Risks of Occupational Vibration Exposures

VIBRISKS

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Executive Summary

Background

Millions of European workers are exposed to mechanical vibration transmitted to their hands from powered tools or transmitted to their whole body from the seats of industrial vehicles. Disorders of the upper limbs caused by hand-transmitted vibration are among the most compensated industrial diseases in several European states and exposure to whole-body vibration is associated with disorders of the spinal system.

The currently standardised methods of assessing the severity of vibration exposures are not based primarily on epidemiological evidence or on an understanding of the relevant mechanisms of injury. They are not sufficient to predict the risks of injury or define optimum means of preventing injury.

Objectives

The principal objective of VIBRISKS was to improve understanding of the risks of injury from exposures to hand-transmitted vibration and whole-body vibration at work by means of multi-national epidemiological studies, supported by fundamental laboratory research and biodynamic modelling.

Secondary objectives were: (i) to contribute to a scientific basis for political decisions on the adequacy of current preventive measures and expenditure on prevention; (ii) to provide guidance on health surveillance that can be applied by occupational health workers across Europe for the minimisation of risk (primary prevention), the screening of exposed workers, and the management of individuals who have symptoms of hand-transmitted vibration injuries (secondary prevention); and (iii) to help industry by reducing the social and economic costs associated with disorders.

Work Programme

The studies of hand-transmitted vibration (HTV) and whole-body vibration (WBV) developed some common tools and procedures. For both HTV and WBV, the work was divided into three components:

- Coordinated multi-national epidemiological field studies of dose-response relationships for adverse outcomes arising from occupational exposures to vibration.
- Laboratory experimental studies and biodynamic modelling to support the field investigations, including the definition of alternative means of evaluating vibration exposures and predicting risk.
- Supporting activities, including: (i) the definition of methods to be used in the epidemiological surveys, and (ii) the integration of the findings from the experimental and biodynamic studies with the results of the epidemiological research so as to provide occupational health guidance.

Results and Achievements

Epidemiological studies

In Italy and Sweden, baseline and follow-up longitudinal epidemiological studies were completed with groups of workers having different exposures to hand-transmitted vibration. A second follow-up survey was completed in Italy. The Italian survey provided evidence of dose-response relationships for sensorineural and vascular symptoms and a dose-effect relationship for cold-induced digital arterial hyper-responsiveness and impaired manual dexterity in HTV-exposed workers. The Swedish study group had only short vibration exposures, but significant associations were found between indices of peripheral vascular and sensory dysfunction and measures of daily and cumulative vibration dose. Vibration exposure and awkward neck postures were associated with neck pain among the workers.

In Italy, Sweden, the Netherlands and the UK, baseline and follow-up longitudinal epidemiological surveys were completed with groups of workers occupationally exposed to whole-body vibration. A further follow-up survey was completed in Italy and an intervention study in the Netherlands continues to investigate the effects of health surveillance and other intervention measures. Various physical and psychosocial factors were found to be associated with an increased risk of low back pain (LBP). The Italian and the Dutch results were consistent with increased risk of LBP in those with higher cumulative exposures to whole-body vibration. However, standardised measures of daily vibration exposure were poorly associated with LBP. Studies in Sweden and the UK did not find clear relationships between WBV and LBP. The findings of a case-control study in the UK suggest that, in the general population, WBV is not an important cause of LBP that is severe enough to result in referral for MRI imaging of the lumbar spine.

Experimental and modelling studies

Collaborative experimental studies were carried out in Italy, Sweden, and the UK to improve understanding of the effects of vibration magnitude, frequency and duration on acute changes in both vascular function (finger blood flow and finger systolic blood pressure) and neurological function (vibration perception thresholds and thermotactile thresholds). The observed changes in vascular and sensorineural function during and following vibration exposure were not consistent with the 'energy-equivalent' time-dependency currently used to evaluate occupational exposures to hand-transmitted vibration. The vascular studies suggest that intermittent vibration is less hazardous than continuous vibration with the same 'energy'. Reductions in finger blood flow were not limited to the finger experiencing force and vibration. Both vibration magnitude and exposure duration influenced thermotactile thresholds.

Collaborative experimental studies by Italy and the UK suggested that recent exposure to force and moderate levels of hand-transmitted vibration will not greatly affect finger systolic blood pressure following cold provocation, as used to identify vibration-induced white finger. In Sweden, prior exposure to vibration on the day of a test was found to influence vibrotactile and thermotactile perception thresholds.

In the UK, studies of the effects of age and gender on vascular function (finger systolic blood pressure after cooling) and sensory function (thermotactile and vibrotactile thresholds) provided normal values to assist the interpretation of clinical and epidemiological studies of the hand-arm vibration syndrome.

In France, a 3-D biodynamic model of a finger was elaborated to understand how vibration propagates in the tissues and how to calculate internal mechanical properties, such as strain. The studies also improved understanding of finite element calculations of visco-hyperelastic behaviour.

In Germany, experiments and modelling of the spinal system led to a new method of predicting spinal stress from vibration in vehicles. A numerical model of the spinal system was extended to predict load on the spine from the forces caused by combinations of driver posture and whole-body vibration. When applied to the vibration measured in the epidemiological studies, the evaluations indicated an underestimation of health risks by the exposure limit value in the Physical Agents (Vibration) Directive.

Supporting activities

Protocols were developed for the epidemiological studies of hand-transmitted and whole-body vibration. These defined measures of vibration dose, means of summarising exposures and their effects, and self-administered and clinically-administered questionnaires for the baseline and follow-up studies. The protocol for hand-transmitted vibration also defined tests for diagnosing the hand-arm vibration syndrome. The protocols are valuable guides for future research and should also assist clinical studies.

VIBRISKS also produced health surveillance guidance that will help occupational health workers to minimise risk, screen exposed individuals, and manage individuals with symptoms of vibration injuries.

Conclusions

The epidemiological and experimental studies of hand-transmitted vibration indicate that improvements are possible to the frequency weighting and the time-dependency currently used to predict the risks of vibration-induced disorders. The results confirm that finger systolic blood pressure after cold provocation is related to vibration exposure, and that both thermal thresholds and vibrotactile thresholds are indicators of sensorineural damage caused by hand-transmitted vibration.

The studies of whole-body vibration indicate that improvements are needed to the method of predicting risks to the low-back. Risks of injury to the low-back due to mechanical forces are complex and multi-factorial and cannot be predicted solely from measurements of vibration. Especially important are postural factors that have been shown to influence spinal forces and the risk of low back pain.

The findings have implications for the Physical Agents (Vibration) Directive of the EU and the development of new standards. However, the subject is very complex and there are many implications associated with any change to current procedures. Further research on hand-transmitted and whole-body vibration is required before specific changes can be confidently recommended.

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1 Introduction and Objectives

Occupational exposures to hazardous levels of hand-transmitted vibration and whole-body vibration are common in the European Union. Some outcomes of exposure are well-recognised: finger blanching (vibration-induced white finger) and sensorineural disorders occur in workers exposed to hand-transmitted vibration, and there is a risk of low-back pain in workers exposed to whole-body vibration, with a considerable social and financial burden of disease from these disorders. For other disorders, such as carpal tunnel syndrome and osteoarthritis, the risks from vibration are less well established. There remain large differences between EU countries in the recognition and diagnosis of disorders and the means of controlling risk.

The control of risks from vibration can be subdivided into: (i) primary prevention (e.g. technical and administrative controls), and (ii) secondary prevention (e.g. health surveillance, limiting further exposure in an affected worker). Primary prevention depends on establishing the range of outcomes that might arise and, for each, characterising the relation between dose of exposure to vibration and the illness caused (the dose-response relationship); this requires an appropriate measure of vibration exposure. Secondary prevention depends on the natural history of vibration-related illness and the identification of the factors that cause, or predict, its progression. For example, initial effects of exposures to hand-transmitted vibration are often mild and can be slow to progress: before withdrawing a worker from any further exposure, the benefits need to be weighed against the economic and social impact on the worker, the employer, and the community. Understanding the natural history and prognostic indicators of disease can inform programmes of health surveillance designed to minimise the consequences of disease.

1.1 Structure of the project

The VIBRISKS project was conceived to provide the information needed to improve both primary and secondary preventive measures for minimising the consequences of occupational exposures to hand-transmitted vibration and whole-body vibration. The studies of hand-transmitted vibration and whole-body vibration were designed to be complimentary, since they involve many common tools and procedures. In both cases, the work was divided into three main components.

1.1.1 Epidemiological studies

Epidemiological studies were carried out to investigate dose-response relationships for adverse outcomes known to arise from exposure to vibration. These comprised:

- Coordinated longitudinal epidemiological studies of workers occupationally exposed to hand-transmitted vibration in Italy and Sweden so as to characterise dose-response relationships and factors responsible for the development of vibration-induced white finger and sensorineural disease.

- Coordinated longitudinal epidemiological studies of workers occupationally exposed to whole-body vibration in Italy, Sweden, the Netherlands and the U.K. so as to: (i) characterise any exposure-response relationship between whole-body vibration and the development or recurrence of disorders; (ii) identify factors that combine to result in the development or progression of the symptoms of disorders so as to improve understanding of the benefits of health surveillance and other intervention measures.

- A case-control study in the UK to determine whether exposure to whole-body vibration contributes to prolapsed intervertebral discs.

1.1.2 Laboratory studies

Laboratory studies were carried out to support the field investigations, by supplying alternative metrics of exposure that are credible in physiological and biodynamic terms and that warrant evaluation. These comprised:

- Experimental studies of the acute vascular and neurological effects of hand-transmitted vibration, and biodynamic modelling, so as to assist understanding of factors influencing exposure-response models.

- Experimental and modelling studies to guide the measurement of body posture and vibration exposure in the epidemiological studies and assist the prediciton of spinal risk from measures of exposure to whole-body vibration.

1.1.3 Integration of the results

The findings from the experimental and modelling studies were integrated with the epidemiological findings so as to provide information needed to improve occupational health guidance.

1.2 Objectives of the project

The principal objectives of VIBRISKS were to improve understanding of the risks of injury from hand-transmitted vibration and whole-body vibration by means of epidemiological studies supported by fundamental laboratory research. This was expected to assist the development of improved occupational health guidance for workers exposed to vibration and their employers.

1.2.1 Hand-transmitted vibration objectives

- To advance understanding of the acute effects of hand-transmitted vibration on peripheral circulation.

- To improve knowledge of the exposure-response relationship between hand-transmitted vibration and the development of chronic vascular disorders.

- To seek a relation between the severity of exposures to hand-transmitted vibration and the development of neurological disorders: sensory symptoms (including numbness and tingling) and also signs of disorder (elevated thresholds for tactile sensation, and other neurological deficits).

- To improve understanding of the factors that combine to result in the progression of the symptoms and signs of vascular disorders, so as to improve understanding of the benefits of health surveillance.

- To provide information needed to improve health surveillance guidelines for the minimisation of risk (primary prevention), the screening of exposed workers, and the management of individuals who have symptoms of hand-transmitted vibration injuries (secondary prevention)

1.2.2 Whole-body vibration objectives

- To define a model predicting the load on the spine from combinations of forces arising from body posture and whole-body vibration.

- To improve knowledge of the exposure-response relationship between whole-body vibration and the development of disorders, especially back pain.

- To improve understanding of the factors that combine to result in the progression of the symptoms of disorders, both with and without intervention at the workplace, so as to improve understanding of the benefits of health surveillance.

- To uncover whether exposure to whole-body vibration contributes to prolapsed inter-vertebral discs.

- To provide information needed to improve procedures for the minimisation of risk (primary prevention), the screening of exposed workers, and management of individuals who already suffer from back pain and other symptoms of spinal injuries (secondary prevention).

2 Hand-transmitted vibration

2.1 Protocol for epidemiological studies of hand-transmitted vibration

2.1.1 Introduction

Early discussions among the VIBRISKS partners led to a decision to draft a protocol for the conduct of the epidemiological studies of hand-transmitted vibration (see Annex 1) and an equivalent protocol for the conduct of the epidemiological studies of whole-body vibration (Annex 12).

The protocol was initially drafted by the leader of workpackage 1 in collaboration with the leader of workpackage 2 and then used to guide the conduct of the epidemiological studies being performed within workpackage 2. At each meeting of the partners, the protocol was reviewed and suggestions were made for additional content. Annex 1 presents the final version of the protocol.

The various partners conducted studies with slightly differing purposes, so not all parts of this protocol are appropriate for all studies. Nevertheless, the protocol assisted the design and conduct of studies with as many similarities as possible, maximising the comparison of results from the research. The protocol is likely to be useful for future studies conducted outside VIBRISKS.

2.1.2 Objectives

The objectives were to agree and record definitions of tests, questionnaires, and diagnostic procedures relevant to the assessment of disorders caused by hand-transmitted vibration and means alternative of quantifying the severity of exposures to hand-transmitted.

2.1.3 Methods and results

The final protocol is a document of more than 90 pages, presented with 11 sections and 11 appendices. The sections of the protocol are summarised below.

