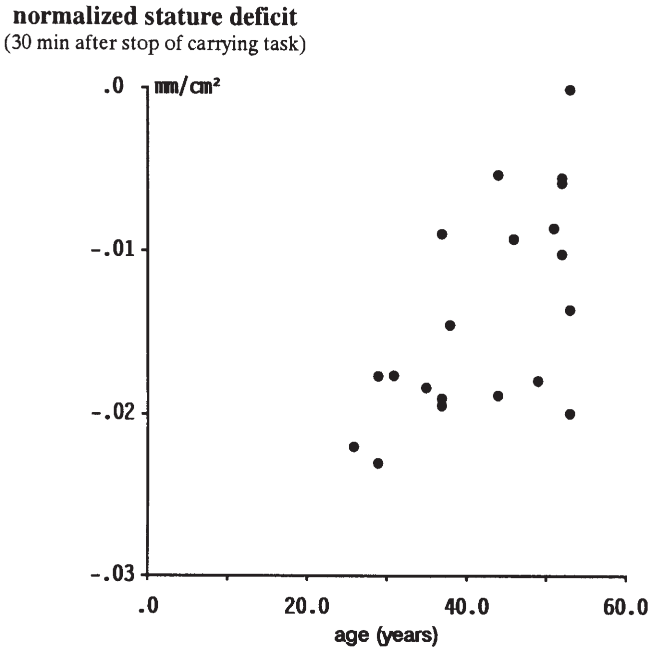

Fig. 8 Relation between age and $\mathbf{d}_3$ (i.e. height deficit 30 min after carrying task) with $\mathbf{d}_3$ normalized to L3 end-plate area ($n = 20$)

Table 6 Coefficients of the significant ($P < 0.01$) correlations between age and QCT parameters ($n = 14$)

Age vs QCT parameters			r
Age	vs	Bone density	–0.75
Age	vs	Compressive strength	–0.67

No indications were found for a systematic difference between radiologically examined and non-examined subjects. No significant difference was found in age, height, weight or any other anthropometric parameter. Therefore, relationships – those that have been established and those that have not – should be valid for the whole cohort.

Bone density of L3 of exposed subjects (Fig. 7) is well in agreement with published data compiled as the average from L1 to L3 on non-exposed controls [16]. Comparing densities of L3 alone is valid, as previous work [4] has shown that trabecular bone density is close to uniform along the whole lumbar spine. This shows that long-term exposure to whole-body vibration had no general effect on bone density in the lumbar vertebrae.

Similarly, MRI measurements of water content do not yield significant differences from normals. The average water content found in this study is 80.5%, with a statistical error of ± 1.4%. This is in good agreement with values in the literature [26], where T2-weighted MR images of cadavers show an average water content of 80.2% ± 0.4%. Similarly, good agreement is found for age dependency of the water content. Nothing can be said here about disc water content under loaded conditions.

No convincing relationship is found between disc water content and stadiometric results. In this context it is pointed out that stadiometric measurements refer to the whole spine, i.e. height changes of the individual discs are totalled. The share of one single degenerate disc may be concealed if its function is taken over by non- or less degenerate discs. Thus, unless the water content exhibits strong variations between subjects, no correlation is likely to be found. In this cohort, however, mean disc water content exhibits slight variations only (see Table 3).

The question raised in this study, of whether the viscoelastic properties of the discs in subjects exposed to long-term whole-body vibration differ from those in a healthy control group, must, therefore, be answered in the negative. No significant difference from the cohort reported in an earlier paper [1] was found in either of the two activities ($P > 0.02$). If there are disc injuries caused by long-term exposure to whole-body vibration, then, within current limits of stadiometric measurements, they do not affect the viscoelastic disc behaviour averaged over the whole spine.

This result may be specified by further investigations with an improved measurement technique, for example by applying long-lasting markers to the skin so that height changes are measured not only during one task or one shift, but from one day to the next. Together with 24-h observation of the subjects, such procedure might throw some light on the strong inter-day variability of height response.

Conclusions

It has been presumed that long-time exposure to whole-body vibration could damage the intervertebral discs. Previously, however, this presumption could not be proven, since quantitative and objective evidence of injuries was lacking. For the first time, a combined stadiometric, MRI and QCT examination has been performed in subjects who have been exposed to long-term whole-body vibration and who showed clinical symptoms suggestive of disc injuries due to vibration exposure. The results of the stadiometric investigations reveal no significant difference from an age-matched cohort of healthy persons. Despite radiological findings in isolated discs, the investigated parameters provide no evidence that lumbar discs of subjects exposed to long-term whole-body vibration differ on average from those of non-exposed subjects with respect to average water content, disc height and viscoelastic behaviour. In addition, QCT examinations revealed no significant difference in the compressive strength of the 3rd lumbar vertebra.

