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Occurrence and magnitude of overload injuries to the lumbar vertebrae and discs of workers exposed to heavy physical exertions or vibration

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**Occurrence and magnitude of overload  
injuries to the lumbar vertebrae and  
discs of workers exposed to heavy  
physical exertions or vibration**

CONTRACT RESEARCH REPORT  
211/1999



## **Occurrence and magnitude of overload injuries to the lumbar vertebrae and discs of workers exposed to heavy physical exertions or vibration**

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The prevalence of irreparable damage to lumbar vertebrae and discs due to occupational overload has not been quantified previously, and the effectiveness of guidelines for prevention of overload damage is undetermined.

Archive lateral thoracolumbar radiographs and work histories of 355 subjects were collected from 8 cohorts in the steel, mining and oil industries as well as from public services. Vertebral height, sagittal plane displacement and disc height were measured, using advanced methods of image analysis. The measured data were compared with age-appropriate data of normative databases, previously compiled from radiographs of unexposed subjects.

Lifting and handling very heavy objects, specifically when working in confined spaces or on uneven ground, lead to a noticeable and significant decrease in the height of lumbar discs. While exposure to vibration on damped machine operators' seats did not lead to a reduction in disc height, vibration and shock loading transmitted from unsprung seats resulted in a noticeable and significant decrease in lumbar disc height. Reduction of vertebral body height was found comparatively rarely.

This study demonstrates, for the first time, objectively and quantitatively that spinal loading in certain industrial workplaces can result in irreparable damage to lumbar discs. The question of whether heavy work is related to the prevalence of symptoms and/or resultant disability remains to be determined, but it is suggested that existing ergonomic guidelines are justified to reduce the risk of irreversible spinal damage.

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## SUMMARY

*Objective:* Quantification of primary mechanical overload injury to lumbar vertebrae and discs caused by long-term exposure to heavy physical exertions or whole-body vibration at the workplace.

*Background:* Current guidelines for manual handling and whole-body vibration are aimed at minimising potential risks to the lumbar spine. However, the prevalence of irreparable damage to lumbar vertebrae and discs due to occupational overload has not been quantified, and the effectiveness of the guidelines in preventing overload damage has not been proven.

*Methods:* Overload damage to the lumbar spine is expected to result potentially in (i) fractures effecting a decrease in vertebral height or a wedge shape of vertebral bodies, (ii) a derangement of the sagittal plane alignment of lumbar vertebrae, resulting in dorso-ventral displacement, or (iii) primary injury to intervertebral discs or fracture of vertebral endplates, resulting in a decrease in disc height. To assess the occurrence and magnitude of such damage, archive lateral radiographic views and work histories of 355 subjects with long-term exposure to heavy physical exertions or whole-body vibration at the workplace were collected from 8 cohorts in the steel, mining and oil industries as well as from public services. Vertebral height, sagittal plane displacement and disc height were measured, employing advanced methods of image analysis compensating for distortion in central projection as well as for variation in radiographic technique, patient posture and stature. The measured data were compared with age-appropriate data of normative databases, previously compiled from radiographs of healthy, male, unexposed subjects (n=737) in the age range between 17 and 57 years.

*Results:* Comparison with normative databases demonstrates that in the cohorts under study (save for a cohort performing a specialised task in a forward bent posture and a cohort of miners with mean age close to 60 y) neither exposure to very heavy physical exertions in manual labour nor exposure to whole-body vibration or shock loading resulted in a height decrease or wedge-shape deformation of lumbar vertebrae. Heavy spinal loading or whole-body vibration did not lead to increased sagittal plane (dorso-ventral) displacement of lumbar vertebrae. Lifting and handling very heavy objects, specifically when working in confined spaces or on uneven ground, lead to a noticeable and significant decrease in the height of lumbar discs. While exposure to vibration on damped machine operators' seats did not lead to a reduction in disc height, vibration and shock loading transmitted from unsprung seats on (in some cases) unsprung machines resulted in a noticeable and significant decrease in lumbar disc height.

*Conclusions:* This study demonstrates, for the first time, objectively and quantitatively that spinal loading in certain industrial workplaces can result in damage to lumbar discs. Heights of vertebral bodies and sagittal plane displacement were generally unaffected. Any workplaces with characteristics similar to those identified here as detrimental are in need of ergonomic redesign. That ergonomic redesign can be effective in reducing spinal overload damage is starkly demonstrated by comparing the results from vibration-exposed cohorts of machine operators using damped as opposed to unsprung seats. The question of whether heavy work is related to the prevalence of symptoms and/or resultant disability remains to be determined, but the results here suggest that existing ergonomic guidelines are justified to reduce the risk of irreversible spinal damage.

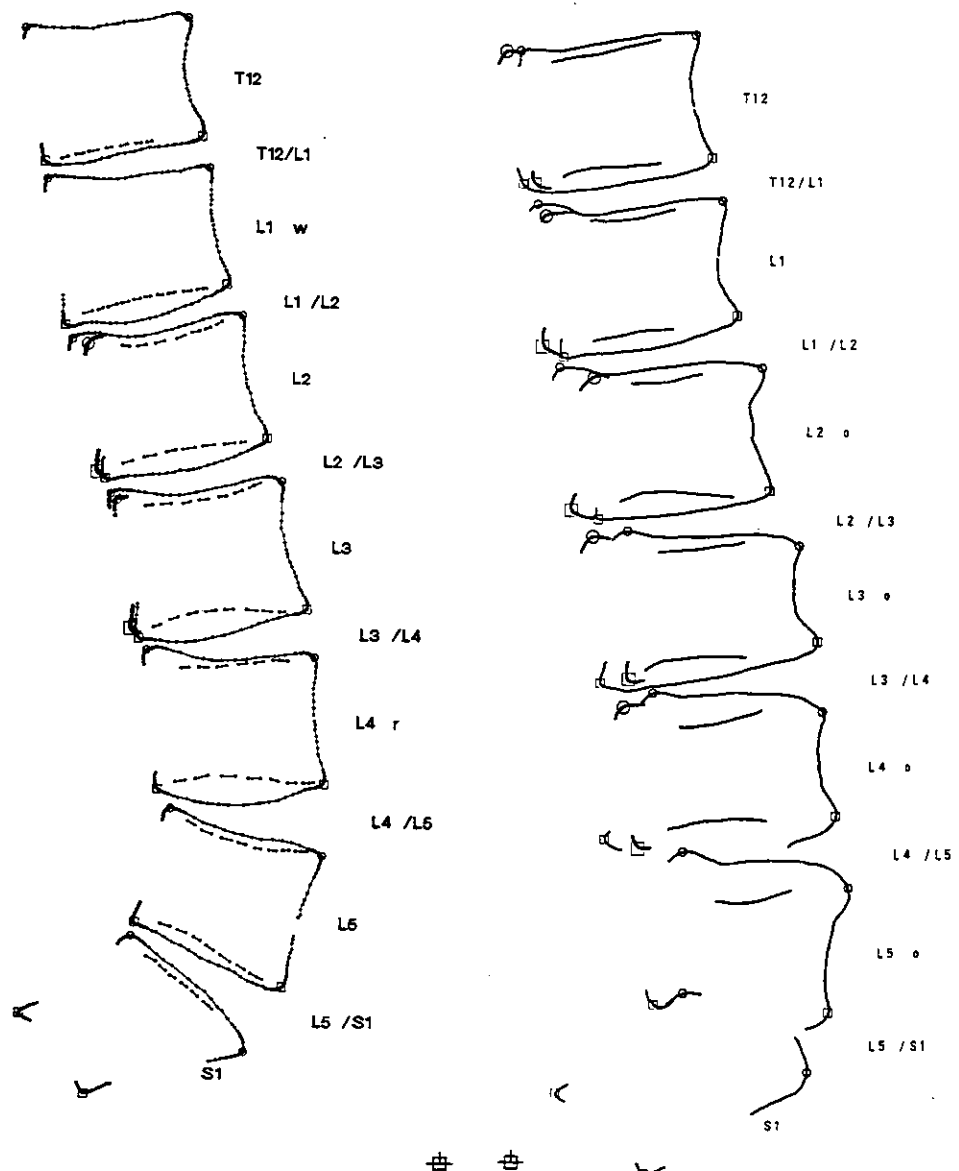


Figure 1.1 Digitised lateral radiographic images of the lumbar spine. The left figure is from a typical spine in the normative database. The right figure is from an extreme example of a spine in one of the heavily exposed cohorts.

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# 1. INTRODUCTION

Epidemiological studies point to heavy and repeated spinal loading, as well as to whole body vibration, as potential causes of low back problems in the labour force, though this relationship is confined largely to symptoms as opposed to disability. Nevertheless, the hypothetical cause-and-effect relationship between overload injuries to vertebrae and discs and clinical back problems is supported by biomechanical model calculations of spinal loading and by results from laboratory tests on spine specimens. The focus here is primary irreparable damage to vertebrae and discs as opposed to normal age-related changes or the putative cumulative strain of paraspinal tissues.

As a preventive measure, regulations on manual handling and lifting and exposure to vibration have been issued, though there is no evidence that they have been effective in reducing back-related disability. Considerable effort is being spent on ergonomic task improvements in various industries, agriculture and public services. The European Directive on safety and health protection in manual handling and lifting calls upon employers to take appropriate measures to minimise potential risks, specifically to the lumbar spine.

In the UK, the Management of Health and Safety at Work Regulations 1992, which came into force on 1 January 1993, require employers to make a suitable and sufficient assessment of the risks to the health and safety of their employees while at work. In respect of manual handling in particular, the Manual Handling Operations Regulations 1992, which came into force on 1 January 1993, apply. Guidance is given in 'Manual handling', published by the Health & Safety Executive (HSE) in 1992. The Regulations establish a clear hierarchy of measures: avoidance of hazardous manual handling operations; assessment of any hazardous manual handling operations that cannot be avoided; reduction of the risk from those operations that cannot be avoided.

Such regulations affect a large percentage of the labour force, so it is surprising that no direct evidence of work-related, primary mechanical overload damage to human lumbar vertebrae and discs has been furnished. Very few previous studies actually investigated the prevalence of overload damage to the lumbar spine in subjects potentially at risk; these few studies were only qualitative. There is not one single published study that assessed the occurrence of work-related overload damage to the lumbar spine objectively and quantitatively.

This study is performed to provide this quantification for the first time. To assess overload damage in the lumbar spine, precision measurements of vertebral height, sagittal plane displacement of vertebrae as well as height of intervertebral discs were performed from archive radiographs of subjects with documented long-term exposure to heavy spinal loading or whole-body vibration. Overload damage to the lumbar spine is expected to result in: (i) fractures effecting a decrease in vertebral height or a wedge shape of vertebral bodies, (ii) a derangement of the sagittal plane alignment of lumbar vertebrae, resulting in dorso-ventral displacement, or (iii) primary injury to intervertebral discs or fracture of vertebral endplates, resulting in a decrease in disc height. Occurrence and severity of such overload damage are quantified by comparing shape and alignment of vertebrae as well as height of discs in exposed cohorts with a normative database of healthy persons.

Development of the scientific tools for precise measurement of height and sagittal plane alignment of lumbar vertebrae as well as height of lumbar discs has been described in previous publications (Brinckmann *et al* 1994, Frobin *et al* 1996, Frobin *et al* 1997). These studies used advanced methods of image analysis in order to process archive radiographs taken in different, generally unknown geometric settings. Compensation for distortion in central projection as well



as compensation for the variation in posture when being radiographed were achieved; this is a prerequisite for performing a retrospective analysis of archive material.

Archive lateral radiographic views of the lumbar spine of subjects with documented long-term exposure to heavy physical exertions or whole-body vibration at the workplace were collected from a variety of sources.

Cohorts exposed to heavy physical exertions and thus to heavy spinal loading at the workplace were drawn from:

- open-cut brown-coal mine and briquette factory, Regis-Breitingen, Germany
- underground potassium salt mine (labourers), Merkers, Germany
- steelworks, Unterwellenborn, Germany
- underground coal mine, Lancashire, England
- offshore oil rig, Dubai, United Arab Emirates

Cohorts exposed to whole-body vibration were drawn from:

- underground potassium salt mine (machine operators), Merkers, Germany
- open-cut brown-coal mine, Köln, Germany
- police force, Belfast, Northern Ireland

Height and sagittal plane alignment of lumbar vertebrae as well as height of lumbar intervertebral discs were measured from the lateral radiographic views of the exposed cohorts. The measured parameters were compared - separately for British and German subjects - with normative, age-appropriate data previously derived from radiographs of unexposed subjects. Thus, the study furnishes direct proof of whether or not the work practice in the workplaces under study resulted in overload damage.

The outcome of the investigation is of interest for a number of reasons:

- If, in specific workplaces, overload damage to vertebrae or discs can be objectively and quantitatively demonstrated, this must lead to ergonomic redesign of the task. If these workplaces were operating under current guidelines, there may be a need for further reduction in loads and/or load frequencies. If damage was found only in older workplaces, it would suggest that the guidelines are beneficial and should be adhered to.
- If overload damage to vertebrae and discs turns out to be negligible in physically demanding workplaces considered at risk and exhibiting a high prevalence of low back problems, two far-reaching conclusions can be drawn: (1) Current regulations obviously suffice to prevent primary overload damage to vertebral bodies and discs. (2) As current regulations and design of tasks obviously do not prevent low back problems, future medical, biomechanical and psychosocial research should pay increasing attention to other potential sources of back problems (*i.e.* other than plain overload injuries to vertebral bodies and discs). Specifically, ergonomic efforts should then concentrate not necessarily on a further reduction of loads to be handled, but possibly more on redesigning the work environment and the organisation of work.

*[In this report Figures 2.1 – 2.4, Figures 4.1 – 4.27 and Figures 8.1 – 8.5 are reprinted from Clinical Biomechanics 1998, 13, Suppl 2. Brinckmann P, Frobin W, Biggemann M, Tillotson M, Burton K. Quantification of overload injuries to thoracolumbar vertebrae and discs in persons exposed to heavy physical exertions or vibration at the workplace. Part II. Occurrence and magnitude of overload injuries in exposed cohorts, S1-S39. Copyright (1998), with permission from Elsevier Science]*

## 2. METHODS

Mere inspection of radiographs and qualitative statements on the presence or absence of pathological deviations from some arbitrary normative standard are considered insufficient for unequivocal assessment or rejection of hypothetical effects of high spinal loading on the integrity of lumbar vertebrae or discs. In view of the large number of workplaces affected and the widespread implications of existing or pending guidelines for safe lifting and handling, hard numerical data seem appropriate.

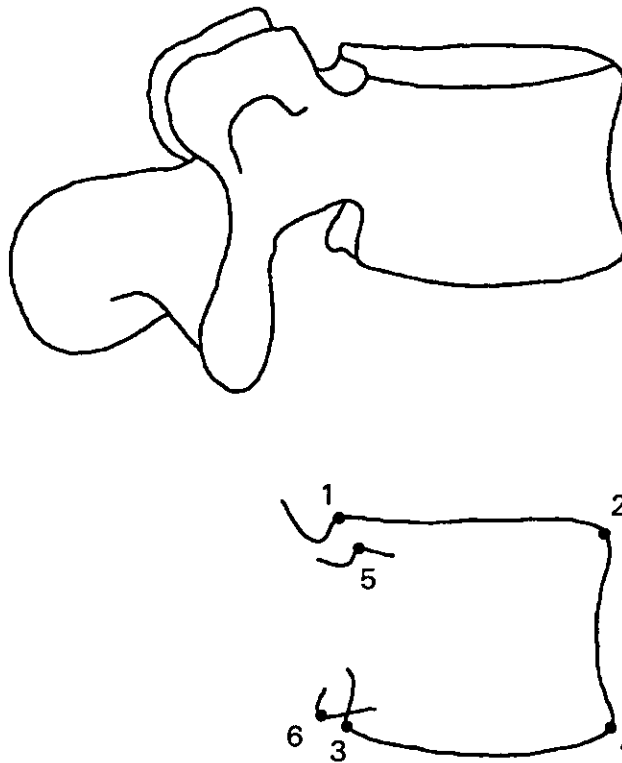
To arrive at a quantitative statement, height of lumbar discs as well as height and sagittal plane alignment of lumbar vertebrae of cohorts with work histories documenting long-term exposure to heavy physical exertions or whole-body vibration have to be measured and compared with age-appropriate data of subjects without pathological findings at the lumbar spine. When planning the study, however, conventional methods of measuring height of discs as well as height and alignment of vertebrae from lateral views of the lumbar spine soon proved to be imprecise or even conceptually questionable. The underlying problem is that the radiographic image is subject to distortion in central projection. If it is intended to arrive at a quantitative result from measuring archive radiographs drawn from a variety of sources, allowance has to be made for variations in exposure geometry, positioning of subjects in the x-ray apparatus, and variations in stature. Furthermore, due to the absence of suitable protocols for quantitative assessment of disc height, vertebral height and sagittal plane displacement, normative values for these parameters were not available in the literature.