2.1.3.1 Introduction

The Introduction explains that the protocol was developed for use by partners in VIBRISKS but that it was envisaged that the document may also be useful for others conducting epidemiological studies, clinical investigations, and experimental studies, of the effects of hand-transmitted vibration.

2.1.3.2 Diagnostic tests

This section of the protocol defines the standardised methodology for conducting diagnostic tests so as to provide as sensitive, repeatable, and reproducible results as possible within the constraints of current knowledge, practicality, simplicity, and cost.

The section defines:

(i) the environment required for the conduct of tests

(ii) the Purdue pegboard test of dexterity

(iii) the Jamar grip meter test of grip force

(iv) the thermal aesthesiometer test of thermal thresholds

(v) the tactile vibrometer test of vibrotactile thresholds

(vi) the measurement of finger systolic blood pressures (at 30°C and 10°C)

(vii) the measurement of finger re-warming times.

2.1.3.3 Colour charts

One of the significant unplanned advances during the course of the VIBRISKS was the definition and testing of colour charts as a means of assisting the identification of vascular symptoms in the hands and fingers. The partners assembled a set of photographs showing various normal and abnormal colours of the whole hand (e.g. normal, whiteness, cyanosis, hyperaemia, patching, etc.) that were applied in the epidemiological studies, the results of which are reported in Section 2.2, below.

The colour charts proved a valuable additional test and appear in final form in an appendix to the protocol (see Figure 2.1).

2.1.3.4 Diagnosis of carpal tunnel syndrome

Some studies suggest an increased prevalence of carpal tunnel syndrome in users of vibratory hand tools, but the role of vibration in the development of carpal tunnel syndrome is not known. One problem has been the variable methods used to identify the presence of carpal tunnel syndrome using clinical means.

The criteria were discussed by the VIBRISKS partners and it was decided that in the VIBRISKS epidemiological studies, *all* of the following criteria would be required for the 'clinical suspicion' of carpal tunnel syndrome:

(i) **classic/probable symptoms** (numbness, tingling, burning or pain in at least two of the digits 1, 2 or 3);

(ii) **nocturnal symptoms**;

(iii) **positive physical examination** (Tinel's test or Phalen's test).

The means of ascertaining the required information was provided by the inclusion of suitable questions in the questionnaires and the definition of standardised means of conducting the Tinel's test and the Phalen's test.

2.1.3.5 Clinical tests for the diagnosis of upper limb disorders

Many clinical tests are used by physicians when examining patients exposed to hand-transmitted vibration, but the tests are not applied uniformly. Appendix 4 to the protocol provides definitions of eight of the clinical tests often used when assessing patients exposed to hand-transmitted vibration.

2.1.3.6 Criteria for clinical diagnosis of neck and upper limb musculoskeletal disorders

When diagnosing disorders, physicians may use different criteria for diagnosing the existence of a disorder of the neck or upper limbs. Appendix 5 to the protocol provides criteria for the clinical diagnosis of 19 common neck and upper limb musculoskeletal disorders.

2.1.3.7 Reported and observed exposure durations

The protocol draws attention to the difficulty in obtaining accurate estimates of the durations of exposures to hand-transmitted vibration. It is common for there to be differences between actual durations of exposure and estimated durations of exposure.

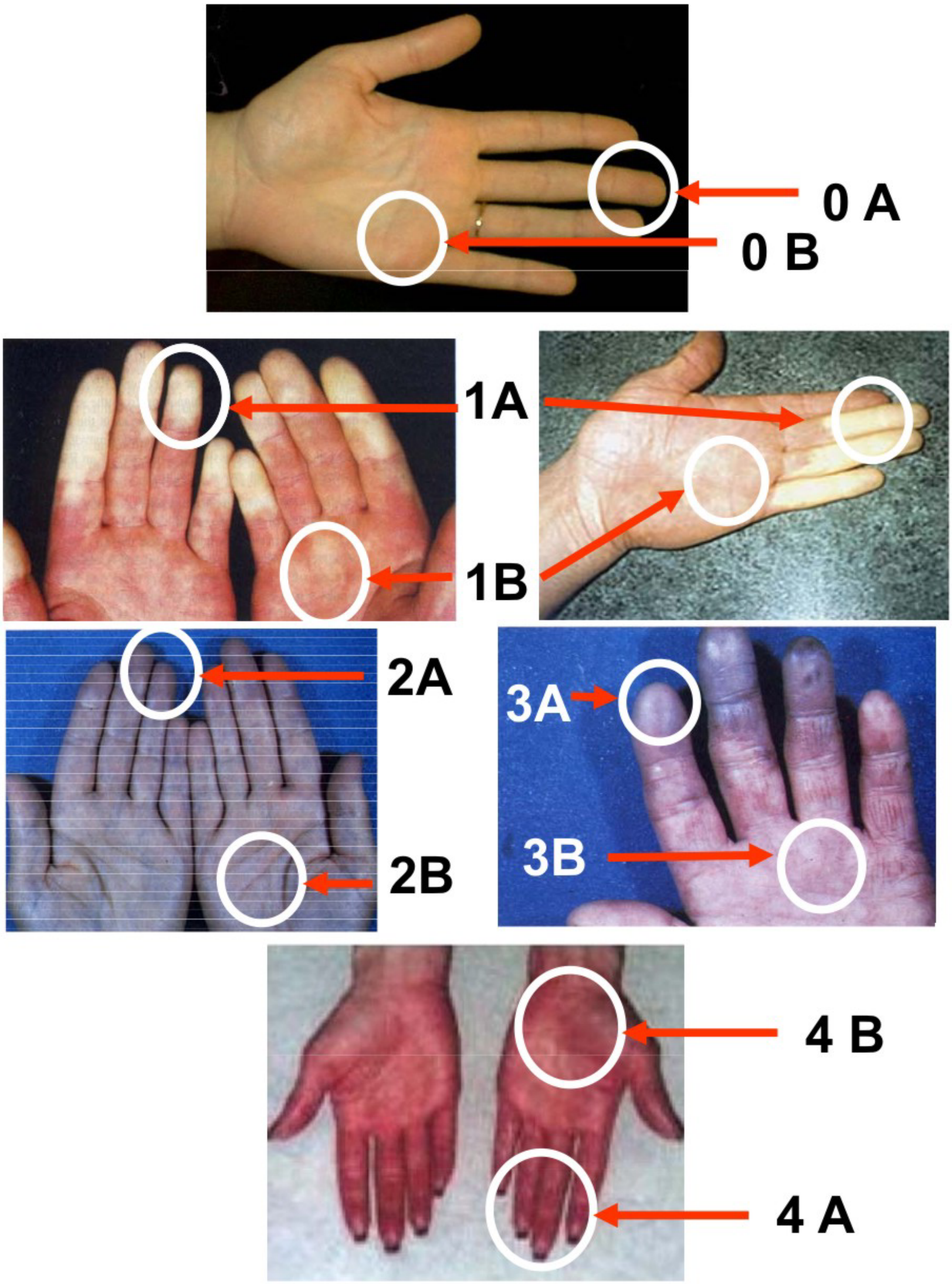

Figure 2.1 Colour charts used to assist the identification of colour changes in the hands and fingers.

The conditions reflected in the colour charts are as follows:
0A = normal colour of fingers
0B = normal colour of hand palm
1A = white finger
1B = white patching of hand palm
2A+2B = acrocyanosis
3A = cyanosis of fingers
3B = bluish patching of hand palm
4A = redness of fingers
4A+4B = erythromelalgia

For research purposes, such as studies within VIBRISKS, it is desirable to obtain accurate estimates of the durations of exposures to hand-transmitted vibration. This may require direct observation or indirect measurement of the duration of vibration exposure. However, the discrepancy between actual and estimated durations of exposure has not been recognized in the evolution of dose-response relationships in guidance on the risks arising from hand-transmitted vibration. In consequence, since actual exposures are often less than estimated exposures, accurately measured exposure durations may underestimate the risk if they are compared with current guidance.

2.1.3.8 Measures of vibration dose

Current standards and legislation make large assumptions as to the manner in which the risks from exposures to hand-transmitted vibration depend on the magnitude, frequency, direction, and duration of exposure to hand-transmitted vibration. One objective of the studies within VIBRISKS, and no doubt future epidemiological studies, was the investigation of the validity of the current assumptions.

The leaders of workpackage 1 and workpackage 2 collaborated on the evolution of 17 alternative measures of dose from exposure to hand-transmitted vibration. Appendix 6 of the protocol defines these alternative measures of vibration dose. The measures include those in past and current standards, but also include some to assist the development of a better understanding of the relative importance of vibration magnitude, vibration frequency, vibration direction, and duration of vibration exposure.

2.1.3.9 Summary of vibration exposures and effects

Exposures to vibration and their effects are complex and often summarised by merely one or two measures, such as the average vibration magnitude and the prevalence of one symptom.

To assist and encourage a more complete summary presentation of findings, Appendix 7 of the protocol gives a summary table that combines typical summary descriptions of the exposed population and their exposures to hand-transmitted vibration with typical summary descriptions of relevant aspect of their health.

The table in Appendix 7 was evolved for the purposes of illustration within VIBRISKS, and was used by partners undertaking epidemiological studies of the effects of hand-transmitted vibration within VIBRISKS, but it should also be useful for other epidemiological studies in the future.

In addition to the tabular summary, it was decided that with VIBRISKS reports of epidemiological studies should provide the following information:

1. Prevalence of vascular, sensorineural, and musculoskeletal symptoms at the cross-sectional survey of the study population
2. Main results of objective tests at the cross-sectional survey
3. Incidence of vascular, sensorineural, and musculoskeletal symptoms at the follow up survey(s) of the study population
4. Comparison of objective test results between the cross-sectional and follow up survey(s)
5. Metrics of vibration exposure and ergonomic risk factors used according to HTV procedure manual
6. Possible exposure-response (for symptoms) or dose-effect (for objective test results) relationships for the cross-sectional survey

7. Possible exposure-response (for symptoms) or dose-effect (for objective test results) relationships for the changes in the outcomes over time during the follow up period(s)
8. Contribution of the two exposure factors (vibration magnitude and duration of exposure) used to construct doses for the prediction of the outcomes (symptoms and objective test results) over time, adjusted for personal, social and health covariates.

2.1.3.10 Questionnaires

Four questionnaires were developed with VIBRISKS and are presented in appendices to the protocol:

(i) Self-administered Questionnaire (Appendix 8a)

(ii) Clinically administered Questionnaire (Appendix 8b),

(iii) Self-administered Follow-up Questionnaire (Appendix 8c),

(iv) Clinically Administered Follow-up Questionnaire (Appendix 8d).

The clinically administered questionnaires should be administered by health professionals.

The VIBRISKS questionnaires were based on questionnaires originally developed within the Vibration Injury Network (VINET), a former EU-funded network involving the current partners. However, the questionnaires were improved based on the experience of the partners. The follow-up questionnaires were newly constructed for the purposes of the longitudinal studies to be performed within VIBRISKS.

The VINET questionnaires have been available on the VINET website and have been accessed by many involved in research and the clinical assessment of vibration-exposed workers. The newly developed VIBRISKS questionnaires have also been made public on the VIBRISKS website and are currently available in English, Italian, and Swedish.

2.1.3.11 References and bibliography

The references to publications used in the development of the protocol are listed in the protocol.

2.1.4 Conclusions

The evolution of the protocol provided a useful focus for discussion among partners, helping to unify understanding of the relevant issues concerned with exposures to hand-transmitted vibration, the diagnostic testing of patients, and the questioning of workers exposed to hand-transmitted vibration. This assisted the studies conducted within workpackage 2 and the collection of data used to form an opinion on dose-response relationships.

The protocol contains valuable guidance for others wishing to undertake epidemiological studies of the effects of hand-transmitted vibration. Just as the protocol grew out of the experience of partners within VINET, it is to be hoped that future collaboration between partners will allow the protocol to be developed further in the future.

2.2 Epidemiological surveys of workers exposed to hand-transmitted vibration

2.2.1 Longitudinal surveys in Italy

This section provides information about the findings of cross-sectional and follow-up studies of HTV exposed workers carried out in Italy over the calendar period 2003-2006. The Clinical Unit of Occupational Medicine, Department of Public Health Sciences, University of Trieste (UTRS), has carried out this longitudinal study of dose-response in HTV-exposed workers in Italy.

2.2.1.1 Objectives

The main objective of this study was to improve knowledge of the dose-response relationship between vibration exposure of the upper limb and development of:

- vascular disorders (vibration-induced white finger, VWF)
- neurological disorders (e.g. numbness, tingling, reduction of manipulative dexterity).

2.2.1.2 Methods

In the cross-sectional survey of 2003-2004, the study populations exposed to hand-transmitted vibration in Italy included two occupational groups:

(i) 221 lumberjacks using chain saws and brush saws, employed in several forestry companies in the Tuscany Region (central Italy) and in the Province of Trento (northern Italy);

(ii) 36 stone processing workers using grinders/cutters, polishers and inline hammers, employed in the Versilia district (Tuscany Region).