References

1. Althoff I, Brinckmann P, Frobin W, Sandover J, Burton K (1992) An improved method of stature measurement for quantitative determination of spinal loading. Spine 17 : 682–693
2. Althoff I, Brinckmann P, Frobin W, Sandover J, Burton K (1993) Die Bestimmung der Belastung der Wirbelsäule mit Hilfe einer Präzisionsmessung der Körpergröße. Schriftenreihe der Bundesanstalt für Arbeitsschutz, FB 683, Dortmund
3. Assheuer J, Lenz G, Gottschlich KB, Schulitz KB (1987) Fett-Wassertrennung im Kernspintomogramm. Fortschr Geb Röntgenstrahlen Neuer Bildgeb Verfahr Ergänzungsbd 147 : 58–63
4. Brinckmann P, Biggemann M, Hilweg D (1989) Prediction of the compressive strength of human lumbar vertebrae. Clin Biomech 4 [Suppl 2]
5. Brinckmann P, Frobin W, Biggemann M, Burton K, Tillotson M (1998) Quantification of overload injuries to thoracolumbar vertebrae and discs in persons exposed to heavy physical exertions or vibration at the work-place. II. Occurrence and magnitude of overload injury in exposed cohorts. Clin Biomech 13 [Suppl 2]
6. Brinckmann P, Wilder DG, Pope MH (1996) Effects of repeated loads and vibration. In: Wiesel SW et al. (eds) The lumbar spine, vol 1, 2nd ed, W.B. Saunders, Philadelphia, pp 181–202
7. Colombini D, Occhipinti E, Grieco A, Faccini M (1989) Estimation of lumbar disc areas by means of anthropometric parameters. Spine 14 : 51–55
8. Corlett EN, Eklund JAE, Reilly T, Troup JDG (1987) Assessment of workload from measurements of stature. Appl Ergonom 18 : 65–71
9. De Puky P (1935) The physiological oscillation of the length of the body. Acta Orthop Scand 6 : 338–347
10. Drerup B, Granitzka M (1994) Bestimmung des Schädigungsgrades von Bandscheiben nach langjähriger Ganzkörpervibrations-Exposition mit Hilfe der Stadiometrie. Schriftenreihe der Bundesanstalt für Arbeitsmedizin, FB10.002, Berlin
11. Dupuis H, Zerlett G (1987) Whole body vibration and disorders of the spine. Int Arch Occup Environ Health 59 : 323–336
12. Fung YC (1981) Biomechanics, mechanical properties of living tissues. Springer, Berlin
13. Holm S (1996) In: Wiesel SW et al. (eds) The lumbar spine, vol 1, 2nd edn. W.B. Saunders, Philadelphia, pp 285–310
14. ISO 2631–1 : 1997 (E) Mechanical vibration and shock: evaluation of human exposure to whole body vibration. 1. General requirements. 2nd edn.
15. Jäger M, Luttmann A (1989) Biomechanical analysis and assessment of lumbar stress during load lifting using a dynamic 19-segment biomechanical human model. Ergonomics 32 : 93–112
16. Kalender WA, Felsenberg D, Louis O, Lopez P, Klotz E, Osteaux M, Fraga J (1989) Reference values for trabecular and cortical bone density in single and dual-energy quantitative computed tomography. Eur J Radiol 9 : 75–80
17. Kazarian LE (1975) Creep characteristics of the human spinal column. Orthop Clin North Am 6 : 3–18
18. Kraemer J, Kolditz D, Gowin R (1985) Water and electrolyte content of human intervertebral discs under variable load. Spine 10 : 69–71
19. Leivseth G, Drerup B (1998) Spinal shrinkage during work in a sitting posture compared to work in a standing posture. Clin Biomech 12 : 409–418
20. Magnusson M, Hult E, Lindström I, Lindell V, Pope M, Hansson T (1990) Measurement of time-dependent height-loss during sitting. Clin Biomech 5 : 137–142
21. Malko J, Hutton W, Fajman W (1999) An in vivo magnetic resonance imaging study of changes in the volume (and fluid content) of the lumbar intervertebral discs during a simulated diurnal load cycle. Spine 24 : 1015–1022
22. Paajanen H, Lehto I, Alanen A, Erkintalo M, Komu M (1994) Diurnal fluid changes of lumbar discs measured indirectly by magnetic resonance imaging. J Orthop Res 12 : 509–514
23. Pope MH, Hanley EN, Matteri RE, Wilder DG, Frymoyer JW (1977) Measurement of intervertebral disc space height. Spine 2 : 282–286
24. Seidel H, Heide R (1986) Long-term effects of whole body vibration: a critical survey of the literature. Inf Arch Occup Environ Health 58 : 1–26
25. Seidel H (1996) Beanspruchungsadäquate Beurteilung wiederholter Kompressionsbelastungen der Wirbelsäule. ErgoMed 20 : 150–160
26. Tertti M, Paajanen H, Laato M, Aho H, Komu M, Kormano M (1991) Disc degeneration in magnetic resonance imaging: a comparative biochemical, histologic, and radiologic study in cadaver spines. Spine 16 : 629–634
27. Urban J (1996) Disc biochemistry in relation to function. In: Wiesel SW et al. (eds) The lumbar spine, vol 1, 2nd edn. W.B. Saunders, Philadelphia, pp 271–281
28. Weidenbaum M, Foster RJ, Best BA, Saed-Nejad F, Nickoloff E, Newhouse J, Ratcliffe A, Mow VC (1992) Correlating magnetic resonance imaging with the biochemical content of the normal human intervertebral disc. J Orthop Res 10 : 552–561