For this reason, the study of exposed cohorts had to be preceded by formulating suitable definitions of vertebral height, sagittal plane displacement and disc height that are independent both of distortion in central projection and of radiographic magnification, small positioning errors and stature. Mean values of these parameters, their natural variance and their dependence on age and gender in an unexposed population with healthy spines had previously been assessed. The new definitions and the measuring technique are briefly reiterated below (Chapter 2.1). Chapter 2.2 outlines the representation of the data measured from the radiographs and the statistical tools employed when comparing exposed cohorts with the normative databases.

### 2.1 MEASUREMENT OF VERTEBRAL HEIGHT, SAGITTAL PLANE DISPLACEMENT AND DISC HEIGHT FROM LATERAL RADIOGRAPHS OF THE LUMBAR SPINE

Previous studies (Brinckmann *et al* 1994, Frobin *et al* 1996, Frobin *et al* 1997) developed precise methods for measuring vertebral height, sagittal plane displacement and disc height, based on the following items: (i) analysis of the imaging of vertebral contours in central projection with reference to image distortion, (ii) definition of objective landmarks (corners) on the image contours, related to the three-dimensional shape of vertebrae, and (iii) construction of geometric parameters describing vertebral height, sagittal plane displacement and disc height, these parameters being virtually uninfluenced by distortion with respect to axial rotation, lateral tilt and off-centre positioning of the vertebrae.

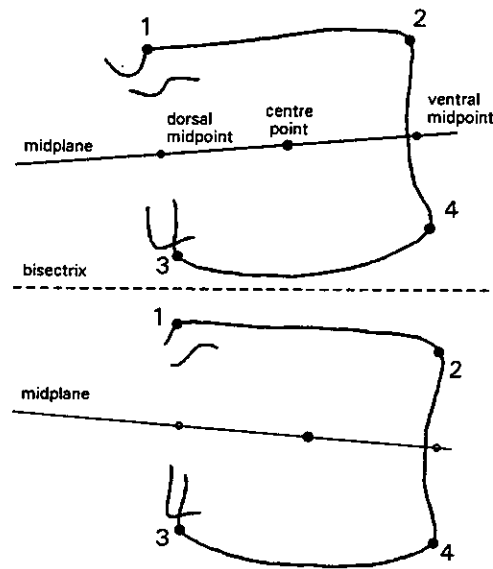
Figure 2.1 shows a mapping of the contours that can be identified in the lateral radiographic image of a lumbar vertebral body. Landmarks, termed ventral and dorsal 'corners', are objectively defined as contour points of maximum distance from reference points positioned within the vertebral silhouette. In many radiographs, the full set of four dorsal corners is not visible due to overlay from other structures or to deficient film quality. But those two dorsal corners (1 and 3) which are positioned on the outermost contours and the two ventral corners (2 and 4) can always be distinguished. Thus, all measurements are based exclusively on corners 1 to 4.



**Figure 2.1** Sketch of a lumbar vertebra and the contours that can be identified in the lateral radiographic image. Corners 1 to 6 are defined as contour points of maximum distance from reference points located within the vertebral silhouette

The pattern of contours and corners undergoes characteristic changes if a vertebra is imaged axially rotated, laterally tilted or off-centre from the central x-ray beam. It has been shown, however, that the relative location of the pair of ventral corners (2 and 4) is virtually unaffected by distortion in central projection. In contrast, the relative location of the pair of dorsal corners (1 and 3) is subject to distortion in central projection, *i.e.* depends strongly on axial rotation, lateral tilt and off-centre position. For this reason, single dorsal corners cannot be considered as reliable landmarks for the purpose of this study.

It is possible, however, to derive auxiliary landmarks which meet the desired criterion of independence of image distortion. Ventral and dorsal 'midpoints' (Figure 2.2) are defined as midpoints between corners 2 and 4 and corners 1 and 3; the 'centre point' marks the middle between the ventral and dorsal midpoints. The line connecting the ventral and dorsal midpoints is termed 'midplane'. The sagittal plane angle between two adjacent vertebrae is given by the angle between their midplanes and is termed 'midplanes angle'. The midplanes angle is counted positive if the wedge opens ventrally. While ventral corners and thus their midpoint are virtually unaffected by distortion, it can easily be shown that this also holds for the dorsal midpoints and the centre points. Thus, the ventral and dorsal midpoints, the centre points and the midplanes are appropriate geometric constructs on which measurements of vertebrae and discs can be based.

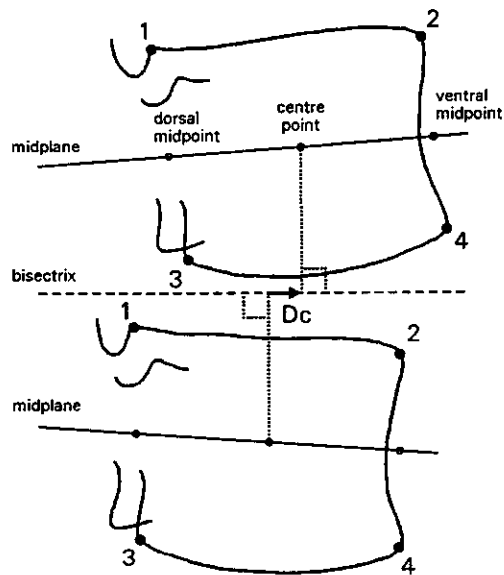


**Figure 2.2** Definition of ventral and dorsal midpoints, centre points, midplanes and bisectrix, derived from corners 1 to 4. Vertebral height is given by the distance between corners 2 and 4, divided by the mean depth (mean of cranial and caudal depth, defined by distance between corners 1-2 and 3-4) of the vertebra

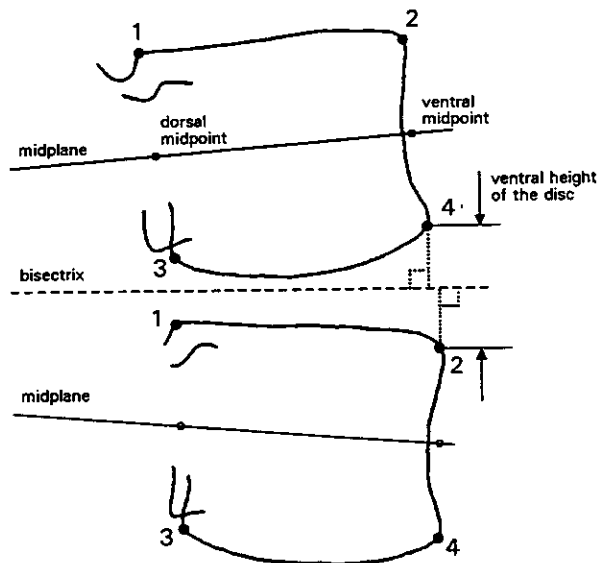
Ventral vertebral height is defined as the distance between the two ventral vertebral corners 2 and 4 (Figure 2.2). To allow for radiographic magnification and variation in stature, ventral vertebral height is divided by mean vertebral depth. Mean depth is defined as the mean of cranial depth (distance between corners 1 and 2) and caudal depth (distance between corners 3 and 4). Both ventral height and mean depth are imaged virtually free from distortion and uninfluenced by off-centre positioning, axial rotation and lateral tilt of the spine. In the following, the term 'vertebral height' is used synonymously for the (dimensionless) ratio 'ventral vertebral height / mean vertebral depth'.

To measure dorso-ventral displacement between adjacent vertebrae, the bisectrix between the midplanes is constructed (Figure 2.3). Displacement  $D$  is given by the distance  $D_c$  between the projections of the centre points, measured in the direction of the bisectrix, and divided by the mean depth of the cranial vertebra. Like vertebral height, displacement  $D$  is a dimensionless number. Displacement  $D$  is counted positive if the projection of the cranial centre point is ventral to the projection of the caudal centre point.

In healthy subjects, sagittal plane displacement depends in a regular fashion on the sagittal plane angle between the vertebrae. Upon extension of the lumbar spine, the cranial vertebra of a motion segment moves - relative to the caudal vertebra - into dorsal direction. The average magnitude of the physiological change of displacement with angle (*i.e.* the slope) was determined from a set of flexion-extension radiographs. The slopes obtained serve to transform displacement measured at arbitrary angles to displacement at fixed 'standard' angles. This permits quantitative comparison between radiographs taken at different postures, for example standing or side-lying, a prerequisite for any comparison between individuals or cohorts.



**Figure 2.3** Definition of dorso-ventral displacement. Displacement is given by the distance  $D_c$  between the projections of the centre points, measured in the direction of the bisectrix and divided by the mean depth of the cranial vertebra



**Figure 2.4** Definition of disc height. Disc height is given by the sum of the perpendicular distances of corner 4 of the cranial vertebra and corner 2 of the caudal vertebra from the bisectrix, divided by the mean depth of the cranial vertebra

The new definition for disc height given below constitutes a logical further development of Farfan's definition: the ventral height of a lumbar disc (Figure 2.4) is defined as the sum of the perpendicular distances of corner 4 of the cranial vertebra and corner 2 of the caudal vertebra from the bisectrix between the two midplanes. To allow for radiographic magnification and variation of stature, ventral disc height is divided by the mean depth of the cranial vertebral body. This quotient is a dimensionless number. In the following, the term 'disc height' is used synonymously for this quotient, *i.e.* for 'ventral height of the disc divided by the mean depth of the cranial vertebra'.

Ventral height of a disc, and thus disc height as defined here, depends on the angle of lordosis. With increasing extension of the spine (*i.e.* increasing midplanes angle), ventral disc height increases. The magnitude of the physiological change of disc height with midplanes angle was determined by linear regression analysis from a set of lateral lumbar radiographs of healthy, unexposed subjects. The regression coefficients obtained serve to correct disc height measured at an arbitrary angle to disc height at 'standard' angles. As in the case of displacement, this correction procedure permits quantitative comparison between radiographs taken in different postures.

The choice of these definitions for vertebral height, sagittal plane displacement and disc height has several important advantages:

(i) All geometric elements of these protocols (ventral height, mean depth, relative location of centre points, location and orientation of midplanes and bisectrix) are virtually uninfluenced by distortion, axial rotation or tilt. It follows that this also holds for vertebral height, displacement and disc height.

(ii) The measurement of disc height is not confounded by variations in sagittal plane displacement. Displacement is measured along the direction of the bisectrix while disc height is measured perpendicular to this direction. Thus, disc height and displacement are measured separately and independently.

(iii) Independence of off-centre position, axial rotation and lateral tilt implies that measurements are not confined to that portion of the radiograph where the central x-ray beam intersects the film plane. Measurements can be performed for all vertebrae, motion segments or discs on a lateral view.

(iv) Special control of patient alignment with respect to the radiographic film and tube is not required; normal positioning is sufficient. Geometry of the x-ray apparatus and posture of the patient need not be known. Thus, retrospective studies using existing radiographs are feasible.

Error studies demonstrated that vertebral height is reproduced with an error (SD) of 0.017 (in units of mean vertebral depth); this corresponds to a relative error of 2.2%. Sagittal plane displacement is measured with an error of 0.0145 (in units of mean vertebral depth). Disc height is measured with an error of 0.014 (in units of mean vertebral depth); this corresponds to a relative error of 4.15%.

The technical procedure for measuring height of discs as well as shape and displacement of vertebrae was designed to eliminate subjective influence as far as possible. Correct identification of vertebral contours (Fig. 2.1) is assisted by observation of systematic, cranio-caudal changes of the contour patterns in dependence on off-centre position, lateral tilt and axial rotation. The endplate contours and the ventral outline of the vertebrae (contours of osteophytes excluded) are mapped onto a transparent foil using a fine pencil. The mappings are digitised (precision 0.125 mm) with measured coordinates spaced 0.2 mm along the contours and stored in a computer. A series of programmes monitors the digitising procedure, checks the geometric properties of the contours, smoothes local contour irregularities, computes the location of the

corner points, calculates derived geometric measures (distances, angles) and parameters (vertebral height, sagittal plane displacement, disc height) and prints a protocol.

## 2.2 MATHEMATICAL AND STATISTICAL TOOLS

The parameters used to describe the morphology of the lumbar spine, vertebral height, sagittal plane displacement and disc height, may depend on age. Furthermore, sagittal plane displacement and disc height depend on the angle between adjacent vertebrae. Before any comparison between exposed and unexposed is made, raw data have thus to be standardised ('corrected') with respect to angle and age. The correction coefficients with respect to angle and age were determined by linear regression analysis from the normative, unexposed cohorts.

To evaluate the effect of exposure to heavy spinal loading or whole-body vibration, data of exposed cohorts are compared with normative databases, separately compiled from data of healthy, unexposed, British and German subjects. Pooling data from several unexposed cohorts drawn from the respective countries formed these databases. The homogeneity of the normative databases was tested by means of ANOVA. Neither the German nor the British database exhibited inhomogeneous class variances. When comparing the cohort means, statistical significance was assessed by the Welch procedure developed by Satterthwaite.

For one sub-cohort, paired radiographs taken at the beginning and at the end of the exposure time were available; the paired t-test was used to assess significance in this longitudinal study. The paired t-test was also used in the assessment of inter-observer differences when measuring vertebral height, sagittal plane displacement and disc height.

Since the coefficients describing the influence of age and angle had been determined by regression from the unexposed cohort, the influence of their statistical fluctuation on the homogeneity of the databases and on the significance of empirical differences and between exposed and unexposed subjects was assessed in a sensitivity study. This study varied the correction coefficients describing the dependence of parameters on angle [ $a$ ] and age [ $b$ ]. The variability of age dependence (correction coefficient  $a$ ) is supplied by the regression technique. In the case of sagittal plane displacement the variability of angular dependence (correction coefficient  $b$ ) is estimated by the population variance found from paired extension-flexion radiographs (Frobin *et al* 1996).

Confidence intervals (ellipses) for the correction coefficients may be defined. In the results, the information drawn from inspection of the minimum and maximum p-values found within the confidence ellipse is not given numerically, but coded into four classes of significance.

- If  $p$ ,  $p_{\min}$  and  $p_{\max}$  are all larger than the level of significance (set to 0.05), the result is classified as not significant. In the results open columns in the figures illustrate this.
- If  $p$  and  $p_{\max}$  are larger than 0.05, but  $p_{\min}$  is equal to or smaller than 0.05, the result is classified as a borderline case, and illustrated by dotted columns.
- If  $p$  and  $p_{\min}$  are both equal to or smaller than 0.05, the result is classified as significant and illustrated by hatched columns.
- If  $p$ ,  $p_{\min}$  and  $p_{\max}$  are all equal to or smaller than 0.05, the result is classified as highly significant and illustrated by black columns.

Only those results qualified under the last two classes of significance are regarded as representing true cohort differences in true workload effects rather than chance effects when comparing exposed and unexposed subjects.

[Full details of the above issues are given in Brinckmann *et al* (1998)].

## 3 MATERIAL

### 3.1 STANDARD OF COMPARISON: THE NORMATIVE DATABASE

Previous studies (Brinckmann *et al* 1994, Frobin *et al* 1997) developed precise and objective methods to measure vertebral height, sagittal plane displacement and disc height from lateral radiographic views of the lumbar spine. Using these new protocols, representative, age-appropriate standard values for these parameters were established. The sets of standard values (denoted as 'normative databases'), determined separately for German and British cohorts, will serve for comparison with exposed subjects. The essential features of data collection and filtering are reiterated below; for details, the reader is referred to the above publications.

To compile the databases, lateral radiographic views of the lumbar spine of males were collected from archives of a variety of institutions in Germany, Switzerland and Great Britain. In part, these radiographs had been taken during pre-employment examinations; in the remaining cases the radiographs had been taken for diagnostic purposes in patients presenting with minor back complaints or to exclude pathological findings unrelated to the lumbar spine.

Radiographs showing signs of osteoporosis, Scheuermann's disease, ankylosing spondylitis, metastatic disease, lumbar scoliosis of more than approximately 5° or radiographs of subjects with previous spinal surgery were excluded, as were radiographs of subjects with a known history of severe spinal loading either at the workplace or in professional athletics. Spines with signs of general degenerative disease and/or osteophytosis remained included; such signs are regarded as increasing in prevalence in the normal ageing process. All radiographs were inspected. Compilation of the normative databases was based exclusively on data from vertebrae, discs or motion segments without findings. Discs adjacent to a vertebra with pathologic findings or discs adjacent to vertebrae displaced in dorso-ventral direction were not included either.

Admittedly, emending a data set by excluding data from pathologic items is problematic, because radiological diagnostic criteria applied are only qualitative. With respect to the German database, the effect of emending has been documented by computation of an additional database from the non-emended data. The numerical difference between the two databases proved to be small (Frobin *et al* 1995).. Emending proved to have very little influence on the results of the comparison between exposed and unexposed subjects.