The control group included 139 workers unexposed to hand-transmitted vibration (supervisors, inspectors, maintenance operators), who have been recruited from various industrial and public utility activities. They were employed in either the same industrial sectors or the same geographical areas as the vibration-exposed workers.

Overall, 299 HTV-exposed workers were investigated over the follow-up period (2003-2006): of these, 61 men underwent one investigation, 47 two investigations, and 191 three investigations. This last group underwent a complete follow-up. In total, 141 control men were investigated: of these, three men underwent one investigation, 31 two investigations and 107 three investigations. This last group underwent a complete follow-up.

In this section, we illustrate the findings of the epidemiological studies of the HTV-exposed workers and the controls who participated in all three surveys (191 and 107 men, respectively), so that a complete set of repeated clinical and laboratory measurements could be analysed.

Medical investigation

The vibration-exposed workers, as well as the control workers, have been investigated by physicians specialising in Occupational Medicine and Industrial Hygiene. They used the medical procedures given in the document “*Protocol for epidemiological studies of hand-transmitted vibration*” (Annex 1).

The vibration-exposed workers and the control subjects examined in Italy were investigated using the following diagnostic tools:

(a) the VIBRISKS clinically administered questionnaire (see Annex 1);

(b) complete physical examination;

(c) cold test with measurement of finger systolic blood pressures at 30°C and 10°C, by means of a strain-gauge plethysmographic technique (ISO 14835-2, 2005);

(d) manual dexterity by means of the Purdue pegboard test (Lafayette Instrument Company, 1985).

The clinical diagnosis of finger whiteness was made on the basis of (i) a medical history alone using standardised questions included in the VIBRISKS questionnaire, and (ii) the administration of colour charts (Maricq and Weinrich, 1988). The colour charts consist of a series of photographs illustrating various degrees of blanching, cyanosis, or redness of the fingers and hands. The extent of finger blanching attacks was assessed using a scoring system described by Griffin (1990).

The cold test consisted of strain-gauge plethysmographic measurement of the change of systolic blood pressure in a test finger at 10°C ($FSBP_{t,10°}$) as a percentage of the pressure at 30°C ($FSBP_{t,30°}$), corrected for the change of pressure in a reference finger during the examination ($FSBP_{ref,30°} – FSBP_{ref,10°}$) (ISO 14835-2):

$$FSBP\%_{10°} = (FSBP_{t,10°} \times 100)/[FSBP_{t,30°} – (FSBP_{ref,30°} – FSBP_{ref,10°})] \quad (\%)$$

The clinical diagnosis of suspected carpal tunnel syndrome was conducted according to international consensus criteria (Rempel, 1998).

Manipulative dexterity was investigated by means of the Purdue pegboard testing method. The test was administered according to a standardised test procedure (LIC, 1985).

All subjects gave signed informed consent to the study, which was approved by the Local Health Authorities.

Measurement and assessment of vibration exposure

Current and past exposures to hand-transmitted vibration were investigated by means of the VIBRISKS questionnaire (see Annex 1) which includes a section dedicated to workplace assessment in terms of exposures to mechanical factors (types of vibrating tools, daily and cumulative exposure duration for each tool), ergonomic risk factors (e.g. repetitiveness, force, awkward postures) and environmental factors (e.g. exposure to cold).

Vibration was measured on the brush saws and chain saws used by the forestry workers, and on the grinders, polishers and inline hammers used by the stone workers. Vibration measurements were made in the field during real operating conditions performed by skilled workers. Vibration was measured in three orthogonal directions according to the procedure defined by International Standard 5349-1 (ISO, 2001). The root-sum-of-squares of the frequency-weighted (a_{vw}) and unweighted (a_{vuw}) r.m.s. acceleration values for the *x*-, *y*- and *z*-axes (also called the vibration total value) was calculated according to the following formula:

$$a_v = (a_x^2+a_y^2+a_z^2)^{½} \qquad (\mathrm{ms^{-2}\ r.m.s.})$$

Questionnaire data, information obtained by interviewing employees and employers, and company records were used to estimate daily exposure duration and total years of tool use. Moreover, to assess daily vibration exposure duration, direct observations of exposure patterns in the workplace were made by supervisors over an entire week period. They used a stopwatch method to record the actual contact time for which the operator's hands were exposed to vibration from the tools.

Daily vibration exposure was assessed in terms of 8-hour energy-equivalent frequency-weighted or unweighted r.m.s. acceleration magnitude, $A(8)$ ($A_w(8)$ or $A_{uw}(8)$, respectively), according to the European Directive 2002/44/EC on mechanical vibration (EC, 2002):

$$A(8)=a_v(T_e/T_0)^{½} \qquad (\mathrm{ms^{-2}\ r.m.s.})$$

where T_e is the daily duration of exposure to vibration a_v (a_{vw} or a_{vuw}) in hours and T_0 is the reference duration of 8 h.

Using the vibration magnitudes and exposure durations, various alternative measures of cumulative vibration doses were constructed for each subject, according to the following general form (Griffin, Bovenzi and Nelson, 2003):

$$dose = \sum_i [a_i^m t_i]$$

where a_i and t_i are the acceleration magnitude (a_{vw} or a_{vuw} in ms^{-2} r.m.s.) and the total exposure duration (hours) respectively, for tool *i*.

Ergonomic risk factors

Ergonomic stressors at the workplace were investigated by means of the VIBRISKS questionnaire which includes a section dedicated to repetitiveness, force, and awkward postures exerted by the neck, upper arms and back during a typical working day (Annex 1).

Physical load was graded by rating the frequency of manual activities on a 4-point response scale (e.g. lifting loads > 25 kg: ”never”, ”1-4 times”, “5-20 times”, ”more than 20 times”).

Scores for neck-upper arm posture, hand-intensive work, and total ergonomic load were calculated for each subject.

2.2.1.3 Results

Vibration measurements and vibration exposure

The vibration total value of the frequency-weighted or unweighted r.m.s. acceleration magnitude averaged, respectively, 5.7 ms^{-2} (a_{vw}) and 38.6 ms^{-2} (a_{vuw}) for the brush saws, 5.2 to 5.5 ms^{-2} (a_{vw}) and 36.8 to 38.1 ms^{-2} (a_{vuw}) for the chain saws, 4.6 ms^{-2} (a_{vw}) and 82.1 ms^{-2} (a_{vuw}) for the grinders, 1.6 ms^{-2} (a_{vw}) and 18.3 ms^{-2} (a_{vuw}) for the polishers, and 19.5 ms^{-2} (a_{vw}) and 229 ms^{-2} (a_{vuw}) for the inline hammers.

Daily vibration exposure, in terms of $A_w(8)$, $A_{uw}(8)$ and daily exposure time, were significantly greater in the stone workers than in the forestry operators (p<0.001). In the two HTV exposed groups, however, there was a significant reduction in daily vibration exposure over the follow up period, mainly in the forestry workers. When $A_w(8)$ was averaged over time, daily vibration exposure exceeded the EU action value of 2.5 ms^{-2} r.m.s. for the forestry workers (3.8 ms^{-2} r.m.s.), and the EU exposure limit value of 5 ms^{-2} r.m.s. for the stone workers (9.4 ms^{-2} r.m.s.).

Prevalence and incidence of vibration-induced disorders in the upper limbs

Table 2.1 reports the point prevalence, period prevalence and cumulative incidence of disorders in the upper limbs of the controls and the HTV exposed workers. In general, the prevalence ratios for vascular and sensorineural symptoms were significantly greater in the HTV exposed workers than in the controls at both the cross-sectional survey (point prevalence) and over the study period (period prevalence).

Over the calendar period 2004 – 2006, the cumulative incidence of finger tingling was 19.2 *vs* 30.8% in the control and HTV-exposed workers, respectively; 5.1 *vs* 12.9% for finger numbness, 0 *vs* 5.7% for suspected carpal tunnel syndrome, 4.4 *vs* 11.4% for cold fingers/hands, 1.9 *vs* 4.4% for VWF assessed by medical history alone, and 0 *vs* 1.7% for VWF assessed by colour charts. As a result, increased risk ratios (RR) for the cumulative incidence of disorders over the follow-up time were observed in the HTV-exposed workers compared with the controls, even though the 95% confidence intervals show that the increased RRs were not statistically significant.

Dose-response relationships for vibration-induced disorders in the upper limbs

To assess possible exposure-response relationship between alternative measures of vibration dose and health disorders in the upper limbs of the HTV-exposed workers, several longitudinal logistic regression models were explored. To avoid spurious findings, the control workers were excluded from data analysis.

After adjustment for potential confounders, significant associations were found between VWF assessed by either medical history alone or colour charts and various alternative measures of daily and cumulative vibration dose (Tables 2.2 and 2.3).

The Wald test for the odds ratio estimates and the quasi-likelihood under the independence model criterion (QIC) statistic for the comparison between non-nested models suggest that models including daily vibration exposure expressed in terms of $A_{uw}(8)$ fit the data better than those which include $A_w(8)$ as a measure of daily vibration exposure.

Significant associations were found between VWF and alternative measures of cumulative vibration exposure. In general, the measures of vibration dose estimated by combining vibration magnitude and duration of exposure were significant predictors of VWF over the follow-up period. Measures of vibration dose determined solely by lifetime exposure duration were either not associated with VWF (years of exposure) or performed worse (total hours of tool use) for the prediction of the vascular outcome. Moreover, regression models seem to suggest that dose measures with high powers of acceleration (i.e. $\Sigma a_i^m t_i$ with $m > 1$) performed substantially better, at least from a statistical viewpoint, for the prediction of VWF over the follow-up period than other measures of lifetime cumulative vibration exposure. Minor differences between doses derived from unweighted acceleration or frequency-weighted acceleration were observed when the data were modelled according to transition models. A preference for vibration doses derived from unweighted acceleration may be noted when regression models were applied to data.

The relations between sensorineural disorders (tingling, numbness, suspected carpal tunnel syndrome) and measures of daily and cumulative vibration doses were less evident than those observed for vascular symptoms (VWF). The pattern of the odds ratios and the information measures of overall model fitting do not suggest a clear preference for a particular measure of either daily vibration exposure ($A_w(8)$ or $A_{uw}(8)$) or cumulative vibration dose with different powers of acceleration magnitude, even though a better fit may be observed for dose measures with high powers of acceleration. Similarly to the findings for vascular symptoms, no or weak associations were found between sensorineural disorders and lifetime exposure duration (years of exposure or total operating time with vibrating tools).

After adjustment for personal characteristics, vibration exposure, and survey, multivariate regression analysis showed no significant effects of ergonomic risk factors (neck-upper arm posture, hand-intensive work, and total ergonomic score) on the occurrence of vascular, sensorineural, and suspected CTS in the HTV exposed workers.

Finger systolic blood pressure indices during local cooling

In general, a trend for an increasing cold response of the digital arteries with the increase in the severity of VWF symptoms assessed by Griffin's score method was observed in both the cross-sectional survey and the two follow-up investigations (Table 2.4). The vibration-exposed workers with moderate VWF (blanching score 13 – 24) and severe VWF (blanching score > 24) showed an increased cold-induced hyperreactivity in the digital arteries when compared with the control workers and the HTV-exposed workers with no vascular symptoms (p<0.001). A multiple comparison test showed no significant differences in the FSBP indices at 10°C between the controls, the asymptomatic HTV-exposed workers and those with mild VWF (blanching score 1 – 12), even though these latter exhibited a greater responsiveness to cold than the other two groups.

Dose-effect relationship for cold provocation of the digital arteries

Tables 2.4 and 2.5 report the results of regression analysis aimed at investigating possible dose-effect relationships for the cold response of digital arteries in the HTV workers. To avoid spurious findings, the control subjects were excluded from data analysis.

After adjustment for several covariates, cold-induced digital vasoconstriction during the follow-up period was related to some measures of vibration exposure. Regression models which include $A_{uw}(8)$ as a predictor variable are associated with better model fitting than models in which daily vibration exposure is expressed as $A_w(8)$. The measures of cumulative vibration dose estimated by combining vibration magnitude and duration of exposure were significant predictors of the increased vasoconstrictor response to cold (i.e. reduction of FSBP%$_{10°}$) in the HTV-exposed workers. Measures of vibration dose determined solely by lifetime exposure duration, such as years of exposure or total hours of tool use, were less strongly associated with FSBP%$_{10°}$ over the follow up period, mainly when transition models were fitted to data. Dose measures with high powers of acceleration (i.e. $\Sigma a_i^m t_i$ with $m > 1$) performed better for the prediction of the vasoconstrictor response to cold during follow up than other measures of lifetime cumulative vibration exposure.

Manipulative dexterity

In the cross-sectional survey, Purdue pegboard scores (dominant hand, non-dominant hand, both hands, sum of hand scores, and assembly) were significantly lower in the HTV-exposed workers than in the control workers ($0.001<p<0.05$). No difference was found between the stone workers and the forestry operators.

Over the one-year follow-up period, Purdue pegboard scores were found to be inversely related to age ($p<0.001$), use of vibratory tools ($0.001<p<0.05$), and smoking habit ($p<0.05$ for the dominant hand). In the total sample, Purdue pegboard scores tended to improve over the follow-up time ($0.001<p<0.05$).