Sagittal plane displacement and disc height show a physiologic dependence on midplanes angle (angle of lordosis). In addition, these two parameters as well as vertebral height depend potentially on age as well. When comparing exposed with unexposed cohorts, the dependence of sagittal plane displacement and disc height on angle and the dependence of vertebral height, displacement and disc height on age are assumed to be identical for exposed and unexposed cohorts. This assumption is necessary, because the ranges of angle and age as well as the number of subjects in the exposed cohorts were generally too small to permit reliable determination of the regression coefficients from each exposed cohort separately. A potential violation of the assumption is expected to have little influence on the results since the regression coefficients only serve to correct the raw data; a small adjustment of these coefficients would result in a 'correction to a correction'.

Within Great Britain as well as in Germany, the radiographs of unexposed subjects had been deliberately collected from different regions and different archives in order to average potential regional differences in spinal morphology and to compensate for potentially confounding effects like selection of subjects or second-order influences of radiographic technique (first-order



influences being eliminated by the measurement protocol). To assess the success of this strategy, the homogeneity of the databases with respect to vertebral height, sagittal plane displacement and disc height was tested by means of one-factor analysis of variance in combination with a sensitivity study varying the regression coefficients for angle and age. Initially both databases exhibited a significant difference in the means of the cohorts drawn from the different archives. As outlined below, this inhomogeneity was probably due to inter-observer bias. The bias could not, however, be determined precisely enough to explain all discrepancies. If, on the other hand, contributions from one observer were omitted in the German as well as in the British database, the resulting, revised databases were separately homogeneous.

### **3.1.1 Database compiled from German subjects**

A set of 627 lateral lumbar radiographs was collected from 10 archives. When all data were pooled, ANOVA revealed significant ( $\alpha = 0.05$ ) differences in sample means with respect to vertebral height, sagittal plane displacement and disc height. Subsequent analysis showed that data from 2 out of the 10 archives were responsible for this divergence. These two cohorts had been mapped by observers B and C, whilst the other 8 had been mapped by observer A. The cohort mapped by observer C comprised 6 gymnasts radiographed in the course of a pre-training medical examination, and the cohort mapped by observer B comprised 121 predominantly young soldiers. The condition of homogeneity was met once these two 'unusual' cohorts were excluded.

The German database for vertebral height, sagittal plane displacement and disc height was compiled from 500 radiographs of unexposed subjects, collected from 8 different archives. Mean age amounted to 31.8 y (SD = 11.9 y, min = 17 y, max = 57 y).

A sensitivity study was performed, varying the regression coefficients a and b (describing the dependence of the parameters on angle and age) within a 95% confidence interval and testing homogeneity of the 8-cohort database by one-factor ANOVA. For vertebral height, displacement and disc height there were no significant differences in the centre of the confidence interval between the 8 cohort means for any anatomical level of the lumbar spine. Only for displacement, height of vertebra L2 and the two lower lumbar discs was a p-value of less than 0.05 found off-centre within the confidence interval.

### **3.1.2 Database compiled from British subjects**

A set of 249 lateral lumbar radiographs was collected from 5 archives and processed in part by observers D, E or F (resulting in 9 sub-cohorts as characterised by origin and investigator). ANOVA revealed significant differences in the means of these 9 sub-cohorts. If, however, the data processed by observer F, contained in 3 sub-cohorts and comprising 12 spines in total, were excluded, the condition of homogeneity was met.

In consequence, the British database for vertebral height, sagittal plane displacement and disc height was compiled from 237 radiographs of unexposed subjects, collected from 5 different archives. Mean age amounted to 32.9 y (SD = 9.8 y, min = 18 y, max = 55 y).

The sensitivity study, performed to test homogeneity while varying the regressions coefficients a and b, showed that at the centre of the confidence interval there were no significant differences between the 6 contributing sub-cohort means, save for height of T12 and displacement L4/L5 and L5/S1. At some levels, the sensitivity study revealed p-values of less than 0.05 off-centre within the confidence interval.

Comparison of the British and the German databases (see Brinckmann *et al*, 1998) showed a small but significant inter-country difference, specifically with respect to vertebral height. This justifies comparing British exposed subjects exclusively with the British database and German exposed subjects exclusively with the German database.

## 3.2 COHORTS EXPOSED TO LIFTING AND CARRYING

Lateral radiographic views of the lumbar spine of males with long-term exposure to lifting and carrying heavy objects were collected from archives of the occupational health departments of an open-cut brown-coal mine and briquette factory, an underground potassium salt mine, an underground coal mine, a steelworks and an offshore oil production company. Radiographs from subjects with Scheuermann's disease or lumbar scoliosis with a Cobb angle larger than approx. 5° were excluded.

For all subjects, age at the date of the radiograph and duration of exposure were documented. For most cohorts, only a qualitative, verbal description of typical exposures was available. Usually, workplace design changed over the years. The number of subjects in each cohort, however, was too small for subdivision into groups with strictly uniform exposure. Interpretation of the results is thus based on typical, average exposure. However, for the cohort of press operators from the steelworks Unterwellenborn, the dose of spinal loading (defined as load times duration of the load) was quantitatively known from a previous biomechanical analysis.

### **3.2.1 Labour force, open-cut brown-coal mine and briquette factory, Regis-Breitingen, Germany**

Radiographs were collected from the occupational health department of the open-cut brown-coal mine and briquette factory in Regis-Breitingen. All workplaces investigated had been characterised by 'exposure to heavy physical exertions' according to the guidelines of the Occupational Medicine Service of the (former) German Democratic Republic (physical load category B11, load intensity category K5, Ministerium für Gesundheitswesen der DDR, 1982). The intensity category 5 was assigned to workplaces where work-related health problems were expected to occur. For the labour force concerned, this classification involved medical control examinations with inclusion of a lateral radiographic view of the lumbar spine at approximately 5-year intervals.

Lateral radiographic views of the lumbar spine and work histories were collected from 66 subjects. The mean age at the date of the radiograph was 41.6 y (SD = 9.4 y, min = 23 y, max = 57 y). The duration of exposure was documented as < 5 years for 3 subjects, between 5 and 10 years for 14 subjects, between 10 and 20 years for 22 subjects and more than 20 years for 27 subjects. Exposure occurred in the years 1950 to 1988. The type of work performed fell mainly into the categories (i) operation of specialised machinery, (ii) manual labour in conjunction with the development of the open-cut mine, (iii) maintenance of machinery, (vi) construction and (v) transport of materials. In some cases, detailed descriptions of the work performed are available (Zarach 1997).

Briquetting moulds are subject to severe abrasion and have to be frequently exchanged. The moulds, weighing between 50 and 75 kg, were lifted by two persons, but additional, strong effort was often required because the moulds were jammed in the press. The moulds were transported to a grinding machine where manual handling was required again. Re-insertion of the overhauled press moulds was usually performed by one single employee. Typically, this occurred 5 to 8 times per shift.

Labour in the course of development of the mine comprised movement of earth, rocks and strip coal by means of pick axe and shovel. Small wagons were loaded and pushed manually over distances of 150 m to 300 m. Shovelling and loading occurred 2 hours to 4 hours per shift, 24 shifts per month. Draining channels had to be prepared. Tubes 5 m to 8 m long weighing up to 150 kg had to be carried over distances of 30 to 40 m over uneven ground by 2 to 3 workers. This work lasted 2 hours to 4 hours per shift. Cable coils, weighing between 10 kg and 40 kg, were each carried by one worker.

Rotary pumps weighing between 30 kg and 50 kg or more had to be installed, in many cases without the use of lifting aids. For maintenance, pumps were carried to the workshop. Dismantling was performed on the floor or on a workbench. Components (mass between 1 kg and 25 kg) were placed in a basin, cleaned manually in a forward bent posture and lifted out again for assembly. Typically, 2 to 3 pumps were processed per shift.

Maintenance of mining machinery and railway equipment comprised handling of heavy (25 kg to 50 kg) parts, in many cases in forward bent postures, kneeling, or in confined spaces. Defective parts and replacements weighing over 50 kg were usually carried by more than one person, but outdoor manual transport was stressful due to the uneven ground. Maintenance of mining equipment, for example of belt conveyors, was often preceded by manual removal of strip coal or spoil. Frequent shovelling of strip coal or spoil was also an integral part of the work of subjects nominally engaged in supervision of machinery like belt conveyors or coal mills. The time spent lifting and carrying heavy parts was estimated at 1 hour to 4 hours per shift.

Construction work required manual lifting and transporting of bricks (30 to 40 kg per lift) and cement or chamotte sacks (50 kg). Bricklaying in confined spaces was performed kneeling, bent forward, or overhead.

Repair, replacement, as well as movement of rails and points required frequent manual handling of objects weighing more than 25 kg. Loads were carried in front of the body, sideways or on the shoulders. Rails and sleepers (2 m to 5 m long) were carried by 4 to 6 workers; partial weight carried by each subject still exceeded 25 kg. Again, outdoor manual transport was stressful due to the uneven and wet ground. The time spent on lifting and carrying heavy objects was estimated at 1 hours to 3 hours per shift.

Firemen on steam engines shovelled coal in a forward bent posture five to six hours per shift. Engine drivers on electric engines as well as drivers of earthmoving machinery and dredgers were nominally exposed to whole-body vibration, but in addition heavy physical exertions were required for occasional loading and unloading of materials or in cases of operating trouble like derailling of engines or wagons.

To summarise, tasks of the cohort drawn from the coal mine and briquette factory were generally characterised by very heavy physical exertions and consequently by high spinal loading. Average intensity of spinal loading differed among workplaces, but one common feature of all workplaces was irregular episodes with peak values of spinal loading.

### ***3.2.2 Labour force, underground potassium salt mine, Merkers, Germany***

Radiographs were collected from the occupational health department of the underground potassium salt mine, Werra Kali AG, Merkers. The work investigated comprised drilling, transport, construction and maintenance. Workplaces in question had been classified by exposure to heavy physical exertions according to the guidelines of the Occupational Medicine Service of the (former) German Democratic Republic (physical load category B11, Ministerium für Gesundheitswesen der DDR, 1982). For the labour force concerned, this classification involved medical control examinations with inclusion of a lateral radiographic view of the lumbar spine at approximately 5-year intervals.

Work histories and lateral radiographic views of the lumbar spine were collected from 51 subjects. The mean age at the date of the radiograph was 43.1 y (SD = 8.7 y, min = 26 y, max = 56 y). The duration of exposure to heavy physical exertions amounted to 21.4 years on average (min 9 y, max 40 y). Exposure occurred in the years 1946 to 1986. In addition to exposure to heavy physical exertions, 2 subjects within this cohort had been exposed between 11 and 16 years to whole-body vibration (physical load category B19, Ministerium für Gesundheitswesen der DDR, 1982) when driving carriers.

The type of work performed fell mainly into the categories (i) drilling and filling of blastholes, (ii) underground materials transport and (iii) maintenance work. In some cases, detailed descriptions of the work performed are available (Weiß 1996):

Drilling comprised carrying or dragging drilling machines (60 to 85 kg) and accessories over distances of 20 to 30 m. Three holes had to be drilled at a specified location before the drill was moved. Movement of these machines was performed kneeling or in the forward bent posture. Typically, this was performed 10 times per shift.

Loose rock had to be removed from the roof of the galleries. This work entailed using a 4 m iron pole with the arms lifted above the level of the shoulders. Heavy physical exertions occurred when repairing broken cables and setting up derailed transport trolleys. When mounting rails, approximately 50% of the time was spent levelling the ground with a pick-axe and shovel in a forward bent posture. Rails with a length of 7 m were assembled in kneeling position, the assembly (400 kg) was carried by a group of 7 men to the desired location and joined to the existing tracks.

Maintenance comprised dismantling, in some cases manual transport, and assembly of mining equipment. Although components up to 300 kg were handled by groups of 4 workmen, work had often to be performed in stooped postures or in confined spaces.

Construction work comprised excavation as well as handling of conventional, heavy construction material, partially in forward bent postures. Maintenance of electrical installations comprised moving 1000 kg cable rolls, carrying and pulling heavy cables and mounting cables at a height of 1.5 to 2 m in the galleries.

Transportation tasks with peak values of physical exertion occurred for example when unloading potassium salt from mine cars or coal from railway wagons. For this purpose, heavy iron handles of the cars had to be moved, often in a jerky fashion, and unloading of the material had to be completed manually.

When shipping end products, fertiliser packed in sacks of 50 or 100 kg was handled by one or two workmen respectively. In a railway wagon, these sacks were laid down in three layers, *i.e.* the sacks for the second and third layer had to be lifted one or two layers upwards. A workman moved approximately 900 50 kg sacks (equivalent to a total of 45 t) per week. Over the year, this type of work amounted to approximately 1/3 of the total worktime.

To summarise, manual labour in the potassium mine required in every case very heavy physical exertions and thus led to peak values of spinal loading.

### **3.2.3 Press operators, steelworks, Unterwellenborn, Germany**

Radiographs of press-operators were collected from the occupational health department of the Maxhütte steelworks, Unterwellenborn. Lateral radiographic views of the lumbar spine were collected from 36 subjects. The mean age at the date of the radiograph was 37.6 years (SD = 10.7 y, min = 23 y, max = 58 y).

The task of a press operator was to grip red-hot iron blocks with iron tongs, to insert the blocks into a stamping press, to remove the pressed workpiece and insert it into the adjacent press and, finally, to remove the workpiece from the pressing line. The mean duration of exposure amounted to 13.4 years (min 1 y, max 37 y). Exposure occurred in the years 1951 to 1988.

For this cohort, the load on the lumbar spine was previously estimated by means of a biomechanical model calculation (Pangert and Hartmann, 1991 and 1994). Mass of the iron blocks varied between 4 kg and 60 kg; mass of the tongs amounted to 3 kg. Posture was usually upright or bent forward between 10° and 25°, in rare cases up to 45°. The contribution of the

length of the tongs to the moment arm of the external load with respect to the lumbar spine varied between 0.2 m and 1.0 m. Calculated maximum load at the level L4/L5 varied between approximately 3000 and 9000 N, depending on the design of the press.

The episodes of maximum loading lasted between 1 s and 4 s; the number of cycles per shift amounted to approximately 600 (Pangert and Hartmann 1994). The authors used this information together with the individual time spent at presses of different ergonomic designs to calculate a load dose. The dose is given by the product of load times duration (in units of Newtons x seconds). For the cohort in question, the average dose amounted to  $8.8 \cdot 10^{10}$  Ns (min  $0.6 \cdot 10^{10}$  Ns, max  $28.5 \cdot 10^{10}$  Ns).

### **3.2.4 Labour force, underground coal mine, Lancashire, England**

Thirty-two radiographs of underground miners were obtained from an archive held by The Arthritis and Rheumatism Council's Epidemiology Research Unit, Manchester. This cohort forms part of the series of population studies starting with the pioneering work of Kellgren and Lawrence (1952). The population from which this cohort was extracted was radiographed in 1956. There were originally 74 miners in the sample, of which the radiographs of 32 men had been preserved. The mean age at the time of the radiograph was 59 y (SD = 7.6 y, min = 43y, max = 69 y). The exposure occurred during the first half of the twentieth century. At that time in that area of England, miners tended to start and finish their working lives as miners, thus the average exposure can be estimated as being of the order of 40 y (with a range of 28 to 50 y).

Detailed work histories are naturally unavailable for this cohort, but there is no doubt that it was physically arduous work performed over long shifts. Mining in those days was largely a manual job, with little in the way of mechanical help (certainly in the early part of the exposure period). The coal would be dug with picks and shovels, often in seams with low headroom necessitating adoption of a stooped posture for long periods. The coal would be shovelled into carts that would be pushed manually along rails, often for distances of some kilometres. In addition to the actual digging of coal, miners were responsible for constructing the underground roadways and laying the rails. Even when some mechanisation of the digging was introduced, transport of heavy equipment to and from the coalface in confined spaces was largely a manual task. The fluid nature of the underground strata frequently would lead to damage to the roadways caused by shifting strata and transport of equipment was particularly arduous (Porter, 1987). Damaged roadways would have to be repaired manually by miners, necessitating carrying of pit props, tools and machinery.

The work performed by this cohort was, in general terms, similar to that of the Merkers cohort (Chapter 3.2.2), but also included similar forward bent postures to those adopted by the press operators at Unterwellenborn (Chapter 3.2.3) and involved manual work whilst kneeling.

### **3.2.5 Labour force, offshore oil rig, Dubai**

The Medical Department of Dubai Oil Company, United Arab Emirates offered radiographs from a mixed-race labour force on offshore oil production platforms. Nineteen radiographs were available, of which 6 were of men having Arab family names and one with an Asian family name, the remaining 12 being of European/Caucasian (mainly British) origin. The mean age for the whole cohort, at the time of the radiograph, was 45.7 y (SD = 7.5 y, min = 36 y, max = 61 y). The mean age of the Caucasian workers was 46.9 y (SD = 7.5 y, min = 36 y, max = 61 y).