After adjusting for individual characteristics and follow-up time, random-intercept linear regression analysis showed that Purdue pegboard scores for the dominant hand, non-dominant hand and both hands decreased with the increase of cumulative vibration dose (Table 2.6). The reduction of assembly score (i.e. number of pins, collars, and washers assembled in a 60-second period) was significantly associated with the increase in cumulative vibration dose and ergonomic stress (neck-upper arm posture, hand-intensive work, total ergonomic score). There was no significant interaction between vibration exposure and ergonomic risk factors.

2.2.1.4 Discussion

In this prospective cohort study of the health effects of hand-transmitted vibration, a greater occurrence of upper limb disorders was observed in HTV exposed workers than in control men, at both the cross-sectional survey and over a two-year follow-up period. The point and period prevalences and the cumulative incidence of peripheral sensorineural and vascular symptoms were found to be about two to four times higher in the vibration-exposed group than in the control group. An increased risk for musculoskeletal symptoms of the upper extremities was also observed in the HTV-exposed workers, even though to a lesser extent when compared to that found for neurovascular disorders.

The findings of two laboratory tests, i.e. a standardised cold test with measurement of finger systolic blood pressure and the Purdue pegboard test, showed that over the study period there was a deterioration of the vascular function and the manipulative dexterity in the HTV-exposed workers compared with the controls. This study suggests that measurement of FSBP after local cooling and the Purdue pegboard test are helpful laboratory tools to monitor prospective vascular and sensory dysfunction respectively, in vibration-exposed workers.

Of the several measures of daily vibration exposure ($A(8)$) and lifetime cumulative vibration dose ($\Sigma a_i^m t_i$) used in this longitudinal study, those derived from unweighted acceleration magnitude gave better predictions for symptoms and signs of vibration-induced disorders than measures derived from acceleration magnitude frequency-weighted according to current standards.

In this study, measures of cumulative vibration dose estimated by combining vibration magnitude and duration of exposure provided better predictions of the occurrence of upper limb disorders than doses determined solely by lifetime exposure duration (years of exposure or total hours of tool use). Moreover, some statistical measures of information showed that regression models including dose measures with high powers of acceleration (i.e. $\Sigma a_i^m t_i$ with $m > 1$) provided better fits to data that those with other measures of lifetime cumulative vibration exposure.

2.2.1.5 Conclusions

In this study, the relationships between alternative measures of daily and cumulative exposures to hand-transmitted vibration (taking account of vibration magnitude, exposure duration and frequency of vibration) and the development of neurovascular disorders were investigated.

Multivariate analysis of health and exposure data showed that after adjustment for potential confounders there was evidence for a dose-response relationship for sensorineural and vascular symptoms in the HTV-exposed worker group. There was also evidence for a dose-effect relationship for cold-induced digital arterial hyperresponsiveness and for impairment to manual dexterity over time.

The results of this prospective cohort study of vibration-exposed workers suggest that improvements are possible to both the frequency weighting and the time-dependency used in current standards to predict the development of vibration-induced disorders.

Detailed information about the findings of longitudinal studies of HTV-exposed workers in Italy is reported in Annex 2.

Table 2.1 Prevalence and incidence of peripheral sensorineural and vascular disorders in the controls (n=107) and the HTV exposed workers (n=191) over the follow up period (2003-2006) in Italy. Data are given as numbers (%). Crude prevalence ratio (PR), risk ratio (RR) and 95% confidence intervals are shown.

Disorder		Prevalence at cross-sectional (2003-04) (%)	Period prevalence (2003-2006) (%)	Cumulative incidence (2004-2006) (%)
Finger tingling (all subjects)	Controls	12.2	29.0	19.2
	HTV workers	45.6	62.3	30.8
		PR 3.75 (2.20-6.39)	PR 2.15 (1.57-2.95)	RR 1.61 (0.97-2.66)
Finger tingling (without CTS cases)[1]	Controls	10.5	27.6	19.2
	HTV workers	38.9	56.4	28.7
		PR 2.68 (1.50-4.78)	PR 2.04 (1.46-2.86)	RR 1.50 (0.89-2.51)
Finger numbness (all subjects)	Controls	7.5	12.2	5.1
	HTV workers	27.2	36.7	12.9
		PR 3.64 (1.80-7.37)	PR 3.02 (1.75 -5.19)	RR 2.56 (0.98-6.67)
Finger numbness (without CTS cases)[1]	Controls	6.7	11.4	5.1
	HTV workers	21.2	30.3	11.5
		PR 3.18 (1.47-6.90)	PR 2.65 (1.48-4.74)	RR 2.26 (0.85-6.01)
Suspected CTS	Controls	1.9	1.9	0
	HTV workers	8.4	13.6	5.7
		PR 4.48 (1.05-19.1)	PR 7.28 (1.76-30.1)	RR +Inf. (1.47 - +Inf.)*
Cold fingers/hands	Controls	14.0	17.8	4.4
	HTV workers	17.3	26.7	11.4
		PR 1.23 (0.70-2.16)	PR 1.50 (0.94-2.41)	RR 2.62 (0.91-7.51)
VWF (medical history)	Controls	3.7	5.6	1.9
	HTV workers	17.3	20.9	4.4
		PR 4.62 (1.68-12.7)	PR 3.74 (1.64-8.52)	RR 2.28 (0.48-10.8)
VWF (colour charts)[2]	Controls	2.6	2.6	0
	HTV workers	10.7	12.2	1.7
		PR 4.06 (0.95-17.4)	PR 4.52 (1.07-19.1)	RR +Inf. (0.36 - +Inf.)*

[1]based on 105 controls and 165 HTV workers; [2]based on 74 controls and 131 HTV workers

*exact 95% confidence interval

Table 2.2 Odds ratios (robust 95% confidence intervals), adjusted by age, smoking, drinking, and survey, for the association between vibration induced disorders, daily vibration exposure and exposure duration in the HTV exposed workers (n=191) over with the follow up period (2003-2006). The generalised estimating equations (GEE) method (standard model) was used to account for correlation between repeated measures within subject during the follow up period. The increase in the odds ratio (OR) for each one unit of increase in vibration dose is shown. The Wald test (p-value) for the OR estimates and the Quasi-likelihood under the Independence model Criterion (QIC) for the comparison between non-nested logistic regression models are also reported. VWF is vibration-induced white finger. CTS is carpal tunnel syndrome. See text for the definition of *A*(8).

Vibration exposure	Health outcomes				
	VWF (medical history)	VWF§ (colour charts)	Tingling	Numbness	Suspected CTS
$A_w(8)$ current (ms^{-2})	**1.15 (1.09 – 1.22)** 24.9 (p<0.0001) QIC=452.9	**1.17 (1.09 – 1.25)** 19.1 (p<0.0001) QIC=211.2	1.03 (0.97 – 1.10) 1.1 (p=0.28) QIC=760.1	1.05 (0.99 – 1.12) 2.7 (p=0.10) QIC=705.8	**1.15 (1.05 – 1.27)** 8.6 (p=0.003) QIC=296.2
$A_{uw}(8)$ current ($ms^{-2} \times 10^{-1}$)	**1.15 (1.09 -1.22)** 29.1 (p<0.0001) QIC=442.3*	**1.16 (1.09 – 1.24)** 25.1 (p<0.0001) QIC=195.9*	**1.07 (1.01 – 1.13)** 4.7 (p=0.03) QIC=752.9*	**1.06 (1.00 – 1.13)** 4.2 (p=0.042) QIC=704.2	**1.11 (1.03 – 1.19)** 7.7 (p=0.006) QIC=296.9
$A_w(8)$ max (ms^{-2})	**1.12 (1.07 – 1.18)** 20.9 (p<0.0001) QIC=471.5	**1.12 (1.07 – 1.18)** 24.0 (p<0.0001) QIC=226.4	1.06 (0.99 – 1.13) 3.5 (p=0.06) QIC=758.7	**1.06 (1.02 – 1.11)** 7.7 (p=0.006) QIC=702.3*	**1.08 (1.00 – 1.17)** 4.0 (p=0.046) QIC=295.6*
$A_{uw}(8)$ max ($ms^{-2} \times 10^{-1}$)	**1.14 (1.08 – 1.19)** 28.2 (p<0.0001) QIC=454.3	**1.14 (1.09 – 1.20)** 35.2 (p<0.0001) QIC=197.7	1.05 (0.98 – 1.12) 1.8 (p=0.19) QIC=758.4	**1.05 (1.00 – 1.10)** 4.2 (p=0.039) QIC=706.1	1.05 (0.99 – 1.11) 2.6 (p=0.10) QIC=297.8
Exposure duration (yrs)	1.03 (0.98 – 1.09) 1.3 (p=0.25) QIC=524.6	1.02 (0.95 – 1.11) 0.3 (p=0.56) QIC=297.1	1.01 (0.97 – 1.05) 0.3 (p=0.58) QIC=772.4	0.97 (0.93 – 1.01) 2.1 (p=0.15) QIC=719.5	1.04 (0.98 – 1.10) 1.5 (p=0.22) QIC=299.5

§based on 131 HTV workers; *better fitting model

Table 2.3 Odds ratios (robust 95% confidence intervals), adjusted by age, smoking, drinking, and survey, for the association between vibration induced disorders and alternative measures of vibration exposure in the HTV exposed workers (n=191) over with the follow up period (2003-2006). The generalised estimating equations (GEE) method (standard model) was used to account for correlation between repeated measures within subject during the follow up period. The increase in the odds ratio (OR) for each one unit of increase in log vibration dose is shown. The Wald test (p-value) for the OR estimates and the Quasi-likelihood under the Independence model Criterion (QIC) for the comparison between non-nested logistic regression models are also reported. VWF is vibration-induced white finger. CTS is carpal tunnel syndrome.

Dose definition	Health outcomes				
	VWF (medical history)	VWF§ (colour charts)	Tingling	Numbness	Suspected CTS
Dose 1 (Σt_i, ln(hours))	**1.78 (1.23 – 2.56)** 9.6 (p=0.002) QIC=497.4	**3.47 (1.67 – 7.22)** 11.1 (p=0.001) QIC=250.9	1.14 (0.93 – 1.40) 1.54 (p=0.22) QIC=765.0	1.29 (0.98 -1.68) 3.4 (p=0.07) QIC=718.7	1.37 (0.97 – 1.92) 3.2 (p=0.08) QIC=296.6
Dose 2 ($\Sigma a_{hwvi} t_i$, ln($ms^{-2}h$))	**1.98 (1.37 – 2.87)** 13.2 (p<0.0001) QIC=481.4	**3.10 (1.80 – 5.35)** 16.6 (p<0.0001) QIC=255.9	1.21 (0.98 – 1.49) 3.0 (p=0.08) QIC=760.3	1.29 (0.99 – 1.67) 3.7 (p=0.06) QIC=714.7	**1.43 (1.01 – 2.03)** 4.2 (p=0.041) QIC=294.5
Dose 3 ($\Sigma a_{hwvi}^2 t_i$, ln($m^2s^{-4}h$))	**1.78 (1.33 – 2.39)** 15.0 (p<0.0001) QIC=476.6	**2.53 (1.70 – 3.78)** 20.6 (p<0.0001) QIC=190.0	**1.24 (1.01 – 1.51)** 4.3 (p=0.04) QIC=757.0	**1.25 (1.00 – 1.57)** 3.9 (p=0.048) QIC=713.8	**1.39 (1.02 – 1.90)** 4.4 (p=0.036) QIC=294.0
Dose 4 ($\Sigma a_{hwvi}^4 t_i$, ln($m^4s^{-8}h$))	**1.33 (1.11 -1.60)** 9.6 (p=0.002) QIC=493.5	**2.67 (1.54 – 4.61)** 12.3 (p<0.001) QIC=202.5	**1.17 (1.01 – 1.35)** 4.6 (p=0.03) QIC=758.7	1.12 (0.97 – 1.28) 2.5 (p=0.12) QIC=714.8	**1.26 (1.02 – 1.55)** 4.6 (p=0.032) QIC=294.2
Dose 5 ($\Sigma a_{huwvi} t_i$, ln($ms^{-2}h$))	**1.65 (1.27 – 2.16)** 14.1 (p<0.0001) QIC=480.5	**4.28 (1.84 – 9.97)** 11.4 (p=0.001) QIC=207.3	1.18 (0.99 – 1.40) 3.5 (p=0.06) QIC=759.7	**1.25 (1.02 – 1.55)** 4.5 (p=0.035) QIC=716.6	1.26 (0.99 – 1.61) 4.4 (p=0.064) QIC=296.1
Dose 6 ($\Sigma a_{huwvi}^2 t_i$, ln($m^2s^{-4}h$))	**1.49 (1.22 – 1.82)** 15.0 (p<0.0001) QIC=475.4*	**3.11 (1.50 – 6.49)** 9.2 (p=0.002) QIC=188.9	**1.19 (1.03 – 1.38)** 5.4 (p=0.02) QIC=754.9	**1.22 (1.04 – 1.44)** 5.9 (p=0.015) QIC=714.1	**1.24 (1.03 – 1.48)** 5.3 (p=0.021) QIC=294.1)
Dose 7 ($\Sigma a_{huwvi}^4 t_i$, ln($m^4s^{-8}h$))	**1.27 (1.11 - 1.45)** 12.3 (p<0.0001) QIC=479.7	**1.94 (1.29 – 2.90)** 10.3 (p=0.001) QIC=179.9*	**1.14 (1.03 – 1.25)** 6.5 (p=0.011) QIC=754.0*	**1.13 (1.02 – 1.26)** 5.8 (p=0.016) QIC=713.2*	**1.16 (1.03 – 1.31)** 6.1 (p=0.014) QIC=293.5*

§based on 131 HTV workers; *better fitting model

Table 2.4 Marginal linear regression of FSBP$\%_{10^\circ}$ on either daily vibration exposure or exposure duration in the HTV exposed workers (n=191) over with the follow up period (2003-2006). The estimated regression coefficients (robust 95% confidence intervals) are given. The generalised estimating equations (GEE) method (standard or transition models) was used to account for correlation between repeated measures within subject during the follow up period. The Wald test (p-value) for the regression coefficients and the Quasi-likelihood under the Independence model Criterion (QIC) for the comparison between non-nested linear regression models are also given.

Vibration exposure	Model 1	Model 2	Model 3	Model 4
	(standard GEE)	(standard GEE)	(transition GEE)	(transition GEE)
$A_w(8)$ current (ms^{-2})	**-2.1 (-3.1 – -1.2)**	**-2.0 (-2.8 – -1.1)**	**-1.6 (-2.3 – -0.8)**	**-1.5 (-2.2 – -0.7)**
	21.0 (p<0.0001)	20.0 (p<0.0001)	17.6 (p<0.0001)	14.4 (p<0.0001)
	QIC=246479	QIC=237039	QIC=128819	QIC=128454
$A_{uw}(8)$ current ($ms^{-2} \times 10^{-1}$)	**-2.0 (-2.8 – -1.2)**	**-1.8 (-2.6 – -1.1)**	**-1.3 (-1.9 – -0.7)**	**-1.2 (-1.9 – -0.6)**
	24.3 (p<0.0001)	22.5 (p<0.0001)	17.6 (p<0.0001)	14.4 (p<0.0001)
	QIC=240344*	QIC=232918*	QIC=128177*	QIC=127867*
$A_w(8)$ max (ms^{-2})	**-1.9 (-2.6 – -1.2)**	**-1.8 (-2.4 – -1.1)**	**-1.2 (-1.8 – -0.7)**	**-1.2 (-1.7 – -0.6)**
	26.8 (p<0.0001)	26.3 (p<0.0001)	18.1 (p<0.0001)	15.9 (p<0.0001)
	QIC=250097	QIC=239019	QIC=130023	QIC=129020
$A_{uw}(8)$ max ($ms^{-2} \times 10^{-1}$)	**-1.8 (-2.5 – -1.1)**	**-1.7 (-2.4 – -0.9)**	**-1.1 (-1.7 – -0.5)**	**-1.0 (-1.6 – -0.5)**
	22.8 (p<0.0001)	20.8 (p<0.0001)	14.6 (p<0.0001)	12.3 (p<0.0001)
	QIC=241349	QIC=233222	QIC=129625	QIC=128998
Exposure duration (yrs)	-0.4 (-0.8 – -0.03)	-0.4 (-0.7 – -0.03)	-0.05 (-0.3 – 0.2)	-0.05 (-0.3 – 0.2)
	4.4 (p=0.036)	4.5 (p=0.034)	0.14 (p=0.71)	0.1 (p=0.71)
	QIC=289541	QIC=267068	QIC=138859	QIC=136906

Model 1: adjusted by age, smoking, drinking, and survey;
Model 2: adjusted by age, smoking, drinking, survey, and VWF score
Model 3: adjusted by age, smoking, drinking, survey, and FSBP$\%_{10^\circ}$ at time-point *t*–1
Model 4: adjusted by age, smoking, drinking, survey, VWF score and FSBP$\%_{10^\circ}$ at time-point *t*–1
*best fitting model

Table 2.5 Marginal linear regression of FSBP%$_{10°}$ on alternative measures of vibration exposure in the HTV exposed workers (n=191) over with the follow up period (2003-2006). The estimated regression coefficients (robust 95% confidence intervals) are given. The generalised estimating equations (GEE) method (standard or transition models) was used to account for correlation between repeated measures within subject during the follow up period. The Wald test (p-value) for the regression coefficients and the the Quasi-likelihood under the Independence model Criterion (QIC) for the comparison between non-nested linear regression models are also reported.

Dose definition	Model 1 (standard GEE)	Model 2 (standard GEE)	Model 3 (transition GEE)	Model 4 (transition GEE)
Dose 1 (Σt_i, ln(hours))	**-3.3 (-5.9 – -0.7)** 6.3 (p=0.012) QIC=283294	**-2.8 (-5.2 – -0.4)** 5.3 (p=0.022) QIC=264285	-1.6 (-3.4 – 0.2) 2.9 (p=0.09) QIC=137555	-1.4 (-3.2 – 0.5) 2.1 (p=0.15) QIC=135980
Dose 2 ($\Sigma a_{hwvi} t_i$, ln(ms^{-2}h))	**-5.3 (-8.0 – -2.6)** 15.0 (p<0.0001) QIC=268520	**- 4.7 (-7.1 – -2.2)** 14.2 (p<0.0001) QIC=253492	**-2.8 (-4.5 – -0.7)** 7.0 (p=0.008) QIC=135591	**-2.3 (-4.2 – -0.4)** 5.5 (p=0.019) QIC=134293
Dose 3 ($\Sigma a_{hwvi}^2 t_i$, ln(m^{2}s^{-4}h))	**-5.9 (-8.2 – -3.6)** 24.6 (p<0.0001) QIC=254661	**-5.3 (-7.4 – -3.2)** 24.9 (p<0.0001) QIC=242163	**-2.8 (-4.5 – -1.1)** 10.7 (p=0.001) QIC=134163	**-2.6 (-4.3 – -0.9)** 8.8 (p=0.003) QIC=132926
Dose 4 ($\Sigma a_{hwvi}^4 t_i$, ln(m^{4}s^{-8}h))	**-4.1 (-5-6 – -2.7)** 29.8 (p<0.0001) QIC=250190	**-3.8 (-5.1 – -2.5)** 31.7 (p<0.0001) QIC=236508	**-1.8 (-2.8 – -0.8)** 12.3 (p<0.0001) QIC=134459	**-1.7 (-2.8 – -0.7)** 10.4 (p=0.001) QIC=132881
Dose 5 ($\Sigma a_{huwvi} t_i$, ln(ms^{-2}h))	**-4.5 (-6.7 – -2.3)** 15.8 (p<0.0001) QIC=265069	**-4.0 (-6.0 – -2.0)** 15.1 (p<0.0001) QIC=250893	**-2.2 (-3.8 – -0.6)** 7.5 (p=0.006) QIC=135040	**-2.0 (-3.7 – -0.4)** 5.9 (p=0.015) QIC=133820
Dose 6 ($\Sigma a_{huwvi}^2 t_i$, ln(m^{2}s^{-4}h))	**-4.3 (-6.0 – -2.5)** 22.9 (p<0.0001) QIC=252809	**-3.9 (-5.5 – -2.3)** 22.8 (p<0.0001) QIC=241012	**-2.1 (-3.5 – -0.8)** 10.1 (p=0.001) QIC=133571	**-2.0 (-3.4 – -0.6)** 8.1 (p=0.004) QIC=132462
Dose 7 ($\Sigma a_{huwvi}^4 t_i$, ln(m^{4}s^{-8}h))	**-3.0 (-4.1 – -1.9)** 28.5 (p<0.0001) QIC=246265*	**-2.7 (-3.7 – -1.7)** 29.3 (p<0.0001) QIC=234926*	**-1.4 (-2.2 – -0.6)** 11.9 (p=0.001) QIC=133353*	**-1.3 (-2.2 – -0.5)** 9.4 (p=0.002) QIC=132151*

Model 1: adjusted by age, smoking, drinking, and survey;

Model 2: adjusted by age, smoking, drinking, survey, and VWF score

Model 3: adjusted by age, smoking, drinking, survey, and FSBP%$_{10°}$ at time-point *t*–1

Model 4: adjusted by age, smoking, drinking, survey, VWF score and FSBP%$_{10°}$ at time-point *t*–1

*best fitting model

Table 2.6 Random-intercept linear regressions of Purdue pegboard scores on ergonomic risk factors and cumulative vibration dose in the study population (n=179) over one-year follow up time. Maximum likelihood estimates of regression coefficients (95% confidence intervals) are adjusted by age, smoking, drinking and follow up time, assuming no exposure to vibration and no/very low exposures to ergonomic stress as the reference categories. *p<0.05; †p<0.01; ‡p<0.001

	Dominant hand	Non-dominant hand	Both hands	Sum of hand scores	Assembly
Model 1					
Neck-upper arm posture					
Low (score 4 – 7)	-0.2 (-0.7 – 0.3)	0.2 (-0.3 – 0.7)	-0.2 (-0-7 – 0.3)	-0.2 (-1.4 – 0.9)	-1.9 (-3.6 – -0.2)*
Medium (score 8 – 10)	-0.1 (-0.6 – 0.5)	0.3 (-0.3 – 0.8)	-0.1 (-0.7 – 0.4)	-0.3 (-1.5 – 1.0)	-3.5 (-5.3 – -1.7)‡
Hard (score 11 – 12)	-0.1 (-0.7 – 0.6)	0.1 (-0.6 – 0.7)	-0.3 (-0.9 – 0.3)	-0.4 (-1.9 – 1.1)	-3.3 (-5.4 – -1.1)†
Vibration dose ($m^2s^{-4}h \times 10^3$)					
Low (0.1 – 1.8)	-0.4 (-1.1 – 0.2)	-0.5 (-1.1 – 0.2)	-0.6 (-1.2 – -0.1)*	-1.5 (-3.1 – 0.03)	-2.4 (-4.6 – -0.3)*
Medium (1.9 – 6.0)	-0.8 (-1.4 – -0.1)*	-0.7 (-1.4 – -0.1)*	-0.8 (-1.4 – -0.2)†	-2.2 (-3.8 – -0.5)†	-3.7 (-6.0 – -1.5)‡
Hard (6.1 – 140)	-1.1 (-1.7 – -0.5)‡	-0.8 (-1.4 – -0.2)†	-1.1 (-1.6 – -0.5)‡	-3.2 (-4.7 – -1.7)‡	-2.2 (-4.2 – -0.2)*
Model 2					
Hand-intensive work					
Low (score 4 – 6)	0.1 (-0.4 – 0.6)	0.2 (-0.3 – 0.7)	0.1 (-0.4 – 0.6)	0 (-1.1 – 1.2)	-1.7 (-3.3 – -0.1)*
Medium (score 7 – 9)	-0.5 (-1.1 – 0.1)	0.2 (-0.4 – 0.8)	-0.1 (-0.6 – 0.5)	-0.2 (-1.5 – 1.1)	-2.8 (-4.7 – -0.9)†
Hard (score 10 – 15)	-0.3 (-0.9 – 0.4)	-0.1 (-0.7 – 0.6)	-0.2 (-0.8 – 0.4)	-0.2 (-1.7 – 1.3)	-2.4 (-4.6 – -0.2)*
Vibration dose ($m^2s^{-4}h \times 10^3$)					
Low (0.1 – 1.8)	-0.3 (-0.9 – 0.4)	-0.4 (-1.0 – 0.3)	-0.6 (-1.2 – 0.1)	-1.3 (-3.0 – 0.4)	-2.0 (-4.3 – 0.4)
Medium (1.9 – 6.0)	-0.5 (-1.2 – 0.2)	-0.7 (-1.4 – -0.1)*	-0.8 (-1.4 – -0.2)†	-2.0 (-3.6 – -0.4)*	-3.3 (-5.5 – -1.1)†
Hard (6.1 – 140)	-0.9 (-1.5 – -0.2)*	-0.9 (-1.6 – -0.2)†	-1.0 (-1.6 – -0.4)†	-3.4 (-5.1 – -1.8)‡	-2.0 (-4.3 – 0.3)
Model 3					
Total ergonomic score					
Low (score 13 – 25)	0.4 (-0.2 – 0.9)	0.5 (0 – 1.1)	0.1 (-0.4 – 0.6)	0.8 (-0.4 – 1.9)	-1.5 (-3.3 – 0.2)
Medium (score 26 – 35)	-0.1 (-0.8 – 0.5)	0.2 (-0.5 – 0.8)	-0.1 (-0.7 – 0.5)	-0.7 (-2.2 – 0.9)	-3.1 (-5.3 – -0.9)†
Hard (score 36 – 57)	0 (-0.8 – 0.8)	0.3 (-0.5 – 1.1)	0.1 (-0.7 – 0.8)	-0.4 (-2.2 – 1.3)	-3.0 (-5.5 – -0.4)*
Vibration dose ($m^2s^{-4}h \times 10^3$)					
Low (0.1 – 1.8)	-0.4 (-1.1 – 0.4)	-0.4 (-1.1 – -0.4)	-0.6 (-1.3 – 0)	-1.0 (-2.8 – 0.8)	-2.1 (-4.6 – 0.4)
Medium (1.9 – 6.0)	-0.6 (-1.4 – 0.1)	-0.7 (-1.4 – 0)	-0.9 (-1.6 – -0.2)†	-1.8 (-3.5 – -0.1)*	-3.1 (-5.5 – -0.6)*
Hard (6.1 – 140)	-1.0 (-1.7 – -0.2)†	-0.9 (-1.6 – -0.2)†	-1.1 (-1.7 – -0.4)‡	-2.9 (-4.6 – -1.2)‡	-1.1 (-3.4 – 1.3)

2.2.2 Longitudinal surveys in Sweden

2.2.2.1 Introduction

Recognition of the extent of the problems from exposures to hand-transmitted vibration is relatively recent and still growing in importance. The ability to combat the problems so as to reduce the risks and social consequences of injury without excessive economic consequences requires a refined understanding of the combination of factors resulting in injury so as to improve risk assessment.