The work required on offshore rigs is arduous but broken by the shift pattern. The men worked offshore for a minimum 12-hour day for 28 days at a time, followed by a 28-day period of rest. The work was split over various areas of the rig, including the drill floor, the pipe deck, the cargo deck and the floating storage units as well as numerous ancillary areas. The following are examples of the tasks, some of which are performed by teams of two to four men: cargo handling; repetitive handling of 20-litre drums downstairs and along restricted aisles; carrying pipes, pumps and valves around various obstacles; pushing suspended lengths of pipe (weight

~800kg) into racks on the derrick; lifting slips (metal wedges to centralise the drill strings) weighing over 100kg every 60-90 seconds for long periods; pushing and pulling to apply torque to tools when connecting drill strings (often in awkward postures); using crowbars to wedge pipes weighing 300-700kg from the deck floor. The common element was manual materials handling of particularly heavy weights under ergonomically unfavourable conditions of constrained space involving bending, twisting, pulling and pushing. Some tasks gradually have been mechanised, but the nature of the environment and physical constraints dictates a need for human applied force on a regular basis. The exposure time exceeded 5 years for all workers in this cohort.

It should be mentioned that only the Caucasian workers properly could be compared with the British database, because inter-racial differences in spinal morphology became apparent (see Chapter 4.1.5).

### **3.3 COHORTS EXPOSED TO WHOLE-BODY VIBRATION**

Lateral radiographic views of the lumbar spine of males with long-term exposure to whole-body vibration were collected from archives of occupational health departments of an open-cut brown-coal mine, an underground potassium salt mine and a unit of the police force. Radiographs from subjects with Scheuermann's disease or lumbar scoliosis with a Cobb angle larger than approximately 5° were excluded.

For all subjects, age at the date of the radiograph and duration of exposure were documented. For the labour force of the potassium salt mine and the police officers, a qualitative verbal description of typical workloads is presented. For the labour force selected from the brown-coal mine, quantitative data describing the vibration exposure are available.

#### ***3.3.1 Machine operators, underground potassium salt mine, Merkers, Germany***

Radiographs of transport and drilling machine operators were collected from the occupational health department of the underground potassium salt mine, Merkers. Workplaces had been classified by exposure to whole-body vibration according to the guidelines of the Occupational Medicine Service of the (former) German Democratic Republic (category B19, Ministerium für Gesundheitswesen der DDR, 1982). For the labour force concerned, this classification involved regular medical control examinations including a lateral radiograph of the lumbar spine at 5-year intervals.

Work histories and lateral radiographic views of the lumbar spine were collected from 55 subjects. The mean age at the date of the radiograph was 37.9 y (SD = 7.6 y, min = 25 y, max = 57 y). Mean duration of exposure to whole-body vibration amounted to 11.5 years (min 5 y, max 26 y). Exposure occurred essentially in the years 1961 to 1988, when driving transport or earthmoving machinery or operating rock drills. For a number of workplaces, detailed descriptions are available (Krause 1994, Weiß 1996).

Operators of underground transport machinery were exposed to whole-body vibration and shock loading transmitted via seat and feet. Prior to 1972/75 rigid wooden seats were standard. Frequency of shock loading due to bumps in the roads was estimated to 50 events per shift. With elastic seats employed up to 1986/89, vertical acceleration was measured at 1.4 m/s<sup>2</sup>. With air-damped seats, used after 1986/89, acceleration amounted to 0.8 m/s<sup>2</sup>. The net mean time spent driving was 4 to 5 hours per shift.

On some carriers, operator seats were mounted at 90 degrees to the direction of motion. This required prolonged axial rotation of the trunk by up to 80 degrees. The same holds for driving machinery employed to remove loose rocks from the roof of galleries. In addition, when

inspecting the gallery roof and observing the machine action, the cervical spine had to be kept in an extended posture. Net mean driving time on such machines amounted to 3 hours per shift.

Truck drivers were exposed to whole-body vibration. In some cases, custom made, unsprung road construction machinery equipped with rigid seats had to be operated. In addition to vibration loading, high spinal loading occurred when manually loading and unloading trucks; loads of up to 50 kg had to be handled.

Drivers of rock drills were predominantly exposed to whole-body vibration. Additional heavy spinal loading occurred when rocks had to be shovelled from blocked drill holes or when loading and unloading 30 kg packages of explosives.

Prior to exposure to vibration, 14 of the 55 subjects performed work characterised by heavy physical exertions and/or work in confined spaces (category B11, Ministerium für Gesundheitswesen der DDR, 1982). This type of work was performed for 8 years on average (min 2 y, max 19 y).

To summarise, exposure within the cohort of transport and drilling machine operators drawn from the potassium salt mine is characterised by exposure to whole-body vibration and shock loading. During the first half of the observation period, seats on earthmoving machinery were usually rigid and unsprung. Only after 1972/75 were elastic seats introduced. In a fraction of cases, exposure to vibration and shock loading was supplemented by exposure to heavy spinal loading due to lifting and carrying.

### **3.3.2 Earthmoving machine operators, open-cut brown-coal mine, Köln, Germany**

Radiographs of operators of earthmoving machinery were collected from the archive of the occupational health department of the Rheinbraun Company, Köln. Lateral radiographic views of the lumbar spine and work histories were collected from 84 subjects. The mean age at the date of the radiograph was 45.8 y (SD = 5.7 y, min 34 y, max 57 y). On average, the exposure lasted 20.5 y (min 6 y, max 34 y). Exposure to whole-body vibration occurred on heavy machinery equipped with low pressure tyres or caterpillar chains. Such machinery was employed to load and transport spoil, coal or rocks, to grade terrain and to excavate or fill pits.

For a sub-cohort of 42 employees, lateral views of the lumbar spine, taken on the occasion of a pre-employment examination at the Rheinbraun Company were available as well. Thus, the data collected from this sub-cohort permit a longitudinal study to be performed, since initial as well as end status are documented. In this sub-cohort, the mean age at the date of the radiograph was 46.5 y (SD = 6.0 y, min 34 y, max 57 y). On average, the exposure lasted 20.4 y (min 6 y, max 33 y).

Operators of earthmoving machinery worked sitting. Deviation from an erect posture occurred when manoeuvring or when driving in reverse. Vibration originating from the engine, the machine frame and specific equipment, for example from the earth grab, was transmitted in vertical direction via the seat pan to the lumbar spine. The frequencies ranged from 1 Hz to 15 Hz. Vibration was overlaid by shock loading at irregular intervals. Shock loading occurred, for example, when dredging or when driving on uneven ground. Shock loading while driving was generally less on machines on caterpillar chains compared with machines on low pressure tyres.

A machine operator usually spent more than 7 hours per shift on some type of earthmoving machine. Each employee was assigned to two or three machine types so that no distinction can be made retrospectively with respect to preference of specific machines. Typically, earthmoving and loading machines were employed 44% of the period of service for loading, 30% for transporting, 14% for empty driving and 12% for maintenance.

All machine seats were adjustable in height, seat pan inclination and backrest inclination. Damping of vibration and shock was achieved by a 70 mm foam cushion mounted on the seat pan. In some machines, seats were mounted on a swing frame equipped with springs and dampers allowing for a swing amplitude of 40 mm.

Vertical acceleration was measured at the seat pan; the k-value (VDI 2057) was determined in third-octave bands, averaged and finally quadratically averaged over time (Köhne *et al* 1981). Representative k-values for earthmoving or excavating machines ranged between 8 and 30. The k-values were found to depend strongly on the type of work performed. Driving a chain-dredger on a natural sandy surface resulted in a k-value of 8.5 while dredging of natural brown coal with this machine resulted in a k-value of 29.8. Drivers' experience and personal driving style also influenced the resulting k-value.

All radiographs of this cohort had been mapped and digitised by observer G. The bias between observer G and observer A, who processed the radiographs for the German database, turned out to be small. Consequently, in cross sectional studies all data measured by observer G were shifted by subtracting this empirical bias.

### **3.3.3 Police force, Northern Ireland**

Radiographs of 19 police officers in the Royal Ulster Constabulary were extracted from archives. These radiographs were clinically requested (for complaints of back pain), but excluded any with serious spinal pathology. The mean age at the time of radiograph was 36.5 y (SD = 7.0 y, min = 26 y, max = 47 y); the period of exposure averaged 12 years.

This cohort represents concomitant exposure to two types of spinal stress: whole-body vibration and shoulder loading. A previous report has shown that both types of stress are separate, but not additive hazards for the development of back pain in these officers (Burton *et al*, 1996).

The main characteristic of this cohort is that they worked in an urban environment under constant threat of terrorist activity. They were compelled to wear body armour (weighing ~8kg) for the duration of their shift, which lasted up to 12 hours. The armour comprised a 'jacket' containing ceramic panels front and back to afford protection from rifle bullets; this garment was suspended on straps over the shoulders. The body armour, as well as representing a heavy shoulder load, made movement awkward (such as when getting in and out of vehicles or apprehending suspects). The officers were also required to wear waist belts on which were hung handguns, ammunition, radio, handcuffs and baton. In addition, they frequently carried rifles. The work involved walking the streets and travelling in armoured vehicles, in addition to chasing and physically apprehending suspected criminals and terrorists. Their routine work also involved regular, strenuous fitness training sessions.

In addition to the exposure to loading *via* the shoulders from wearing body armour, they spent considerable periods of each shift riding in (or driving) vehicles. When in vehicles, they would need to wear their body armour. There are two main types of ground vehicle used daily, whilst helicopters were an occasional alternative. When patrolling in 4-wheel drive vehicles, a number of officers would sit in the back on padded bench-type seats with minimal back support. Otherwise, they would travel in conventional cars with armour plating, which adds to the weight of the car and impedes easy access and egress; the suspension was modified and particularly firm. They could spend up to 10 hours per shift working in such vehicles, with only relatively short breaks.

This cohort, therefore, was exposed to a combination of patrolling on foot with shoulder loading (from the body armour), intermittent physical exertions (fitness training and apprehending suspects) and whole body vibration (from prolonged periods in vehicles with relatively stiff suspension). The officers generally tend to join the force at an early age, and remain in service until retirement; increasing rank did not negate the requirement to wear body armour. If they are



off work, due to back trouble for instance, they almost invariably return to normal work (including the wearing of body armour) rather than being detailed to restricted duties. These police officers, therefore, regularly were exposed to greater physical stresses than would be experienced by officers in a typical British police force.

## 4 RESULTS

Mechanical overload injury to lumbar vertebrae or discs can be caused by single episodes, when the load exceeds the compressive strength of the structures, or by fatigue failure resulting from repeated loading. Overload damage to the lumbar spine is expected to result potentially in (i) fractures, effecting a decrease of vertebral height or a wedge shape of vertebral bodies, (ii) derangement of the sagittal plane (dorso-ventral) alignment of lumbar vertebrae due to 'wear and tear' of ligaments, or (iii) primary injury to intervertebral discs or fracture of vertebral endplates, both resulting in a loss of disc tissue and thus in a decrease in disc height.

To investigate the occurrence and magnitude of such morphological alterations, the data measured from the radiographs of the German and British exposed cohorts were compared with the normative databases of the respective countries. For all cohorts, the effect of exposure on the parameters 'vertebral height', 'sagittal plane displacement' and 'disc height' was assessed for vertebrae T12 to L5, or motion segments and discs T12/L1 to L5/S1. Not all radiographs imaged complete spines from T12 to S1, and some vertebrae or discs could not be measured due to inferior image quality.

The comparison between exposed subjects and the normative database is presented in graphical format (Figures 4.1 to 4.27). In these figures, the difference 'cohort mean minus normative database' is displayed not in absolute numbers but divided by the SD of the respective parameter in the unexposed cohorts. (Numerical presentation of these data can be found in Brinckmann *et al*, 1998).

In the figures, the deviation from normal is indicated for four significance classes. (1) Open columns = 'not significant', assigned in cases where  $p$  as well as  $p_{\min}$  and  $p_{\max}$  were all larger than 0.05. (2) Dotted columns = 'borderline case', where both  $p$  and  $p_{\max}$  were larger than 0.05 while  $p_{\min}$  was equal to or smaller than 0.05. (3) Hatched columns = 'significant', where both  $p$  and  $p_{\min}$  were equal to or smaller than 0.05. (4) Black columns = 'highly significant' where  $p$ ,  $p_{\min}$  and  $p_{\max}$  were equal to or lower than 0.05. [The term 'borderline' was chosen because a significant difference between exposed subjects and the normative database could not be excluded but was regarded as unlikely].

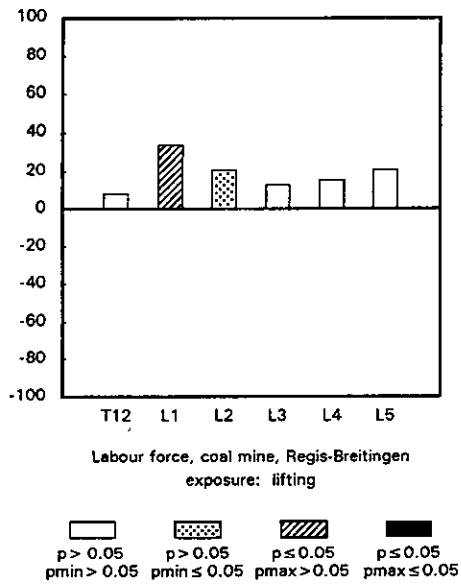
## **4.1 EFFECT OF EXPOSURE TO LIFTING AND CARRYING**

### ***4.1.1 Labour force, open-cut brown-coal mine and briquette factory, Regis-Breitingen, Germany***

Vertebral height and sagittal plane displacement (save T12/L1) exhibit no systematic deviation from normal (Figures 4.1 and 4.2).

Discs L1/L2, L2/L3 and L5/S1 show a significant height decrease with respect to normal (Figure 4.3). Discs L3/L4 and L4/L5 show a borderline decrease of height, while height of T12/L1 does not deviate significantly from normal. The uniform pattern of height decrease, noted at all lumbar levels (though characterised by different classes of significance), supports the inference that this cohort exhibits a work-related loss of lumbar disc height.

Vertebral height: exposed vs. normal subjects  
(in % of the SD of vertebral height of normals)



Sagittal plane displacement: exposed vs. normal subjects  
(in % of the SD of displacement of normals)

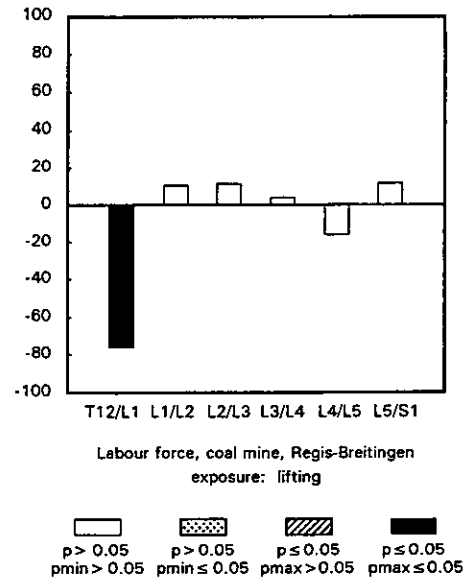


Figure 4.1 Vertebral height of the labour force exposed to lifting and carrying, drawn from the open-cut brown-coal mine and briquette factory, Regis-Breitingen, in relation to the German database

Figure 4.2 Sagittal plane displacement of the labour force exposed to lifting and carrying, drawn from the open-cut brown-coal mine and briquette factory, Regis-Breitingen, in relation to the German database

Disc height: exposed vs. normal subjects  
(in % of the SD of disc height of normals)

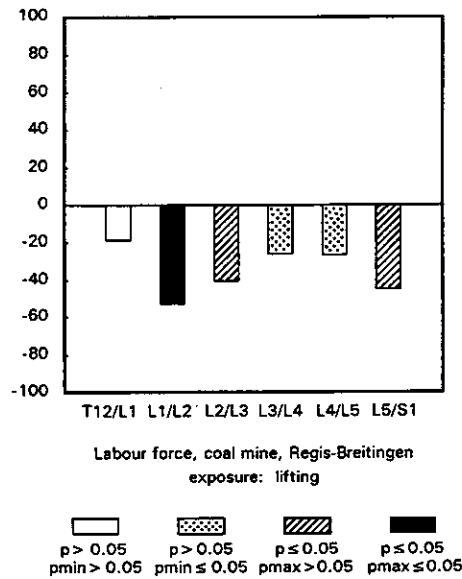


Figure 4.3 Disc height of the labour force exposed to lifting and carrying, drawn from the open-cut brown-coal mine and briquette factory, Regis-Breitingen, in relation to the German database

#### **4.1.2 Labour force, underground potassium salt mine, Merkers, Germany**

Vertebral height and sagittal plane displacement exhibit no systematic deviation from normal (Figures 4.4 and 4.5).

At all lumbar levels, disc height shows a considerable, significant decrease in relation to normal (Figure 4.6). As in the case of the cohort drawn from the brown-coal mine in Regis-Breitingen, the uniformity of the pattern supports the inference that the documented disc height decrease was due to the specific, extreme workload of this cohort.

From the identical archive, radiographs of 63 males between 17 and 27 years of age, taken on the occasion of a pre-employment examination, had been collected (this set forming part of the German database). It can be shown (Appendix 8.2) that comparison of the exposed cohort with this young, not exposed cohort reveals no difference in vertebral height or displacement but a significant reduction in disc height. This shows that the decrease in disc height observed in the exposed subjects cannot be explained by geographical variation in spine morphology; thus, the inference of workload as a causative factor is further supported.