Although there are standardised methods of assessing the severity of vibration exposures, they are not based on epidemiological evidence or on an understanding of the relevant mechanisms of injury and they are not satisfactory methods for predicting the risks of injury. Notwithstanding these limitations, the EU Machinery Safety Directive and the Physical Agents Directive require the use of existing methods to quantify the vibration on tools and machines, limit exposures to vibration at work and decide on the provision of health surveillance.

Prolonged exposure to hand-transmitted vibration from powered tools or processes is associated with an increased occurrence of symptoms and signs of disorders in the vascular, neurological and musculoskeletal systems of the upper limbs. This group of disorders is called *hand-arm vibration syndrome (HAVS)*. The vascular component of the hand-arm vibration syndrome is represented by a secondary form of Raynaud's phenomenon known as vibration-induced white finger (VWF). The neurological component is characterised by a peripheral, diffusely distributed neuropathy with predominant sensory impairment. The musculoskeletal component includes upper limb muscle and tendon

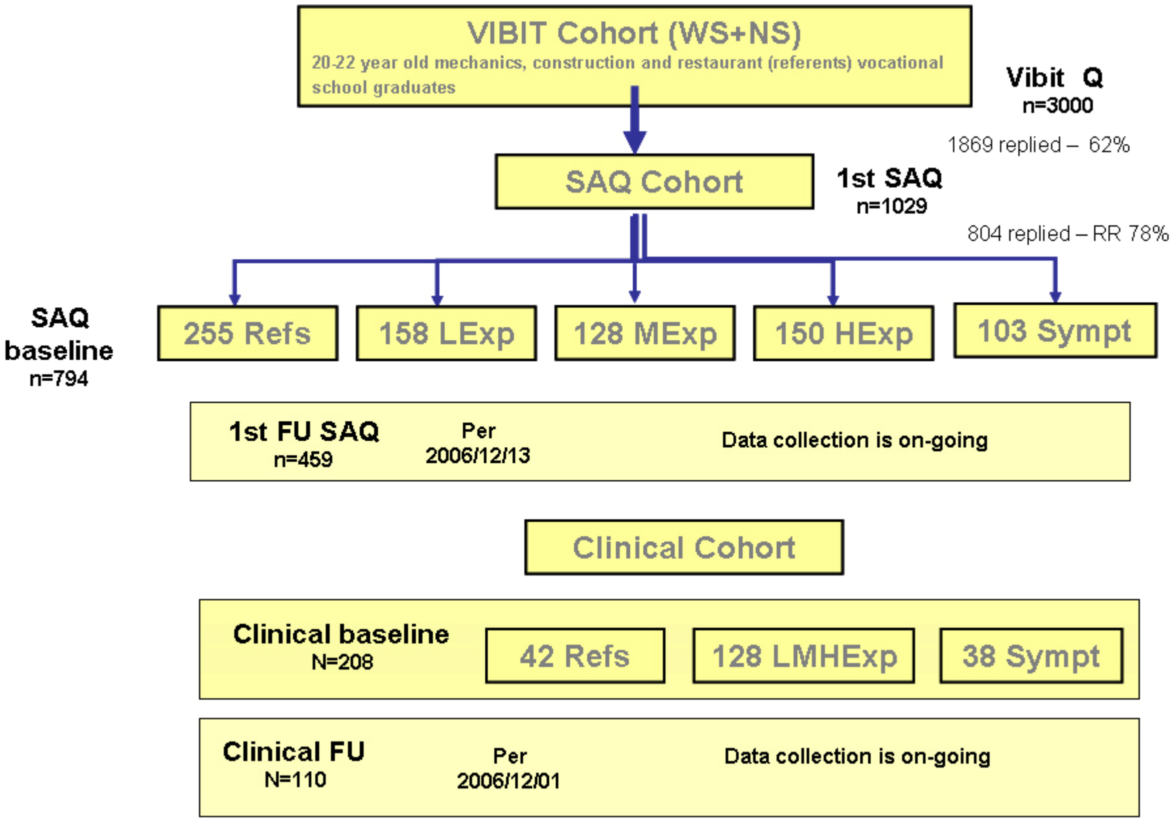

Figure 2.2 Swedish cohorts. WS= Western Sweden, NS= Northern Sweden. Q=questionnaire. LExp= low hand-transmitted vibration exposed, MExp= median hand-transmitted vibration exposed, HExp= high hand-transmitted vibration exposed. Sympt= workers with tingling or colour changes of fingers in Vibit questionnaire. FU= follow up.

disorders and has been reported in workers who use hand-held vibrating tools as well as in nerve trunk entrapment syndromes. Despite the large number of studies published in the relevant literature, the form of the exposure-response relationship for HAVS is not yet clear. There are still significant uncertainties related to the choice of reliable clinical tests for an accurate diagnosis of the different components of HAVS.

2.2.2.2 Objectives

The objective of the surveys was to improve knowledge of the dose-response relationship between vibration exposure and development of (a) vascular disorders (VWF) and (b) neurological disorders (e.g. numbness, tingling and elevated vibrotactile and thermotactile thresholds) of the upper limb.

2.2.2.3 Methods

The Swedish study group, surveyed by Partner 4 (UMUH), consists of students that had graduated from vocational high schools in 2001, 2002 and in 2003 in northern and western Sweden. The occupations of the participants were construction, auto-mechanics and restaurant workers (originally 3000 were asked). A short screening self-administered questionnaire, with questions comparable to the VIBRISK self-administered questionnaire (WP2-N8) but less detailed was used (Annex 3). A study base of 1868 young workers (1561 men and 307 women) who answered the screening questionnaire was used as the base for setting up the Swedish VIBRISKS HTV cohorts. The cohort of 1868 young workers with different levels of HTV exposure (1561 men and 307 women) is referred to in the following sections as the Vibit-cohort.

A total 1029 workers from the Vibit-cohort were given a baseline questionnaire which was a Swedish translation of the VIBRISKS self-administered questionnaire (SAQ) developed within WP1 (i.e VIBRISKS Working documents WP4-N12 and WP4-N8, respectively). The 1029 workers were those from the Vibit-cohort that had answered yes to a question whether they volunteered to participate in further research studies. This questionnaire was answered by 804 workers (response rate: 78%). Of these, some were returned due to untraceable individual addresses and some declared that they did not want to participate in the study. Thus, 794 young workers were included in the final Swedish SAQ HTV cohort.

From the Vibit-cohort, 208 young workers were enlisted in a clinical assessment cohort according to the work plan. In the following sections this group is referred to as the Swedish Clinical HTV cohort. These young workers had different levels of HTV exposures. Effect

Table 2.7 Characteristics of the study population "young workers" (VIBIT cohort Sweden cross-sectional survey). Data are given as medians and range (lowest-highest) or numbers (%).

	Controls men	HTV exposed men	Controls women	HTV exposed women
Number of persons	498	1060	204	102
Age (yrs)	21 (19-27)	21 (19-27)	21 (18-24)	20 (18-26)
Height (cm)	180 (165-196)	182 (165-197)	167 (150-184)	167 (150-185)
Weight (kg)	77 (55-118)	78 (65-116)	62 (44-102)	62 (45-115)
BMI (Kg/m^2)	23,6 (17,8-35,1)	23,6 (18,2-35,1)	22,3 (16,6-38,7)	22,1 (17,2-39,1)
Smokers (n)	74 (15%)	151 (14%)	51 (25%)	33 (32%)
Total abstainers of alcohol (n)	46 (9%)	61 (6%)	7 (3%)	5 (6%)
Daily HTV exposure (min)	0	45 (1-540)	0	20 (1-480)

measurements, which included physical examination and testing, were conducted (finger systolic blood pressure (FSP), thermal perception thresholds, vibrotactile perception thresholds, monofilament, Purdue dexterity test, Jamar test, pinch strength). Physical examinations were conducted in line with a Swedish version of the clinically administrated questionnaire developed in WP1, i.e. VIBRISK Working Document WP1-N13 and WP4-N7. Assessment of exposure was based on individual interviews. The raw data collection was completed during 2005 and data evaluation and statistical analysis (with SPSS and SAS) is ongoing. The follow-up of these 208 workers was conducted September to December 2006.

Figure 2.2 illustrates the break-down of the Swedish cohorts.

2.2.2.4 Results

Results from the VIBIT cohort

The screening questionnaire was completed by 1868 respondents (1561 men and 307 women). The median age of the respondents was the same for the exposed and non-exposed (controls) men and women (Table 2.7). The range of daily exposure among the HTV exposed had a large range (Table 2.8). Thus it was possible to enlist workers with different levels in the 208 workers sub cohort for the effect examination and laboratory tests.

The prevalence of white fingers in exposed and not exposed men and women were low and as expected in the age category in the different groups (Table 2.8). The prevalence of possible CTS (night tingling) in exposed and not exposed men and women were high in all the different groups (Table 2.8).

There were associations between HTV exposure and night tingling and wrist pain for men, neck, arm and low back pain for women (Table 2.9).

Results from the baseline SAQ HTV cohort

The population summary shown in Table 2.10 has been established on the basis of data obtained through the self-administered HTV questionnaire.

Table 2.8 Prevalence of upper limb disorders in the controls and the HTV exposed in the study population "young workers" (VIBIT cohort Sweden cross-sectional survey): numbers and (%).

	Controls men	HTV exposed men	Controls women	HTV exposed women
Number of persons	498	1060	204	102
Tingling/numbness in hands/fingers (7d last year)	41 (8%)	90 (8%)	22 (11%)	19 (18%)
At night tingling/numbness in hands/fingers (possible CTS 30d)	49 (10%)	152 (14%)	33 (16%)	25 (24%)
Coldness in hands/fingers (30d)	111 (22%)	274 (26%)	109 (53%)	64 (62%)
Finger whiteness colour chart (30d)	17 (3%)	42 (4%)	7 (3%)	7 (7%)
Neck pain (7d last y)	160 (32%)	350 (33%)	89 (44%)	64 (62%)
Arm pain (7d last y)	126 (25%)	304 (29%)	67 (33%)	62 (60%)
Wrist pain (7d last y)	71 (14%)	246 (23%)	62 (30%)	42 (41%)
Low back pain (7d last y)	174 (35%)	381 (36%)	93 (46%)	60 (58%)
Stress (burn out)	182 (37%)	405 (38%)	109 (53%)	57 (56%)

Table 2.9 Associations of upper limb disorders and HTV exposure in the study population "young workers" (VIBIT cohort Sweden cross-sectional survey). Prevalence ratios (PR) and 95% confidence intervals (95% CI) are reported, assuming the controls as the reference category (PR=1,0).

	Prevalence ratio HTV exposed men	95%CI	Prevalence ratio HTV exposed women	95%CI
Tingling/numbness in hands/fingers (7d last y)	1,03	0,70-1,52	1,71	0,97-3,01
At night tingling/numbness in hands/fingers (possible CTS 30d)	1,45	1,07-1,97	1,50	0,94-2,38
Coldness in hands/fingers (30d)	1,16	0,95-1,40	1,16	0,95-1,42
Finger whiteness color chart(30d)	1,16	0,67-2,01	1,98	0,71-5,50
Neck pain (7d last y)	1,02	0,88-1,20	1,42	1,15-1,77
Arm pain (7d last y)	1,13	0,95-1,35	1,54	1,17-2,02
Wrist pain (7d last y)	1,62	1,27-2,07	1,34	0,98-1,83
Low back pain (7d last y)	1,03	0,89-1,19	1,28	1,02-1,60
Stress (burn out)	1,04	0,91-1,20	1,04	0,74-1,24

Results from the clinical cohort

Finger systolic blood pressure

For the 162 males with vibration exposure the mean FSBP 10 degrees was 93.5 mm Hg (95% CI 89.4-97.6) and for the 7 females with vibration exposure the FSBP was 74.4 mm Hg (95% CI 59.2-89.6). The mean maximal weighted acceleration for any tool used by the subjects was 3.1 for the exposed females and 5.4 for the exposed males. In a linear multiple regression using FSBP as the dependent variable vibration exposure dose, room temperature and gender were significant factors (Table 2.11). Vibration exposure dose calculated as maximal weighted any tool, or maximal weighted A(8) or current weighted acceleration were significant in the regressions. However, neither duration nor duration times vibration level as measures of vibration exposure dose were significant in the regressions.

If only vibration exposed subjects were entered into the regression the significant relation between FSBP and maximal weighted acceleration persisted. The relationship between FSBP and outside temperature and nicotine use was not significant.

Table 2.10 Population summary

Population	**SWEDISH SAQ HTV COHORT**	
Population Swedish Cohort N= 852 (Age 19-26 yrs)	Not or very low exposed	Mechanics/construction workers
Number included: 793	315	478
Median age 2005 (upper and lower quartiles)	22 yrs (Q1=21; Q3=22)	22 yrs (Q1=21; Q3=22)
Tool(s)	No tools	Grinders, drills etc
Assessed exposure among exposed – Mean (SD)		
Dose 1: Total hours exposure		636 (2726)
Dose 2: a*t weighted total dose		1911 (10369)
Dose 3: a^2*t weighted total dose		8074 (4156)
Dose 4: a^4*t weighted total dose		190856 (920880)
Dose 8: A – max weighted any tool		2,62 (2,76)
Dose 10: Total exposure years		2,2 (2,9)
Dose 14: Current weighted A(8)		0,85 (1,41)
Dose 16: Leisure time exposure hours		23,5 (194)
Dose 17: Leisure a*t weighted total dose		81,6 (1003)
Dose 18: Work & Leisure sum hours		671 (2739)
Dose 19: Works & Leisure a*t weighted total		2038 (10457)
Dose 20: Work & Leisure total dose per year		1042 (2050)
From questionnaire (symptoms)		
(n=number of questionnaire replies)	**Not/very low exposed**	**Exposed**
% who have ever experienced any colour changes in the fingers	22,4 (299)	31,8 (466)
% who have ever experienced tingling	21,7 (304)	35,9 (471)
% who have ever experienced numbness	17,5 (303)	30,3 (472)
% who have had or have neck pain	42,8 (304)	46,8 (472)
% who have had or have shoulder pain	63,1 (141)	62,4 (242)
% who have had or have elbow pain	18,7 (139)	27,3 (238)
% who have had or have wrist pain	42,4 (139)	40,2 (239)

Table 2.11 Multiple linear regressions of FSBP (mm Hg), right-hand digit 3 as dependent variable as a function of gender (male=0, female=1), age, room temperature (degrees Celsius) and vibration exposure dose defined in different ways. Parameter estimate given/ probability.

Vibration dose definition	Intercept	Gender	Age	Room temperature	Vibration dose	R-squared
Duration (hours)	20.8/0.6	-11.8/0.06	0.32/0.87	3.34/0.002	-0.0007/0.6	0.10/0.0005
Weighted acceleration x duration	25.4/0.5	-12.5/0.05	0.26/0.90	3.21/0.002	-0.0003/0.25	0.10/0.0003
Maximal weighted acceleration any tool	45.0/0.25	-19.7/0.004	-0.08/0.97	3.10/0.002	-2.30/0.006	0.13/0.0001
Maximal weighted acceleration A(8) each tool	27.4/0.48	-15.3/0.02	0.50/0.80	3.04/0.003	-5.24/0.03	0.12/0.0001
Current weighted acceleration A(8)	29.1/0.45	-16.3/0.01	0.41/0.83	3.07/0.002	-4.87/0.004	0.14/0.0001

Neurological disorders

The thermal sensitivity (lower threshold for warmth and higher for cold) was generally higher for women both exposed and unexposed to vibration. When comparing unexposed men or women with vibration-exposed men or women, a lower sensitivity was noted for the vibration exposed groups. The mean differences were significant for the difference limens for the second and fifth fingers both on the left- and right-hand-side. The contrast between exposed and unexposed tended to be larger for cold perception compared to warmth perception. The excluded subjects had less sensitive thresholds compared to the corresponding mean values of the male group. A weak significant relation (r^2 .02 and 03) was found between reduced thermal perceptual sensitivity and length. Analysis of individual outliers highlighted the possible influence also from pain, sequelae after accidents and vascular function.

Musculoskeletal disorders

The prevalence of ever having experienced neck pain was 41.1% for the men and 58.8% for the women. Neck pain in the last seven days was reported by 16.3% of the men and 31.8% of the women.

All three exposure indices showed increased odds ratios among the highest exposed for having experienced neck pain ever and neck pain in the past week (Table 2.12, data only shown for men). Dose-response relations were observed in all three exposure indices.

Table 2.12 Univariate association between neck pain and the different ergonomic exposure indices for men. Presented as odds ratios (OR) and 95% confidence intervals (95% CI).

	Neck pain ever			**Neck pain last 7 days**	
Exposure variables	OR	95% CI	n	OR	95% CI
Neck posture [n=545]					
Reference (0-4)	1.0	--	166	1.0	--
Low (5-7)	2.0	1.19-3.3	125	1.9	0.94-4.1
Medium (8-9)	2.4	1.43-4.0	114	2.5	1.20-5.1
High (10-12)	3.7	2.31-6.1	140	3.2	1.68-6.6
Hand-intensive work [n=540]					
Reference (0-5)	1.0	--	140	1.0	--
Low (6-8)	1.6	0.97-2.8	119	1.4	0.63-3.3
Medium (9-11)	1.6	0.94-2.7	124	2.6	1.24-5.5
High (12-15)	3.4	2.10-5.6	157	3.3	1.70-6.9
Total ergonomic exposure [n=535]					
Reference (0-21)	1.0	--	134	1.0	--
Low (22-31)	2.0	1.21-3.4	138	2.0	0.90-4.6
Medium (32-41)	2.0	1.20-3.5	128	2.7	1.27-6.2
High (42-60)	4.3	2.58-7.3	135	4.1	1.97-9.0

2.2.2.5 Discussion

Finger systolic blood pressure

For the 162 males with vibration exposure, the mean FSBP 10 degrees was 93.5 mm Hg (95% CI 89.4-97.6) and for the 7 females with vibration exposure the FSBP was 74.4 mm Hg (95% CI 59.2-89.6). The mean maximal weighted acceleration for any tool used by the subjects was 3.1 for the exposed females and 5.4 for the exposed males. In a linear multiple regression using FSBP as the dependent variable vibration exposure dose, room temperature and gender were significant factors. Vibration exposure dose calculated as maximal weighted any tool, or maximal weighted A(8) or current weighted were significant in the regressions. However, neither duration nor duration times vibration level as measures of vibration exposure dose were significant in the regressions. However, the young-worker cohort had few years of exposure and probably subjected to little secondary healthy worker effect.

Neurological disorders

The results indicate thermal sensory impairment related to vibration exposure, gender, length, and disease (e.g. diabetes). These findings are in agreement with the results from other studies. Sensory impairment, despite the young adults' short vibration exposure-time and mainly low exposure, calls for strict methodology and careful interpretation of results before a small diameter nerve fibre neuropathy should be diagnosed as vibration-induced in individual cases. Conventional clinical and electro diagnostic investigations of subjects with neurological sensory disturbances fall short in evaluating the status of the small calibre afferent systems, leaving QST of thermal perception as one optional diagnostic tool in addition to pain perception.

The vibrotactile thresholds for the exposed group are somewhat higher, which may indicate a negative effect due to vibration exposure. Also, the neutral zone for thermotactile perception is somewhat wider for the exposed group which may support this idea.

Musculoskeletal disorders

Young men with an 8-hour weighted vibration exposure level above 1.7 m/s^2 had an increased risk of developing neck pain compared to those with an exposure level below 0.5 m/s^2. This is, to our knowledge, the first time exposure to hand-arm vibration has been observed to increase the risk of neck pain in a study with a prospective approach. However, as has been pointed out by others, with the present study design it is impossible to conclude that the increase in risk is due to hand-arm vibration exposure *per se*, since the assessments of ergonomic stressors were incomplete.

2.2.2.6 Conclusions

The dose-response relationship for vascular disorders measured as result of finger systolic blood pressure was better modelled by vibration level than duration or level multiplied with duration.

The dose-response relationship for neurological disorders measured as thermotactile perception threshold showed a negative effect on vibration exposure despite to short exposure time in the Swedish cohort.

The dose-response model for a musculoskeletal disorder (neck pain) showed that vibration level increased the risk of neck pain in our prospective cohort study.

2.3 Normal values of finger systolic blood pressure and thermotactile and vibrotactile perception thresholds

2.3.1 Introduction

Finger systolic blood pressures, thermotactile thresholds, and vibrotactile thresholds are used in the diagnosis of the vascular and neurological components of the hand-arm vibration syndrome (HAVS).

When diagnosing disorders, finger systolic blood pressures thermotactile thresholds and vibrotactile thresholds are compared to normal values, but the normal values are currently not adjusted for either gender or age.

This research is described in full in Annex 4 (Experimental studies of normal values for finger systolic blood pressure) and Annex 5 (Experimental studies of normal values for thermotactile and vibrotactile thresholds).

2.3.2 Objectives

To compare finger systolic blood pressures, thermotactile thresholds and vibrotactile thresholds in males and females and in younger and older persons. To provide normal values of finger systolic blood pressure, thermotactile thresholds, and vibrotactile thresholds for younger and older males and females.

Additionally, for finger systolic blood pressures, the values were compared on four different fingers. For thermal thresholds, the effects of the contact area (small and large) and stimulus location (glabrous and non-glabrous skin) were compared.

2.3.3 Methods

Eighty healthy subjects participated in the study: 20 males and 20 females aged 20 to 30 years, and 20 males and 20 females aged 55 to 65 years.

Subjects were students, office workers, or retired office workers with no history of regular use of hand-held vibrating tools. None reported cardiovascular or neurological disorders, connective tissue disease, injuries to the upper extremities, a history of cold hands, or were on medication likely to affect finger systolic blood pressures. Each age group included white, Asian and mixed race subjects. The subjects were similar in handedness and distribution of smoking but older subjects reported a greater consumption of alcohol.

Finger systolic blood pressures

Finger systolic blood pressures were measured using strain-gauge plethysmography following local cooling in accord with International Standard 14835-2 (2005). The FSBPs were measured simultaneously in the thumb and the index, middle, ring, and little fingers of the dominant hand using a multi-channel plethysmograph (*HVLab*, ISVR, University of Southampton). Mercury-in-silastic strain gauges were placed around the distal phalanges at the base of the nail on all five digits. A cuff for air-inflation was fixed around the proximal phalanx of the thumb. Water-filled cuffs were fixed around the middle phalanges of the other four fingers. The FSBPs were measured at 30°C and 10°C with an initial cuff occlusion pressure of 200 mmHg and an occlusion duration of 5 minutes.

The results of the cold test were expressed as the change of systolic blood pressure in the fingers (test fingers) at 10°C ($FSBP_{t,10°}$) as a percentage of the pressure at 30°C ($FSBP_{t,30°}$), corrected for the change of pressure in the thumb (i.e. the reference finger) during the examination ($FSBP_{ref,30°} - FSBP_{ref,10°}$):

$$FSBP_{\%10°} = (FSBP_{t,10°} \times 100)/[FSBP_{t,30°} - (FSBP_{ref,30°} - FSBP_{ref,10°})]$$

In accord with ISO 14835-2 (ISO, 2005), measurements were performed in a laboratory with a median temperature of 21.6 °C (range 20.4 to 22.2°C) and smoking, drinking of alcohol, and caffeine consumption were restricted for two hours prior to the experimental session.

Each of the 80 subjects attended the laboratory on one occasion. Measurements were made while the subjects were supine with their dominant hand resting on a support alongside their body at the level of the heart. The non-dominant hand was also alongside the body. After acclimatisation for about 30 minutes, subjects lay supine for 10 minutes during which the fingers were instrumented. Finger systolic blood pressures were then measured at 30°C and then at 10°C. The experimental session lasted about 25 minutes.

Thermal thresholds

An *HVLab* Thermal Aesthesiometer was used to measure thermotactile thresholds (warm and cold thresholds) via the method of limits. Thresholds were measured on the non-dominant upper limb at the three marked locations (the distal phalanx of the middle finger, the thenar eminence, and the forearm) using two circular stimuli: 1 cm diameter (0.79 cm^2 area) and 2.8 cm diameter (6.18 cm^2 area). Depending on the test, the temperature of the applicator increased or decreased (at 1°C per second) from the reference temperature (32.5°C). Subjects were instructed to press the response button as soon as they perceived a change in temperature. The temperature of the applicator then returned to the reference temperature at 1°C per second and was held at 32.5°C for a random interval (between 3 and 5 seconds) before the temperature increased or decreased again. Six hot and six cold thresholds were determined and the means of the hot and cold thresholds were calculated from the last four judgements. The experiment was conducted in a quiet room with a temperature range of 22 to 26°C.