Vertebral height exposed vs normal subjects  
(in % of the SD of vertebral height of normals)

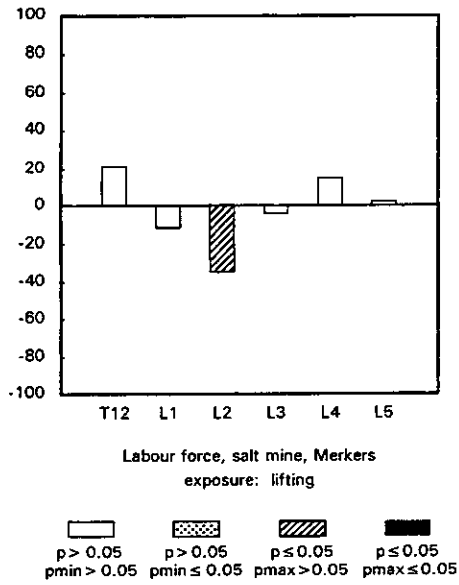


Figure 4.4 Vertebral height of the labour force exposed to lifting and carrying, drawn from the underground potassium salt mine, Merkers, in relation to the German database

Sagittal plane displacement exposed vs normal subjects  
(in % of the SD of displacement of normals)

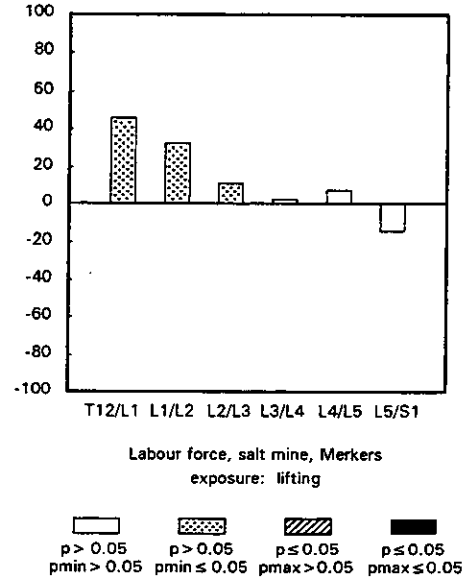


Figure 4.5 Sagittal plane displacement of the labour force exposed to lifting and carrying, drawn from the underground potassium salt mine, Merkers, in relation to the German database

Disc height: exposed vs. normal subjects  
(in % of the SD of disc height of normals)

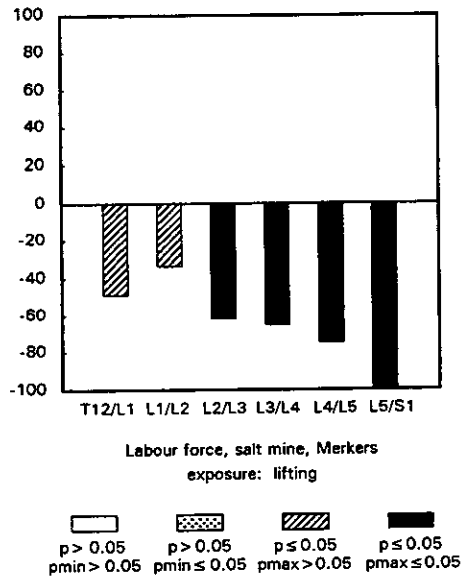


Figure 4.6 Disc height of the labour force exposed to lifting and carrying, drawn from the underground potassium salt mine, Merkers, in relation to the German database

#### **4.1.3 Press operators, steelworks, Unterwellenborn, Germany**

In the cohort of press operators, the height of vertebrae T12 and L1 is significantly reduced while the height of the lower lumbar vertebrae does not deviate from normal (Figure 4.7). The height reduction of T12 and L1, indicating a crush or wedge-shape deformation, can be explained as being due to high spinal loading experienced in the forward bent posture, the typical workload of this labour force.

Sagittal plane displacement exhibits a modest increase (Figure 4.8) while disc height does not deviate from normal (Figure 4.9).

From the identical archive, radiographs of 43 males between 17 and 29 years of age, taken on the occasion of a pre-employment examination, had been collected (this set forming part of the German database). When comparing exposed subjects with this young, unexposed cohort, the height decrease of vertebrae T12 and L1 was evident as well (Appendix 8.2). This shows that the decrease in vertebral height cannot be explained by geographical variation in spine morphology. The inference of workload as a causative factor is further supported.

Vertebral height exposed vs normal subjects  
(in % of the SD of vertebral height of normals)

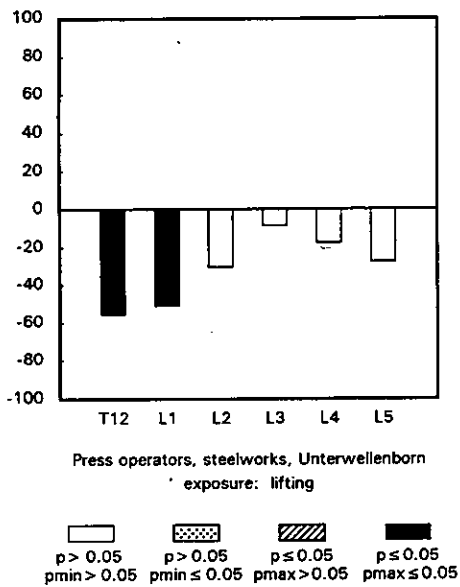


Figure 4.7 Vertebral height of press operators exposed to lifting and carrying, drawn from the steelworks, Unterwellenborn, in relation to the German database

Sagittal plane displacement exposed vs normal subjects  
(in % of the SD of displacement of normals)

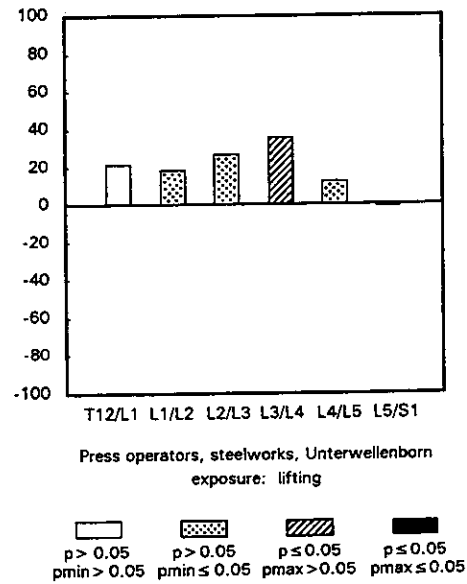


Figure 4.8 Sagittal plane displacement of press operators exposed to lifting and carrying, drawn from the steelworks, Unterwellenborn, in relation to the German database

Disc height: exposed vs. normal subjects  
(in % of the SD of disc height of normals)

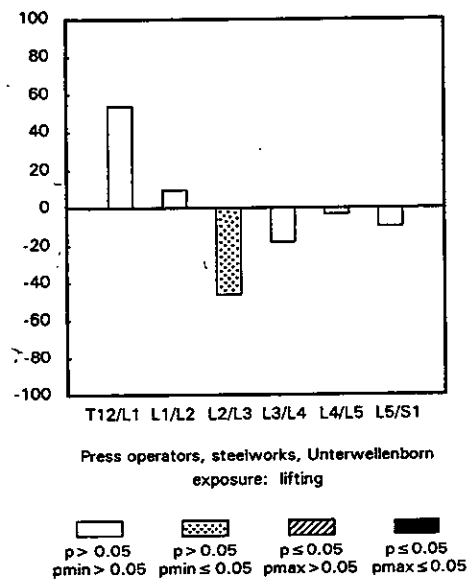


Figure 4.9 Disc height of press operators exposed to lifting and carrying, drawn from the steelworks, Unterwellenborn, in relation to the German database



#### **4.1.4 Labour force, underground coal mine, Lancashire, England**

The cohort exhibits a uniform pattern of decrease of vertebral height (Figure 4.10), but sagittal plane displacement showed some irregularities (Figure 4.11). There was a generalised decrease of disc height (Figure 4.12).

This cohort had a mean age considerably older than the others, and the men were working mainly during the first few decades of the twentieth century. Because the subjects making up the normative database were on average somewhat younger, it is reasonable to presume that these results are confounded with age, but some attempt has been made to correct for this.

There is an overall similarity in the pattern of results to those seen in the Merkers and the Unterwellenborn cohorts (Chapter 3.3.1), which were made up of younger men doing the same sort of work. There was a greater loss of vertebral height in the British miners, which may reflect an influence from age, or possibly from (unconfirmed) nutritional deficiencies.

Kellgren and Lawrence have already noted the decrease of disc height (referred to as disc degeneration) in their study on rheumatism in miners (Kellgren & Lawrence, 1958). They found the changes to be more prevalent among the miners than among age-matched males doing less strenuous jobs. In this respect, the results of the present study support the conclusions of the pioneering work of the earlier investigators of this cohort.

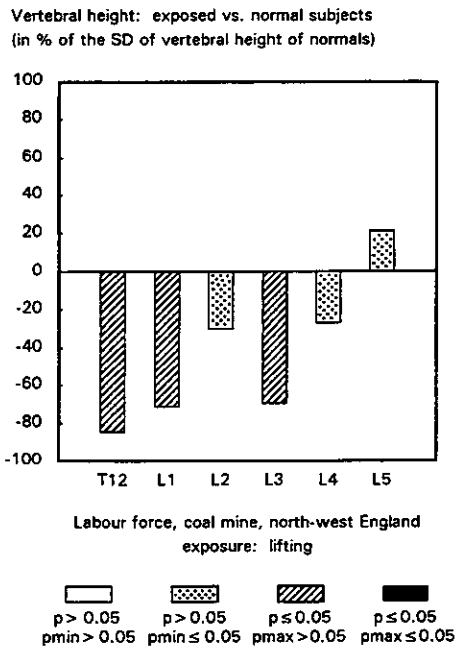


Figure 4.10 Vertebral height of the labour force exposed to lifting and carrying, drawn from the underground coal mine, Lancashire, England, in relation to the British database

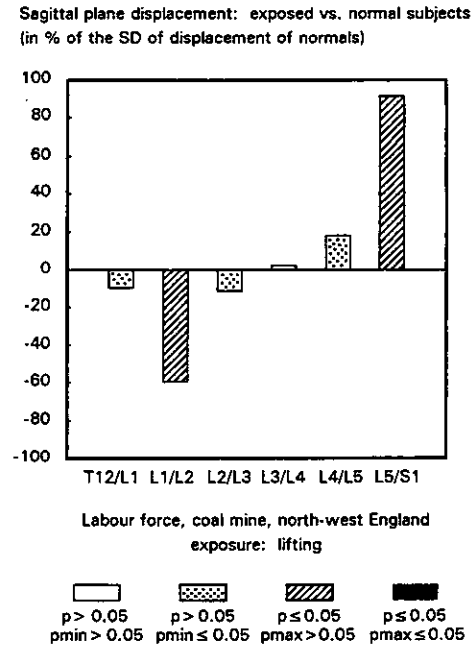


Figure 4.11 Sagittal plane displacement of the labour force exposed to lifting and carrying, drawn from the underground coal mine, Lancashire, England, in relation to the British database

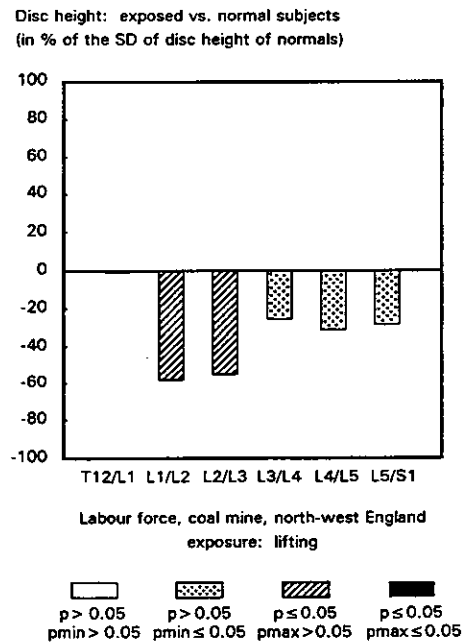


Figure 4.12 Disc height of the labour force exposed to lifting and carrying, drawn from the underground coal mine, Lancashire, England, in relation to the British database

#### **4.1.5 Labour force, offshore oil rig, Dubai**

As described in Chapter 3.3.5, the cohort consisted of 12 subjects of Caucasian (mainly British) origin and 7 subjects of Arab or Asian origin. Upon comparison of the cohort with the British database it was noted that the height of lumbar discs was substantially ( $> 2SD$ ) larger than normal. This discrepancy increased when only the data from the 7 labourers of Arab/Asian origin were analysed. This led to the conclusion that a normative database, compiled from Caucasians, may not be applicable to subjects of differing ethnic origin.

The subjects with Arab or Asian names were therefore excluded to allow presentation of the results for the Caucasian sub-group of this cohort.

Vertebral height for the Caucasians turned out to be generally larger than for the normative database (Figure 4.13), while displacement tended to be reduced (Figure 4.14). Disc height showed no systematic deviation from normal, but was higher at L5/S1 in particular (Figure 4.15).

A general discussion raised the possibility that this cohort may display a 'healthy worker' effect. That is to say, the nature of the job is itself selective; it attracts strong, fit men. In addition, those who find it too arduous tend to leave the work after a short period (though not necessarily because of back injury).

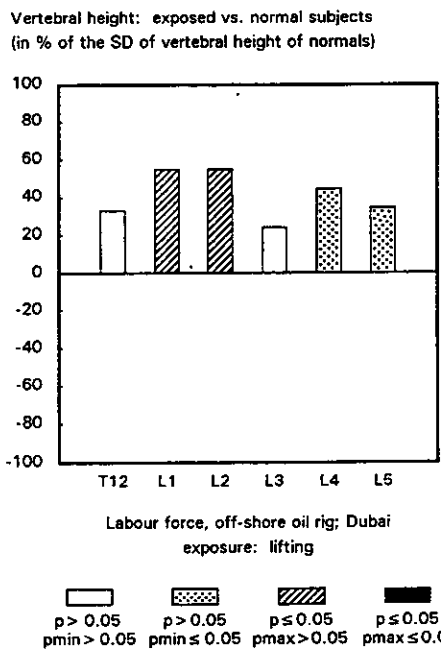


Figure 4.13 Vertebral height of the labour force exposed to lifting and carrying, drawn from the off-shore oil rig, Dubai, in relation to the British database

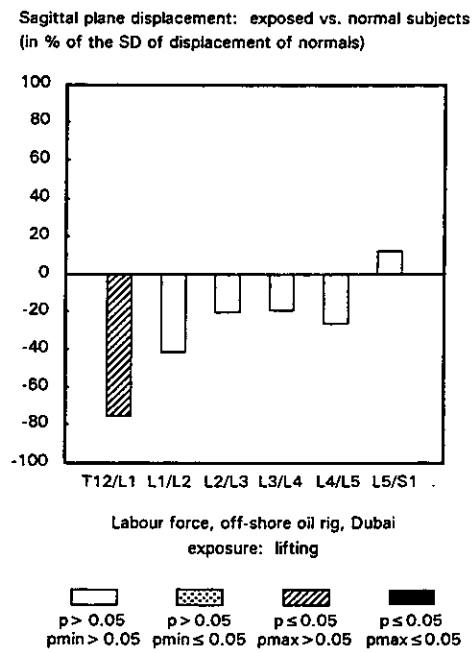


Figure 4.14 Sagittal plane displacement of the labour force exposed to lifting and carrying, drawn from the off-shore oil rig, Dubai, in relation to the British database

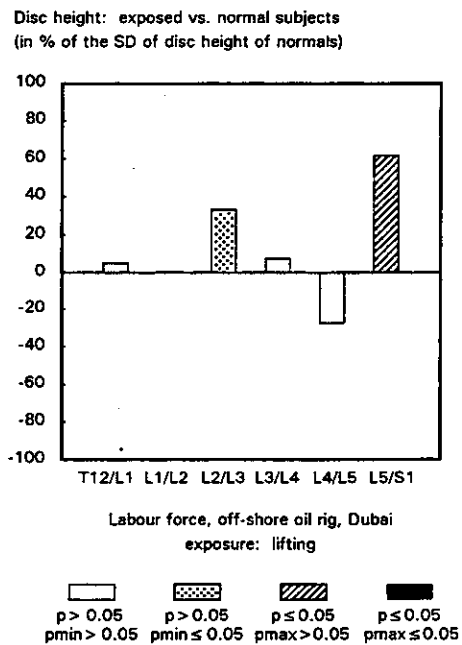


Figure 4.15 Disc height of the labour force exposed to lifting and carrying, drawn from the off-shore oil rig, Dubai, in relation to the British database

## **4.2 EFFECT OF EXPOSURE TO WHOLE-BODY VIBRATION**

### ***4.2.1 Machine operators, underground potassium salt mine, Merkers, Germany***

Vertebral height (save for T12) did not deviate from normal (Figure 4.16). At three levels, sagittal plane displacement deviated from normal, though with a different sign (Figure 4.17). This indicates that the work performed was associated with an irregular disturbance of the sagittal plane alignment of the lumbar vertebrae.

Lumbar discs L1/L2 to L5/S1 show a significant height decrease in relation to normal (Figure 4.18). The uniform pattern of height decrease further supports the inference that the type of work performed by this cohort resulted in a decrease in disc height.

Vertebral height: exposed vs. normal subjects  
(in % of the SD of vertebral height of normals)

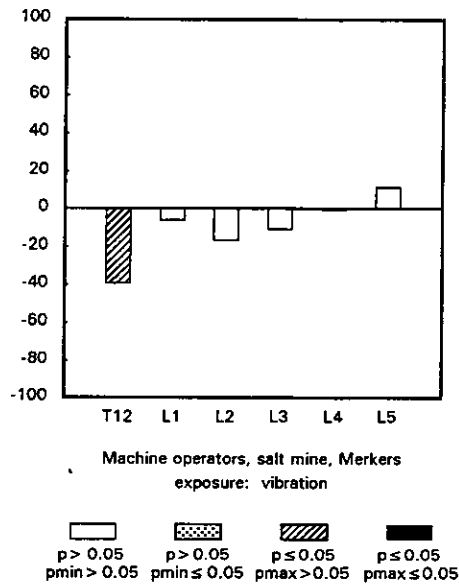


Figure 4.16 Vertebral height of machine operators exposed to whole-body vibration, drawn from the underground potassium salt mine, Merkers, in relation to the German database

Sagittal plane displacement: exposed vs. normal subjects  
(in % of the SD of displacement of normals)

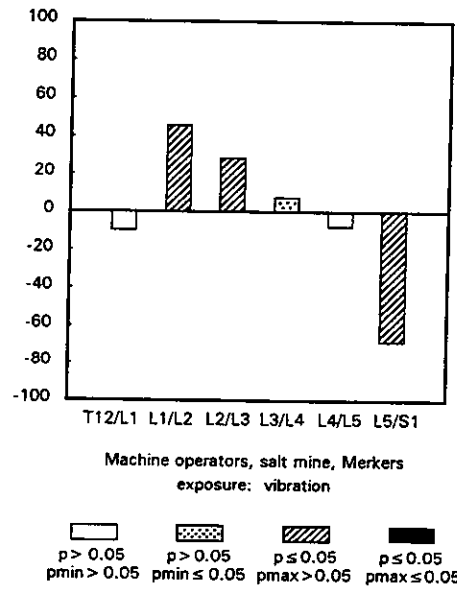


Figure 4.17 Sagittal plane displacement of machine operators exposed to whole-body vibration, drawn from the underground potassium salt mine, Merkers, in relation to the German database

Disc height: exposed vs. normal subjects  
(in % of the SD of disc height of normals)

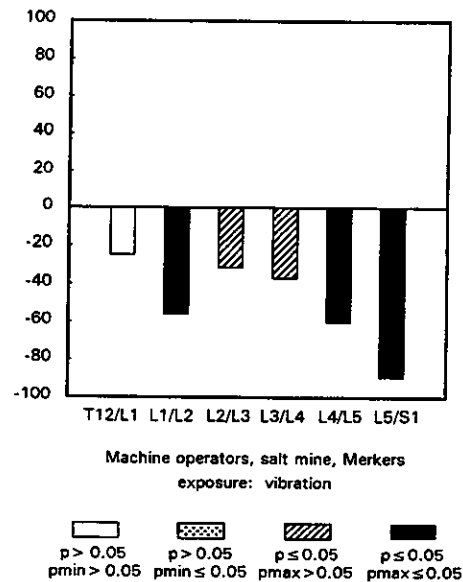


Figure 4.18 Disc height of machine operators exposed to whole-body vibration, drawn from the underground potassium salt mine, Merkers, in relation to the German database

#### **4.2.2 Earthmoving machine operators, open-cut brown-coal mine, Köln, Germany**

The lumbar vertebrae show a systematic though not significant (save L4) trend towards increased vertebral height (Figure 4.19). Sagittal plane displacement (Figure 4.20) and disc height (Figure 4.21) exhibit no significant and only small deviations from normal.

As mentioned in Chapter 3.3.2, in addition to those radiographs taken at the end of the exposure, radiographs taken at the pre-employment examination were available for a sub-cohort of 42 subjects. This allowed a longitudinal study comparing the morphology of those vertebrae, motion segments or discs which were imaged in the post-exposure (final) as well as in the pre-employment (initial) radiographs. The longitudinal study covered an average of 20.4 years.

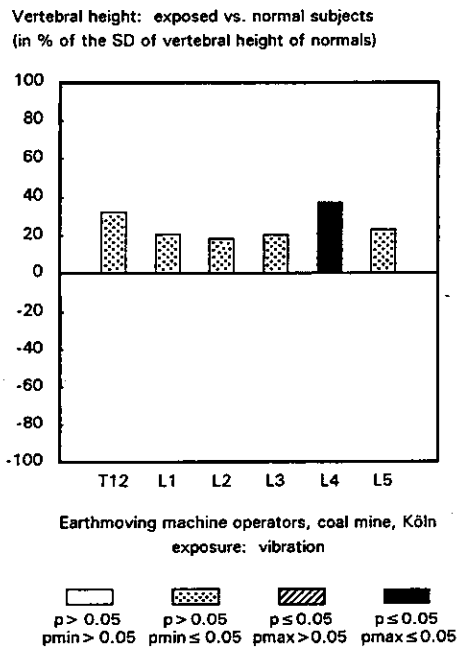


Figure 4.19 Vertebral height of earthmoving machine operators exposed to whole-body vibration, drawn from the open-cut brown-coal mine, Köln, in relation to the German database

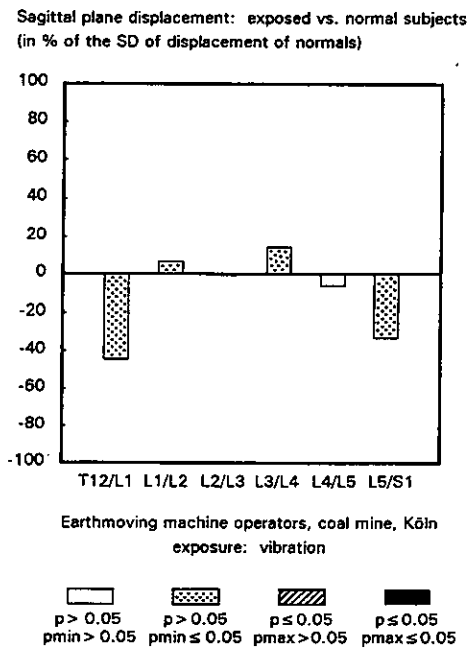


Figure 4.20 Sagittal plane displacement of earthmoving machine operators exposed to whole-body vibration, drawn from the open-cut brown-coal mine, Köln, in relation to the German database

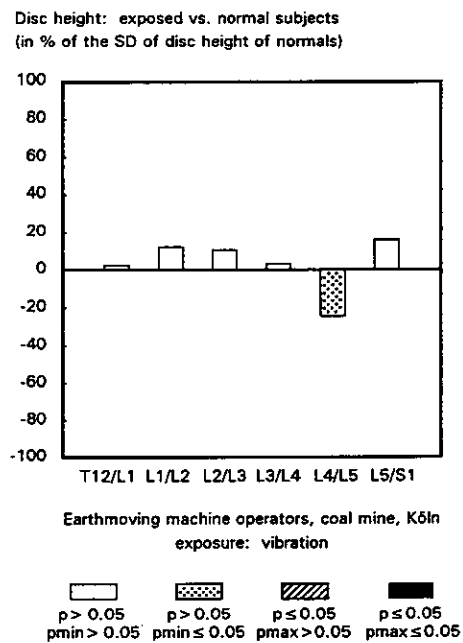


Figure 4.21 Disc height of earthmoving machine operators exposed to whole-body vibration, drawn from the open-cut brown-coal mine, Köln, in relation to the German database



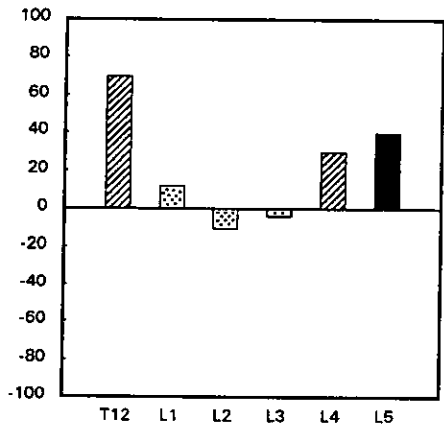
***Longitudinal study - earthmoving machine operators, open-cut brown-coal mine, Köln, Germany***

The longitudinal study (Figures 4.22 to 4.24) showed a significant increase in the height of vertebrae T12, L4, and L5 as well as of discs L1/2 and L2/L3 in the observation period; displacement (save for T12/L1) showed no change.

At first sight these results seem to be in conflict with the results of the cross sectional study showing the whole cohort in the final state not deviating from the German database. If, however, the data from the 42 pre-employment radiographs were compared with the German database, it could be demonstrated that the initial height of vertebrae T12, L4 and L5 and of discs L1/L2 and L2/L3 was lower than normal in these cohorts. Thus, the height increase of vertebrae and discs observed in the longitudinal study was responsible for data from these subjects showing only small deviations from normal in the final state.

It follows that morphological signs of overload injuries, *i.e.* decreased height of vertebrae or discs or increased displacement, are quantified neither in the cross sectional nor in the longitudinal study. Instead, there is evidence of a height increase of lumbar vertebrae and a height increase of discs in the exposure period.

Vertebral height: final minus initial state  
(in % of the SD of vertebral height of normals)



Earthmoving machine operators, coal mine, Köln  
exposure: vibration

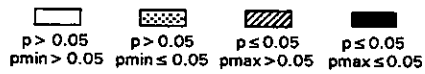
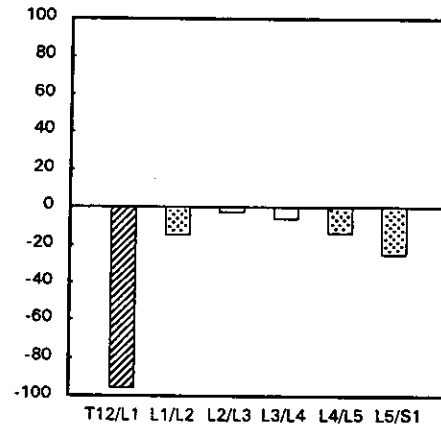


Figure 4.22 Change of vertebral height of earthmoving machine operators exposed to whole-body vibration, drawn from the open-cut brown-coal mine, Köln, assessed in a longitudinal study

Sagittal plane displacement: final minus initial state  
(in % of the SD of displacement of normals)



Earthmoving machine operators, coal mine, Köln  
exposure: vibration

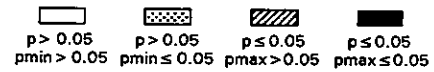
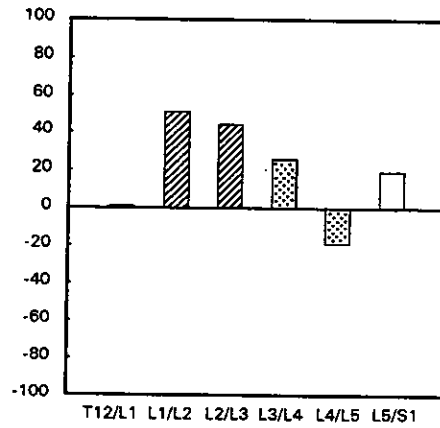


Figure 4.23 Change of sagittal plane displacement of earthmoving machine operators exposed to whole-body vibration, drawn from the open-cut brown-coal mine, Köln, assessed in a longitudinal study

Disc height: final minus initial state  
(in % of the SD of disc height of normals)



Earthmoving machine operators, coal mine, Köln  
exposure: vibration

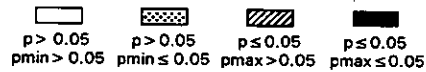


Figure 4.24 Change of disc height of earthmoving machine operators exposed to whole-body vibration, drawn from the open-cut brown-coal mine, Köln, assessed in a longitudinal study

#### **4.2.3 Police force, Northern Ireland**

As pointed out earlier, this cohort was unique in having a dual exposure: loading from heavy body armour and from whole body vibration. The results show a trend towards decreased height of lumbar vertebrae, though this was statistically significant only for vertebra L2 (Figure 4.25). Sagittal plane displacement also displays a tendency to deviate from normal, deviation being significant at the level L2/L3 (Figure 4.26). The height of lumbar discs did not display any substantial deviation from normal (Figure 4.27).

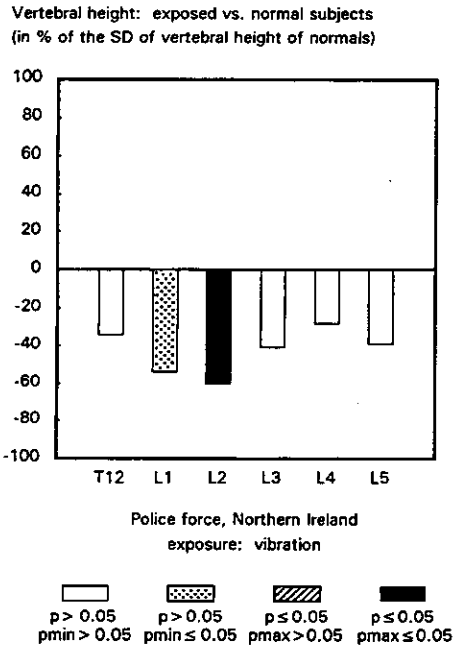


Figure 4.25 Vertebral height of police force, Northern Ireland, exposed to whole-body vibration in relation to the British database

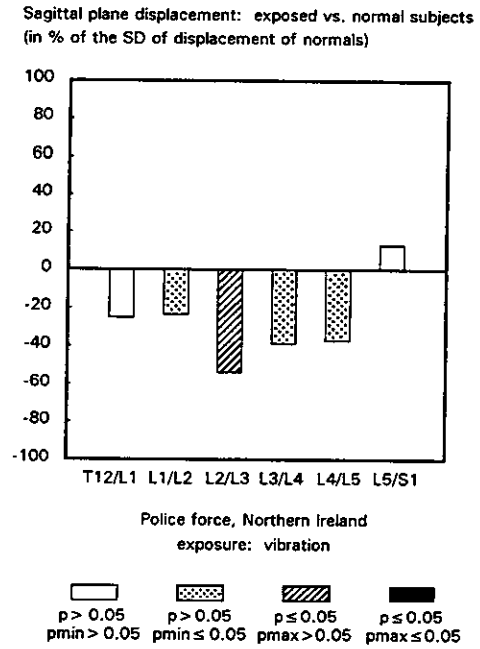


Figure 4.26 Sagittal plane displacement of police force, Northern Ireland, exposed to whole-body vibration, in relation to the British database

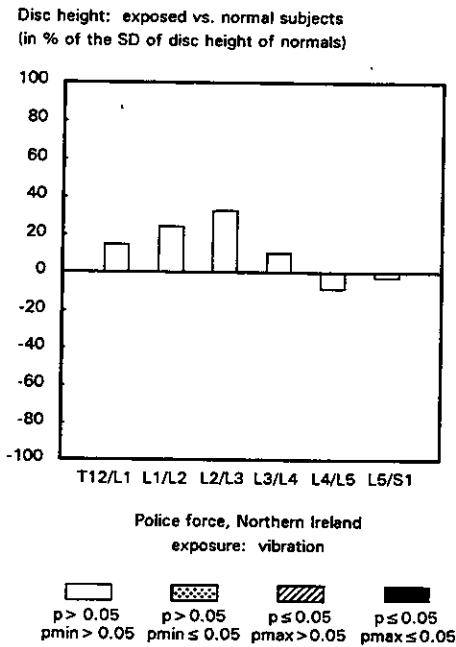


Figure 4.27 Disc height of police force, Northern Ireland, exposed to whole-body vibration in relation to the British database

## 5 SHAPE ANALYSIS OF DISCS AND VERTEBRAE

An alternative treatment of the data was developed in parallel with the methods described in Chapter 4, partly to explore the data from a different perspective, and partly to act as a confirmatory study. This new approach utilises a method of statistical shape analysis by which deviations in the vertebral and discal shape of spines in exposed cohorts could be compared with those in unexposed databases. The method establishes two overall shape 'values' for a given lumbar spine (L1 - S1), one based on the vertebrae and one on the discs.

On the basis of a cohort of spines not exposed to heavy physical exertions or whole-body vibration, this approach seeks initially to identify the typical shape of lumbar spine elements. Once the four corners of each vertebra are located in 2-dimensional space in the position they would occupy if all vertebral lengths and disc angles were suitably standardised, it is possible to choose one spine from the unexposed cohort which is median in some sense. Having identified the typical (median) spine, it is then possible to tabulate the extent to which other standardised spines differ naturally from this typical 'normative' spine.

Having established the shape of the typical spine and the extent to which spines in the unexposed cohort naturally differ from the typical spine, a series of exposed spines can then be compared with it, and the divergence from the typical spine considered in the context of the naturally occurring variability. Here it must be stressed that the analysis is based on four points per vertebra whose registered position is subject to many sources of variability including filming, mapping and digitising. In the more sophisticated approach described in Chapter 4, measures have been specially designed which minimise the effect of filming errors and the smallness of other errors established. Here these sources of error, principally radiographic technique, are not tackled and it is necessary for a radiologist to screen out films showing abnormalities due to deficient radiographic technique.

The following analysis has as its basis a large set of British lateral lumbar radiographs from 237 males drawn from the unexposed cohorts used as the British normative database described in Chapter 3.1.2, the selection criterion being that the spines were satisfactorily imaged for the entire L1 - S1 region.

### 5.1 METHOD

A dedicated computer program was written in Fortran to perform the following series of steps to establish a basis against which to make comparisons.

1 Read in 4-point co-ordinate data for a set of complete normal males: these constitute the original 'likeness'. It is necessary to scale these pictures to compensate for differences in relative focal distance. It is not possible to derive an absolute estimate of vertebral size from these likenesses, so a median spine is chosen and its dimensions in mm taken as standard.

Reflecting the differing precision of measurement in the ventral and dorsal regions, the scaling is based on three points for each vertebra: dorsal mid-point, ventral caudal corner, and ventral cranial corner.

For each vertebra in turn, establish the scale factor by which the likeness needs to be changed so that the sum of squares of distances between the above three points for the vertebra and corresponding points for the average standardised vertebra is as small as possible.

2 Scale the likeness of the vertebra. The average is then corrected to reflect this adjustment. Then cycle through the spines in the cohort until changes become very small.

3 Calculate the scale factor for each spine as the geometric mean of scale factors at each level and produce a scaled likeness for each spine.

4 Adjust the likenesses to correct for lordosis. This is done by rotating each vertebra about the centre of the caudally contiguous disc until the mid-planes angle is equal to the standard angle at that level. This standard has been established from a large cohort of non-exposed males as described previously.

5 Produce and store scaled lordosis-corrected likenesses.

6 On the basis of these likenesses of *both* vertebral and disc measures, identify the typical or 'Golden' spine: that is to say the spine that is median in some sense. Store this likeness and its principal parameters.

7 Store measures of variability or deviation of the other spines from this Golden spine. The measures chosen to characterise a vertebra or disc are similar to those chosen in earlier chapters. The main difference is that where previously each measure was scaled as it was taken and a dimensionless number obtained, here the scaling is already completed and the measurements are now in scaled millimetres.

9 When wishing to make comparisons with radiographs of exposed spines, two approaches are possible: (A) Run the whole analysis with Basis and test spines together to see how exposed spines 'fit into' the overall set of results. (B) Compare the exposed spines with the Golden spine using the stored estimates of variability to construct tolerance intervals for the measure of interest.

In the results described below, approach A has been used. The 'fit' for each spine has been based on the three-point approach described above, but the three points used are the corresponding points for the disc space. Fit is thus calculated as the sum, over all the five disc spaces, of the sum of the squares of the three point deviations from the golden spine. This total was corrected for missing spinal elements and then square-rooted.

The exposed cohorts were the three British cohorts previously described in Chapter 3: Underground coal miners from Lancashire (Chapter 3.2.4), oil riggers working in Dubai (Chapter 3.2.5) and police officers from Northern Ireland (Chapter 3.3.3). In total, 63 subjects were used for these analyses. It would have been preferable to use a Basis that more closely represented the age range for exposed discs, but access was restricted to the one normative database (Chapter 3.1.2).

The quintile cut-offs for the deviations for discs in the Basis were determined, and the percentage of discs from each source within these regions calculated; the sources were variously the cohorts or combinations of cohorts. Discs lying above the fifth quintile were categorised as 'cases' and the odds ratio for exposed and unexposed discs was calculated along with its 99% confidence interval.

To illustrate the difference in the pattern of the distribution of deviations between exposed and unexposed discs, a bar chart was plotted. An error bar plot was used to indicate how different the mean deviations were for these two groups.

## 5.2 RESULTS

The focus of the results reported here is for the discs. The root mean square (RMS) deviations from the median spine for the three exposed cohorts and the normative database are given in Table 5.1. It can be seen that the mean deviation is greatest for the cohort of Lancashire miners,

followed by the cohorts of oil riggers and police officers. The latter two differed very little, except that the variance was greater for the police officers. The mean deviation for the normative database was less than all three exposed cohorts.

Table 5.1 Root mean square deviation in fit from the median spine for three British exposed cohorts and the British normative (unexposed) database.

Cohort	Mean RMS deviation	SD	n
Lancashire miners	9.83	3.69	32
Dubai oil riggers	7.65	1.34	12
Northern Ireland police officers	7.55	2.80	19
British normative database	6.69	1.93	237

If all three exposed cohorts are brought together and compared with the unexposed database, the mean difference in fit of exposed and unexposed spines is statistically significant at the 1% level (see Figure 5.1)

The box plots shown in Figure 5.2 illustrate the spread of values for individual spines within the exposed and unexposed cohorts. The positive skewness of the distribution for the exposed spines (discs) is clearly contrasted with the higher degree of symmetry for the unexposed spines. It can be seen that both cohorts have a few outliers beyond the upper tail.

The data conveniently can be viewed in terms of quintiles of the deviation from the median spine. Figure 5.3 illustrates how the 5<sup>th</sup> group dominates for the Lancashire miners, whilst groups 4 and 5 are key for the police officers and particularly so for the oil riggers. The spines from the unexposed cohort are reasonably evenly distributed, but predominate in the lower two quintiles.

When the Basis was used to define an upper quintile category for deviation from the median spine, and the three exposed cohorts were combined, then 43% of exposed spines were in the fifth category (highly divergent from the median spine) compared with the 20% for unexposed spines.

This distribution can be used to calculate an odds ratio. Suppose the incidence or frequency of major deviation is associated in two groups ('cases' and 'controls') of individuals with the presence or absence of exposure to spinal loading. Table 5.2 gives the numbers of spines falling into the defined categories. There is a statistically significantly greater chance of a spine being in the upper quintile for deviation from the median spine if it is from an exposed cohort ( $P < 0.001$ ). The odds ratio of an exposed spine being classed as a case is 3.03 (99% confidence interval = 1.39 to 6.61). As can be seen from Figure 5.3, it is the Lancashire miners that make the major contribution to this statistic.

The outcome of this treatment of the British data mirrored the results from the previous analyses (Chapter 4). That is that extreme exposures to physical stress at the workplace are associated with evidence of overload damage to spinal elements; with more normal exposures, the picture is less clear.

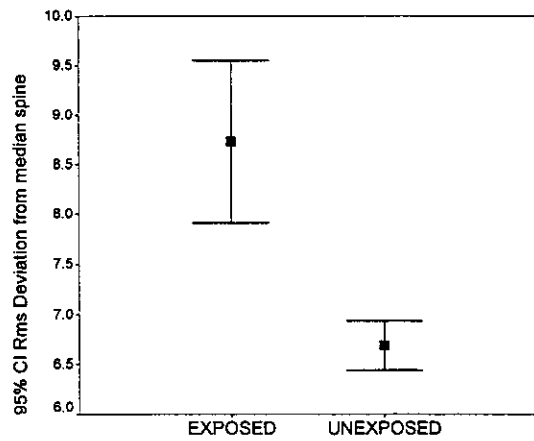


Figure 5.1 Means and 95% confidence intervals for RMS deviation from median spine for exposed and unexposed cohorts

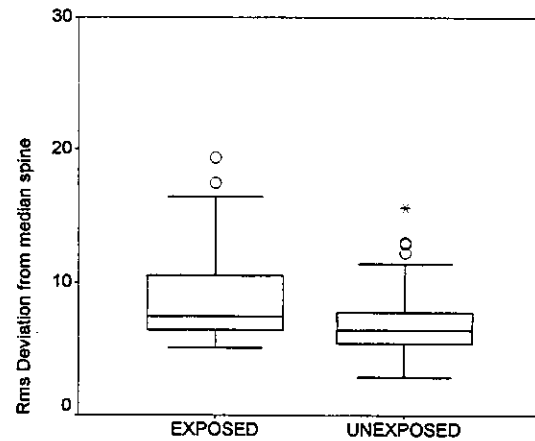


Figure 5.2 Box plots of RMS deviations from median spine for exposed and unexposed cohorts

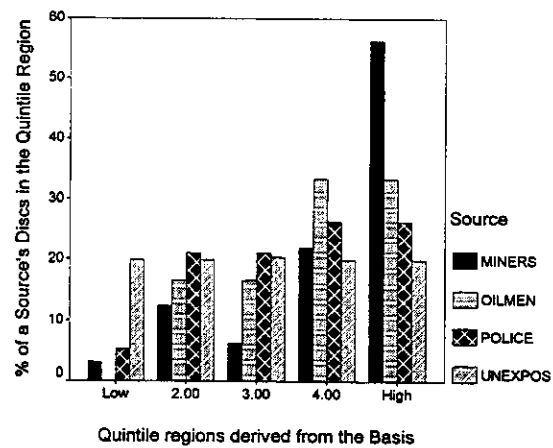


Figure 5.3 Percentage of spines from the three British exposed cohorts and the British database cohort falling into the quintiles for deviation from the median.

Table 5.2 The number (%) of spines from exposed and unexposed cohorts being classed as a 'case' or a 'control' by reference to the number that fall into the fifth quintile for deviation from the median spine.

	Exposed	Unexposed	Total
'Case'	27 (43%)	47 (20%)	74
'Control'	36 (57%)	190 (80%)	226



## 6 DISCUSSION

It is widely believed that occupational low back disorders are related to physical demands of the work, and that particularly high demands (over a period of time) will have damaging consequences for tissues of the lumbar spine. This issue of whether heavy spinal loading at the workplace may induce primary overload damage to structures such as vertebrae and discs has long been debated in the fields of biomechanics and ergonomics. The basic positions held in the debate may be summarised as follows:

*A.* It is assumed that in voluntary, anticipated tasks - as opposed to traumatic events - maximum muscle forces and thus maximum loads on ligaments and joints are limited by intrinsic, physiological regulation so that primary overload damage of the tissues cannot occur. In addition, it is pointed out that the high spinal loading required at some workplaces will be met by adaptation and training of muscles, tendons, ligaments and bone. Thus, occurrence of overload damage to the spine due to heavy physical exertions at the workplace is averted.

*B.* While the intrinsic limitation of muscle forces and adaptation processes of the tissues are generally acknowledged, it is argued that the bipedal posture in combination with work habits cannot be accommodated by adaptation, thus placing the human lumbar spine at a special risk. Thus, occurrence of overload damage to the spine due to deliberate, voluntary, heavy physical exertions at the workplace is considered possible.

Hypothesis *B* gains support when results of biomechanical model calculations or direct measurement of lumbar spine loading are compared with the *in-vitro* strength of lumbar vertebrae and intervertebral discs. Such comparisons show that there is, on average, no margin of safety between spinal loads when lifting and carrying heavy objects and the strength of lumbar vertebrae or discs. Repeated loads, as experienced in whole-body vibration, are estimated to be of low magnitude, but the number of load cycles accumulated in years of exposure could, however, potentially effect fatigue failure of these tissues.

The spines of patients with osteoporosis may serve as a model for a spine with insufficient strength of the anatomical structures to withstand *in-vivo* workloads. The morphological changes observed in the osteoporotic spine closely correspond to those changes observed upon *in-vitro* testing of the strength of spine specimens: height decrease and wedging of vertebral bodies, depression of vertebral endplates, irregular ventro-dorsal displacement of vertebrae and decrease in disc height due to endplate fracture or extrusion.

The study reported here was designed to contribute to the debate by furnishing direct proof of whether or not primary overload damage to lumbar vertebrae or discs occurs through exposure to heavy physical exertions (and thus high spinal loading) or through exposure to whole-body vibration at the workplace. To this end, the morphology of lumbar vertebrae and discs in cohorts exposed to heavy physical exertions or whole-body vibration at the workplace was measured and compared with age-appropriate data of healthy, unexposed subjects. The measurement method was based on previous work that had established precise procedures for determination of vertebral height, sagittal plane displacement and disc height from lateral radiographic views of the lumbar spine.

### ***Vertebral height***

The results show that in all the cohorts selected, save the press operators from Unterwellenborn and the miners from Lancashire, the height of lumbar vertebrae of exposed subjects does not deviate from normal. In other words, crush- or wedge-type fractures of lumbar vertebrae are

rarely observed. This statement holds irrespective of whether exposure was due to lifting and carrying or to whole-body vibration.

In the cohort of press operators, the height of T12 and L1 was found to be significantly decreased. It is inferred that this injury at the thoracolumbar junction is caused by the forward bent posture adopted when lifting the heavy press-instrumentation. In the cohort of miners, drawn from the underground mine in Lancashire, the decrease of vertebral height (also concentrated in the upper lumbar region) may be interpreted as being due to work-related overload damage from similar work postures. However, it has to be pointed out, that the mean age of the subjects was close to 60 years. Thus, the compressive strength of the vertebrae might have been decreased by the onset of osteoporosis, possibly related to nutritional deficiencies during the early part of the twentieth century.

Spinal loading among the cohorts investigated, estimated from the mass of the objects handled (often exceeding 50 kg) and the postures adopted (often forward bent), would suggest spinal compressive forces in excess of the vertebral compressive strength (even of young subjects). Thus a noticeable occurrence of pathological deformation of lumbar vertebrae (crush- and wedge-type fracture as well as endplate fracture) would be expected. While the observed decrease in disc height (see below) could well be due to endplate fracture, the finding that vertebral height (measured at the anterior cortical shell) was virtually unimpaired is surprising. This negative finding suggests that critical reconsideration should be given to the foundation and interpretation of model calculations for spinal loading as well as to the results of *in-vitro* strength testing of lumbar vertebrae. More important in a practical respect, the result of this study shows that (in general) current regulations on lifting and carrying suffice to prevent crush- or wedge-type fracture of lumbar vertebrae.

#### ***Sagittal displacement***

In some cohorts investigated, sagittal plane displacement of lumbar vertebrae exhibited small, irregular deviations from normal. To evaluate the magnitude of such deviations, it has to be kept in mind that sagittal plane alignment of lumbar vertebrae is extremely regular in the normative population (Frobin *et al* 1977). Deviation from normal, scaled in units of the SD of normals, is thus a very sensitive measure. In those cohorts where deviation of sagittal plane displacement from normal was observed, no systematic relation to a coincident decrease in disc height could be observed.

#### ***Disc height***

Disc height was found to be substantially and significantly decreased in the cohorts drawn from the salt mine at Merkers, and from the coal mines both at Regis-Breitingen and in Lancashire; all were exposed to high spinal loading. The disc height decrease was not observed at isolated anatomical levels, but virtually all levels of the lumbar spine were affected.

Experience from *in-vitro* tests and observations from osteoporotic spines suggest that such disc height decrease is caused by loss of disc tissue predominantly due to endplate fracture of the adjoining vertebrae. Thus, the results demonstrate the occurrence of primary overload damage to lumbar discs in these cohorts.

All three cohorts in question had been exposed to lifting and handling heavy objects in awkward postures. In fact, workloads in these plants had been very high, *i.e.* much higher than current regulations would permit. It follows that, if workplaces with workloads similar to those described above do still exist, a high incidence of irreversible damage to lumbar discs can be expected. This suggests that strict adherence to present regulations on lifting and handling should remain a requirement. It would be interesting, for instance, to see if improvements in mining work in the UK over the last 30 years or so has resulted in an absence of overload damage.

Comparison of the cohorts exposed to whole-body vibration shows that significant decrease of disc height is observed in the cohort drawn from the potassium salt mine at Merkers while no effect was seen in the cohort drawn from the brown-coal mine at Köln or the Northern Ireland police force. It is concluded that this difference is due to the different workplace design in these locations. The earthmoving machines of the brown-coal mine in Köln were equipped with comfortable, damped seats, whilst the seats used by the police officers had some measure of internal springing. In contrast, the machinery at the Merkers potassium salt mine was often unsprung and, furthermore, was equipped with unsprung, wooden seats. In addition to exposure to vibration, the subjects from Merkers were exposed to lifting and handling heavy objects; the shoulder loading experienced by the police officers (due to their body armour) was modest by comparison. Thus, comparing these cohorts demonstrates quantitatively and in a dramatic fashion the benefit that may result from substantial ergonomic improvements at the workplace, such as those found here (i.e. installation vehicle springing, damped seats and reduction of accompanying, heavy manual labour).

A high prevalence of back pain is reported from drivers of earthmoving machinery as well as from bus and truck drivers. The results reported from the cohort drawn from the brown-coal mine in Köln show that exposure to whole-body vibration on damped drivers' seats does not induce primary mechanical overload damage to lumbar vertebrae or discs. It follows that the anecdotal high prevalence of back pain reported in this cohort, likewise reported by bus or truck drivers, does not originate from overload injuries of discs or vertebrae. Other reasons for reported back problems need to be investigated.

The increased height of some discs and vertebrae, seen in the longitudinal study on earthmoving machine operators being supplied with damped seats, is puzzling. In principle, 'training effects' on vertebrae and discs from cyclic, long-term mechanical stimulation cannot be ruled out. Larger cohorts, however, would need to be investigated before definite conclusions can be drawn.

#### ***Shape analysis***

The result of applying shape analysis method to the data from the British cohorts reflects the findings from the other analysis. Focusing on disc shape, it is clear that the cohorts exposed to heavy physical demands on the spine (Lancashire miners, Dubai oil riggers and Northern Ireland police officers) display, on average, a greater deviation from the shape found among cohorts forming the British unexposed database. The difference is largely attributable to the miners and is statistically significant only for this cohort, although there is a trend for the oil riggers and (to a lesser extent) the police officers to differ from the unexposed database.

There was no indication that the dual exposure experienced by the police officers (heavy body armour and vehicular whole-body vibration) combined so as to increase the risk of significant overload damage, though numbers were somewhat limited.

#### ***Limitations***

Certain limitations of the study should be addressed:

(i) Compilation of a normative database as a standard of comparison is problematic because radiographs had to be drawn from existing archives; it could not be assumed that the radiographs contained no pathologically deformed vertebrae or discs, so the data were emended by excluding pathologically deformed vertebrae, motion segments or discs. However, the prevalence of pathological vertebrae and discs in the normative cohort was found to be low, and it has been shown that the basic conclusions of this study are not altered by the emending (Brinckmann *et al* (1998)).

(ii) The dependence of vertebral height, sagittal plane displacement and disc height on age and (in the last two) on the angle of lordosis was determined from unexposed cohorts. Even when

based on a large number of radiographs (500 for the German and 237 for the British database), the accuracy of this method is limited, specifically with respect to the dependence on age (Frobin *et al*, 1997). Furthermore, it had to be assumed that identical age and angle dependency were applicable for exposed and normative cohorts. The resulting error was investigated in a sensitivity study with the coefficients describing age and angle dependence varied in 95% confidence intervals. In consequence, all deviations from normal are designated by four classes of significance. 'Hard data' on occurrence of overload damage are provided when deviation from normal was classified 'significant' and when in addition all lumbar vertebrae, motion segments or discs showed similar effects; see for example, the disc height decrease within the salt mine labour force (Figure 4.6).

(iii) Inter-observer bias when measuring vertebral height, displacement and disc height was extremely small, *i.e.* lower than 0.01 (in units of mean vertebral depth). Yet when measuring a large number of radiographs of unexposed and exposed subjects, a bias of this magnitude (if not corrected) could still simulate significant differences between cohort means. A correction for inter-observer bias, however, had to be performed only for one exposed cohort (earthmoving machine operators, coal mine, Köln).

(iv) It is a general drawback of cross sectional studies that nothing can be said about those subjects who are initially exposed but leave the cohort for whatever reason before their final status can be documented. If the type of work performed is detrimental to health, it is reasonable to assume that those subjects with the highest level of tolerance with respect to the workload 'survive' in the exposed cohorts ('healthy worker effect'). The results of a cross sectional study will thus quantify a lower limit for the work-related overload damage. Fluctuation of the labour force in the companies under investigation was, however, low, especially in the plants in Regis-Breitingen, Merkers and Unterwellenborn (former German Democratic Republic), and in the Northern Ireland police force. Only in the Dubai oil rig workers was a healthy worker effect considered likely. It is therefore assumed that the documented overload damage to the lumbar spine closely approximates the damage that would have been observed in longitudinal, prospective studies.

(v) Accurate quantification of workloads is known to be complex and problematic (Ferguson & Marras, 1997); objective valid methods are an ideal rarely encountered. In this study, workloads necessarily had to be assessed retrospectively and (in the main) subjectively. In an attempt to ensure that estimates were as accurate as possible, numerous experts from the industries concerned or the actual workplaces were consulted. Furthermore, the cohorts used came from environments that generally had obvious, markedly different levels of exposure to the stressors under consideration. The level of precision for estimating workloads was deemed sufficient to answer the broad questions posed here.

(vi) The archive material used for this study did not include clinical details, so there is no possibility here specifically to explore the question of whether there is a relationship between physical stress/overload damage and back pain or its attendant disability. However, some information is available from two of the populations from which archive cohorts were obtained. A previous report on the British coal miners in north-west England (Lawrence, 1969) concluded that there was a relationship between lumbar disc degeneration (evidenced by conventional radiological inspection) and a past history of back pain and sciatica. But, while disc degeneration was more prevalent among the miners than in less strenuous occupations, back complaints from the miners were no more common than from the other occupations (Kellgren, 1961). In an epidemiological study of the police force in Northern Ireland (Burton *et al*, 1996), it was found that exposure to body armour and working in vehicles were independent (not additive) factors associated with an earlier onset of first-time back trouble than for officers not exposed to these physical stressors. A similar relationship was not found, however, for the persistence of symptoms. The relationship between symptoms (or disability) and overload damage remains unclear.

## 7 SUMMARY AND CONCLUSIONS

Height of lumbar vertebrae, sagittal plane displacement and height of lumbar intervertebral discs have been measured from archive radiographic views of 355 subjects from five cohorts with long-term exposure to heavy spinal loading and three cohorts with exposure to whole-body vibration at the workplace. The data were compared with normative databases compiled from 737 healthy subjects. The results quantitatively document the occurrence and magnitude of overload damage to lumbar vertebrae and discs in exposed cohorts. This damage is distinct from age-related changes (at least under about 60 years of age) and is unlikely to be due to anything other than occupational loading.

- Overload-related deformation of vertebral bodies, *i.e.* a decrease in vertebral height or wedging, is rarely seen. This holds for cohorts exposed to whole-body vibration as well as for cohorts exposed to very heavy spinal loading due to lifting and handling. Overload damage to vertebral bodies is documented only in the thoracolumbar junction of a cohort performing a specialised, strenuous task in a forward bent posture and a cohort of older miners.
- Sagittal plane alignment of lumbar vertebrae is only minimally impaired either by exposure to heavy spinal loading or by exposure to vibration, *i.e.* there is very little tendency for vertebrae to be displaced in ventral or dorsal direction.
- Heavy spinal loading due to frequent lifting and handling of objects with a mass exceeding 50 kg and/or handling of heavy objects in confined spaces and on uneven ground results in a significant decrease in disc height within the entire lumbar spine. If workplaces with similar characteristics still exist, a redesign is strongly indicated in order to avoid future occurrence of overload damage to lumbar discs.
- Whole-body vibration has no measurable detrimental effect on vertebral height, sagittal plane displacement or disc height if the workers' seats are damped and peak acceleration thus stays below certain limits. It follows that primary overload damage to vertebrae or to discs is not responsible for the high prevalence of back problems in labour forces with sustained exposure to whole-body vibration.
- Whole-body vibration and shock loading, experienced if earthmoving machines or rock drills are unsprung and operators' seats are unsprung as well, result in a significant decrease in the height of lumbar discs. The comparison of the results from two vibration-exposed cohorts (damped seats vs. unsprung seats on unsprung machines) impressively demonstrates the ability of workplace redesign to decrease the health risk to the labour force.
- The extent to which overload damage may result in back symptoms or disability remains to be determined, but any system of work containing the sort of workplace factors shown here to be associated with irreparable damage are obviously unacceptable. However, it does not follow that all workers in such environments will sustain overload damage. When looking at groups of workers doing less strenuous work, any high prevalence of back symptoms and/or related disability that might be observed is not likely to be due to occupational overload damage of the vertebrae and discs. However, due to individual variability in tissue properties and the like, it is not possible to extrapolate that a given worker exposed to work controlled by current guidelines cannot sustain overload damage.
- Future research to amplify these findings may usefully explore the potential for using non-invasive imaging methods such as magnetic resonance imaging. If the resolution of such scans can be shown to be adequate, prospective studies could help to refine future guidance on safe working practices.

## 8 APPENDIX

### 8.1 COMPARISON BETWEEN BRITISH AND GERMAN DATABASES

To explore the potential difference between the two databases, all subjects who entered the British database were pooled into a single cohort and compared with the German database (in the identical fashion as exposed cohorts are compared with the database). Vertebral height of British normals (Figure 8.1) appears to be significantly increased when compared with German normals. With respect to sagittal plane displacement and disc height there was no difference between the British and German normals.

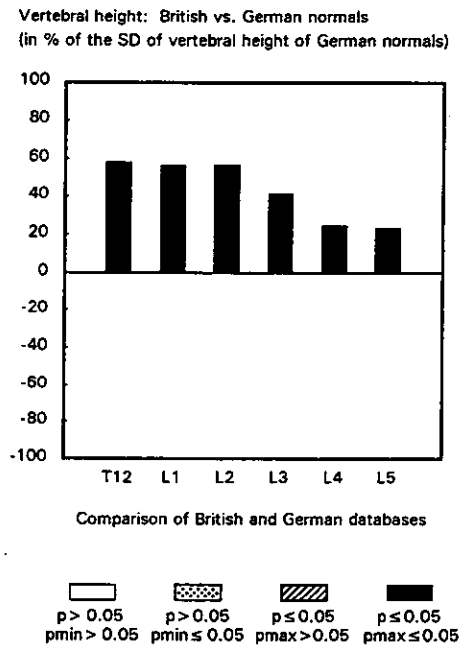


Figure 8.1 Vertebral height of British normals in relation to the German database

Whether inter-observer difference could be responsible for the discrepancy between the two databases was considered. The majority of the radiographs of the British and German unexposed cohorts (normals) had been mapped and digitised by a single observer for each country. An inter-observer comparison between these two was performed. Shifting the British data by the inter-observer bias did not achieve agreement with the German database. Rather, in addition to the initial discrepancy with respect to vertebral height, there was now also disagreement with respect to disc height.

It is concluded that a small (but significant) difference exists between British and German databases. This difference cannot be explained by inter-observer bias; it is thought to reflect a geographic variation of spine morphology. The existence of this difference justifies separate comparison of the exposed cohorts with the appertaining British or German databases.

## **8.2 COMPARISON OF EXPOSED COHORTS WITH UNEXPOSED COHORTS, DRAWN FROM THE IDENTICAL ARCHIVE**

If, with respect to vertebral height, displacement or disc height, exposed cohorts deviate from normal, the question arises of whether the deviation could be due to a regional (geographic) variation in spine morphology instead of being caused by the workload. The comparison of the British and German databases has already shown that geographic differences may exist.

To investigate the issue, three exposed cohorts were compared with unexposed cohorts collected from the identical archives (these unexposed cohorts contributing in part to the German database). When evaluating the result of such comparisons, it has to be kept in mind that the magnitude of the deviation from normal as well as the class of significance may be different when an exposed cohort is compared either with the German database or with a database derived from a local sub-cohort.

With respect to vertebral height, the 'lifting'-exposed cohort drawn from the salt mine at Merkers, showed no deviation from normal when compared with the German database (Figure 4.4); virtually the identical result is obtained if this cohort is compared with a cohort of young, healthy subjects from the same location (Figure 8.2).

Disc height of the 'lifting'-exposed Merkers cohort turned out to be decreased when compared with the German database (Figure 4.6). The identical pattern of disc height decrease is seen when this cohort is compared with a cohort of young, healthy subjects from the same location (Figure 8.3).

Likewise, identical conclusions are reached when disc height of the vibration-exposed cohort drawn from the salt mine at Merkers is compared with the German database (Figure 4.18) or with unexposed, young, healthy subjects from the same location (Figure 8.4).

If vertebral height of the press operators drawn from the steelworks at Unterwellenborn is compared with unexposed, young healthy subjects from the same location (Figure 8.5), the height decrease of vertebrae T12 and L1 is obvious as in the comparison with the German database (Figure 4.7). (Due to the small number of subjects in the cohort of unexposed young healthy subjects, however, the difference 'exposed minus unexposed' is now classified as 'not significant'.)

It is concluded that the reduction in disc height documented in the exposed cohorts drawn from the salt mine at Merkers and the decrease of vertebral height seen in the press operators drawn from the Unterwellenborn steelworks are not due to local variations in spine morphology but are work-related.

Vertebral height: exposed subjects vs. young cohort,  
drawn from the identical archive (% of SD of normals)

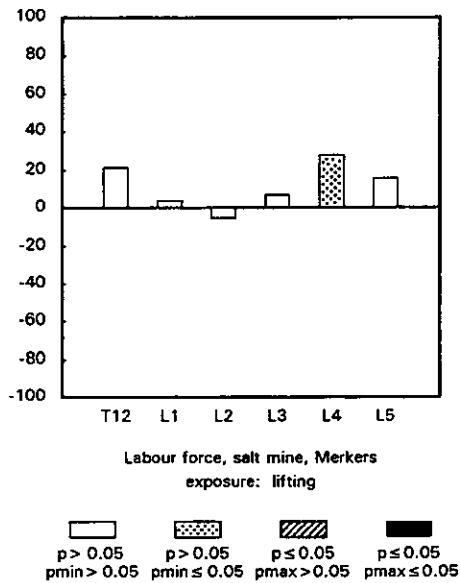


Figure 8.2 Vertebral height of the labour force exposed to lifting and carrying, drawn from the underground potassium salt mine, Merkers, in relation to a young, healthy cohort, drawn from the identical archive

Disc height: exposed subjects vs. young cohort,  
drawn from the identical archive (% of SD of normals)

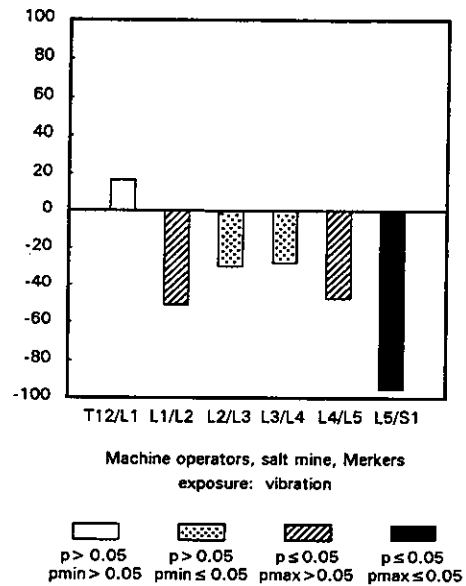


Figure 8.3 Disc height of the labour force exposed to lifting and carrying, drawn from the underground potassium salt mine, Merkers, in relation to a young, healthy cohort, drawn from the identical archive

Disc height: exposed subjects vs. young cohort,  
drawn from the identical archive (% of SD of normals)

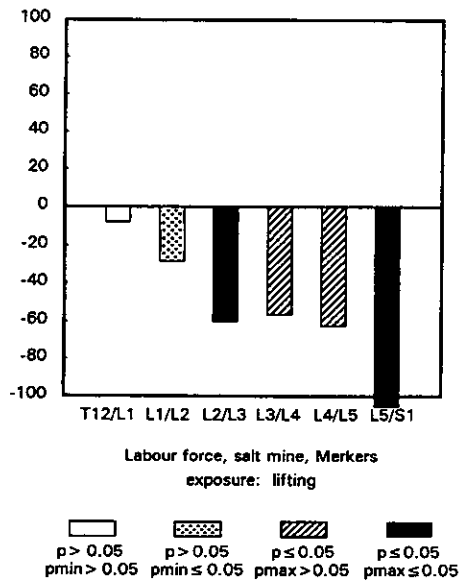


Figure 8.4 Disc height of the labour force exposed to whole-body vibration, drawn from the underground potassium salt mine, Merkers, in relation to a young, healthy cohort, drawn from the identical archive

Vertebral height: exposed subjects vs. young cohort,  
drawn from the identical archive (% of SD of normals)

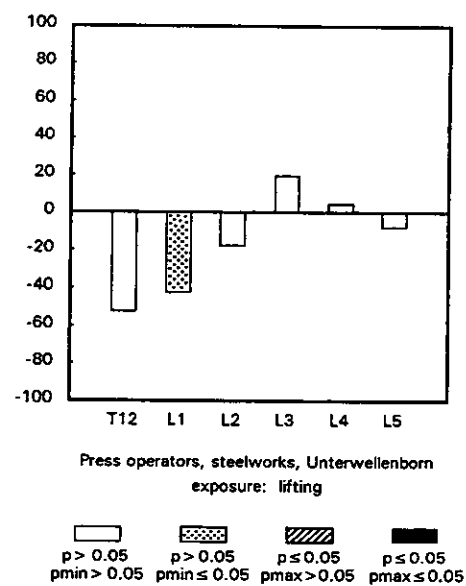


Figure 8.5 Vertebral height of press operators, exposed to lifting and carrying, drawn from the steelworks Unterwellenborn, in relation to a young, healthy cohort, drawn from the identical archive



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