Vibrotactile thresholds

An *HVLab* Tactile Vibrometer was used to measure vibrotactile thresholds (at 31.5 Hz and 125 Hz to assess the function of the Meissner and Pacinian corpuscles, respectively) via the von Békésy method in a manner compliant with the methods in ISO 13091-1 (2001). Thresholds were measured on the distal phalanx of the middle finger of the non-dominant hand. Subjects placed their finger such that the centre of the whorl was over the centre of the probe of the applicator. The magnitude of the vibration on the applicator increased from zero at the start of the test. Subjects were instructed to press and hold the response button down as soon as they perceived a vibration sensation and to release the response button as soon as they did not perceive the vibration. Measurements were performed for a minimum of six reversals over a duration of at least 45 seconds and the mean was calculated from all the peaks and troughs with the exception of the first peak and first trough. The experiment was conducted in a quiet room with a temperature range of 22 to 26°C.

Ethical approval

The experiments were approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research at the University of Southampton (UK).

2.3.4 Results

Finger systolic blood pressures

The median %FSBPs for the females and the males aged 20 to 30 years or aged 55 to 65 years are compared in Table 2.13.

On all four digits exposed to cold, the median %FSBPs were higher in younger females compared to younger males. However, the reduction was statistically significant only on the middle finger (p=0.028). For the older subjects, the median %FSBPs on all four digits were similar for females and males (p>0.1).

On all four digits, the median %FSBPs were lower for the older females than the younger females. The reduction in %FSBP in older females was significant in three digits (p<0.05), and marginally significant in the middle finger (p=0.084). There were no significant differences in %FSBPs between younger and old males (p>0.1) – the median %FSBPs were similar on three digits but lower on the index finger in the older males.

Table 2.13 Median %FSBP (IQR) at 10°C in four digits of younger (20 to 30 years old) and older (55 to 65 years old) males and females.

Age (years)	Gender	Index	Middle	Ring	Little
20-30	female	92 (16.7)	91 (18.9)	91 (15.3)	99 (17.9)
	male	89 (13.3)	86 (12.8)	87 (12.8)	92 (14.4)
55-65	female	84 (20.8)	84 (18.3)	81 (12.3)	88 (16.5)
	male	81 (13.6)	87 (13.6)	86 (10.9)	91 (14.1)

There were no overall significant differences in %FSBP across the four digits for the younger males or the younger and older females (Friedman; p>0.1). In the older males the %FSBP differed across digits ($p < 0.01$; Friedman) and was significantly greater in the little finger than the other three digits ($p<0.05$).

Thermal thresholds

Table 2.14 shows the hot and cold thresholds for younger and older female and male subjects obtained with the smaller stimulus (1-cm diameter) and larger stimulus (2.8-cm diameter) at three locations.

Younger females were more sensitive to temperature than younger males. Hot thresholds were significantly lower in females with the 1.0-cm diameter stimulus at the finger and the thenar eminence and with the 2.8-cm diameter stimulus at the finger, the thenar eminence and the forearm ($p<0.05$, Mann-Whitney). Cold thresholds were significantly higher in females with both the 1.0-cm and the 2.8-cm diameter stimulus at the finger ($p<0.05$).

Differences in sensitivity between the genders were less apparent in the older subjects. Hot thresholds were significantly lower in females with the 1.0-cm diameter stimulus at the thenar eminence and the forearm and with the 2.8-cm diameter stimulus at the forearm ($p<0.05$, Mann-Whitney). There were no gender differences in cold thresholds with either stimulus area at any of the three locations.

The larger stimulus (2.8-cm diameter) gave significantly lower hot thresholds and higher cold thresholds at all locations and with both genders.

When using the 2.8-cm diameter stimulus, there were no statistically significant differences in thermotactile thresholds at any location between the younger and older males or between the younger and older females. When using the 1.0-cm diameter stimulus, there were no differences between the younger and older males but hot thresholds were higher and cold thresholds were lower at the finger and the forearm for the older females.

Vibrotactile thresholds

Table 2.15 shows the vibrotactile thresholds at 31.5 Hz and 125 Hz for the groups of younger and older male and female subjects.

There were no statistically significant differences in vibrotactile thresholds between the younger males and females. There were no statistically significant differences in vibrotactile thresholds between older males and females. There were no significant correlations between either room temperature or skin temperature and either of the two vibrotactile thresholds.

There were no significant differences in vibrotactile thresholds between the younger and older males or between the younger and older females.

Table 2.14 Median (IQR) hot and cold thresholds.

Age (years)	Gender	Stimulus diameter	Hot Thresholds (°C)			Cold Thresholds (°C)		
			Finger	Thenar eminence	Forearm	Finger	Thenar eminence	Forearm
20–30	Female	1.0 cm	37.9 (3.54)	38.1 (3.69)	39.7 (8.43)	27.1 (5.25)	28.9 (3.39)	27.5 (3.79)
		2.8 cm	35.9 (2.19)	34.0 (1.96)	35.6 (2.12)	29.4 (1.65)	30.8 (1.88)	30.8 (2.64)
	Male	1.0 cm	41.9 (5.40)	41.6 (4.56)	43.7 (8.34)	23.3 (9.21)	28.5 (5.51)	26.6 (7.75)
		2.8 cm	37.3 (2.30)	35.6 (2.11)	37.1 (4.19)	26.9 (2.86)	30.5 (2.89)	30.4 (3.60)
55–65	Female	1.0 cm	40.7 (6.65)	39.1 (3.75)	39.2 (5.86)	24.0 (9.33)	26.0 (5.68)	24.8 (4.32)
		2.8 cm	37.4 (3.86)	34.7 (1.46)	35.3 (1.55)	28.6 (5.36)	30.5 (1.23)	30.9 (2.99)
	Male	1.0 cm	44.2 (7.96)	42.2 (5.95)	43.5 (6.17)	21.9 (15.81)	24.5 (6.24)	25.7 (8.15)
		2.8 cm	38.2 (5.51)	34.9 (1.50)	36.3 (2.51)	27.5 (3.71)	30.1 (2.19)	29.8 (4.37)

Table 2.15 Median (IQR) vibrotactile thresholds

Age (years)	Gender	31.5 Hz (ms^{-2} r.m.s.)	125 Hz (ms^{-2} r.m.s.)
20-30	Female	0.11 (0.06)	0.23 (0.36)
	Male	0.12 (0.09)	0.23 (0.69)
55-65	Female	0.12 (0.11)	0.29 (0.36)
	Male	0.14 (0.05)	0.23 (0.31)

2.3.5 Discussion

Finger systolic blood pressures

Currently, within the UK and some other countries, an indication of unusual response to cold is indicated using two criteria: it is assumed that there is a ‘possible problem’ if the %FSBP is less than 80% and a ‘probable problem’ if the %FSBP is less than 60%. These percentages correspond to the mean %FSBP less one and two standard deviations, respectively, from values reported in healthy persons by Lindsell and Griffin (1998). Assuming the values are normally distributed, these values correspond, respectively, to the values below which there are 18% and 2.5% of the %FSBPs in normal healthy persons.

Table 2.16 shows the %FSBPs corresponding to the mean %FSBP less one and two standard deviations from the mean values measured in the present study. It may be seen that the current value for indicating ‘possible dysfunction’ (i.e. less than 80%) is broadly similar to the mean %FSBP less one standard deviation in the younger males and females and fairly similar to values for the older males and females. The current value for indicating ‘probable dysfunction’ (i.e. less than 60%) is also similar to the values corresponding to the mean %FSBP less two standard deviations in the older males and females and fairly similar to values for the younger males and females.

Thermal and vibrotactile thresholds

As with finger systolic blood pressures, when diagnosing the hand-arm vibration syndrome, the criteria for abnormality have two categories: a ‘possible disorder’ and ‘probable disorder’, corresponding to the mean threshold plus (or minus) one standard deviation and the mean threshold plus (or minus) two standard deviations. These correspond to values exceeded by 18% and 2.5%, respectively, of a population of healthy persons.

For thermotactile thresholds, a ‘possible disorder’ is assumed for hot thresholds greater than 45°C and cold thresholds less than 22°C; a ‘probable disorder’ is assumed for hot thresholds greater than 48.5°C and cold thresholds less than 19°C. For vibrotactile thresholds, a ‘possible disorder’ is assumed for 31.5 Hz thresholds greater than 0.3 ms^{-2} r.m.s. and 125 Hz thresholds greater than 0.7 ms^{-2} r.m.s.; a ‘probable disorder’ is assumed for 31.5 Hz thresholds greater than 0.4 ms^{-2} r.m.s. and 125 Hz thresholds greater than 1.0 ms^{-2} r.m.s.

Tables 2.17 and 2.18 show the means plus (or minus) one and two standard deviations for the thermotactile and vibrotactile thresholds of subjects in the current study. For the vibrotactile thresholds, the means and standard deviations were calculated after logarithmic transformation to obtain Gaussian distributions – transformation was not required for the thermal thresholds.

The hot and cold thresholds corresponding to ‘possible disorder’ and ‘probable disorder’ in each subject group, and for all 80 subjects, were within range of values determined by Lindsell and Griffin (1998). This indicates that less than 18% and less than 2.5% of healthy persons will exceed the currently used thermal thresholds corresponding, respectively, to ‘possible’ and ‘probable’ disorders.

The predicted 31.5 Hz and 125 Hz vibrotactile are also within the range of values determined by Lindsell and Griffin (1998, 2002), with the exception of the younger males where three men had thresholds outside the criterion for ‘probable disorder’ at both 31.5 and 125 Hz, compared to about one in forty (2.5%) for a normal distribution. Apart from their unusual thresholds, there were no reasons to exclude these subjects, so it is assumed they either occurred by chance or were due to undetected disorder. The high thresholds of these three young males also affected the overall results, resulting in higher predicted thresholds at 125 Hz. The same three subjects gave thermal thresholds that fell within the range of normal values (i.e. within the mean plus one standard deviation).

Table 2.16 Predicted values of %FSBP for 'possible disorder' (mean minus one standard deviation) and 'probable disorder' (mean minus two standard deviations) for the four groups of 20 subjects and the combined group of 80 subjects.

Criterion	Age (years)	Gender	Predicted values of %FSBP			
			Index	Middle	Ring	Little
'Possible disorder' (mean – 1 SD)	20-30	female	81	81	81	85
		male	78	73	76	84
	55-65	female	69	71	74	79
		male	71	69	70	75
	Overall		74	73	75	80
'Probable disorder' (mean – 2 SD)	20-30	female	68	68	71	72
		male	67	62	63	76
	55-65	female	55	57	63	69
		male	58	53	57	62
	Overall		61	59	63	68

2.3.6 Conclusions

Although there are some differences in the %FSBPs associated with age, gender, and finger, the differences may be sufficiently small to use a single value criterion when deciding on abnormalities in FSBP associated with cold provocation in males and females aged 20 to 65 years.

Similar distributions of normal values can be assumed for the vibrotactile thresholds of healthy males and healthy females. However, for thermotactile thresholds young healthy females are more sensitive heat and cold than young males.

In healthy persons aged between 20 and 65 years, the results suggest that an age correction may not be needed when identifying whether thermal thresholds or vibrotactile thresholds are abnormal.

Table 2.17 Predicted thermotactile thresholds for 'possible disorder' (mean plus one standard deviation for hot thresholds or mean minus one standard deviation for cold thresholds) and 'probable disorder' (mean plus two standard deviations for hot thresholds or mean minus two standard deviation for cold thresholds) for the four groups of 20 subjects and the combined group of 80 subjects.

Criterion	Age (years)	Gender	Predicted values of thermotactile thresholds (°C)	
			Hot	Cold
'Possible disorder' (mean – 1 SD)	20-30	Female	37.9	27.6
		Male	41.0	24.9
	55-65	Female	41.1	24.5
		Male	42.0	24.5
		Overall	40.7	25.2
'Probable disorder' (mean – 2 SD)	20-30	Female	39.6	26.1
		Male	44.0	22.6
	55-65	Female	44.3	21.1
		Male	44.9	21.6
		Overall	43.6	22.6

Table 2.18 Predicted values of vibrotactile thresholds for 'possible disorder' (mean plus one standard deviation) and 'probable disorder' (mean plus two standard deviations) for the four groups of 20 subjects and the combined group of 80 subjects.

Criterion	Age (years)	Gender	Predicted values of vibrotactile thresholds (ms^{-2} r.m.s.)	
			31.5 Hz	125 Hz
'Possible disorder' (mean – 1 SD)	20-30	Female	0.20	0.51
		Male	0.35	0.95
	55-65	Female	0.22	0.68
		Male	0.19	0.59
		Overall	0.24	0.68
'Probable disorder' (mean – 2 SD)	20-30	Female	0.33	1.06
		Male	0.79	3.25
	55-65	Female	0.39	1.48
		Male	0.26	1.04
		Overall	0.43	1.60

2.4 Hand-transmitted vibration experimental Work

2.4.1 Acute effects of vibration on vascular function

2.4.1.1 Introduction

Experimental studies are required for the interpretation of epidemiological data and the establishment of appropriate dose response models for vibration-induced vascular disorders in the fingers and hands.

2.4.1.2 Objectives

Three experimental studies were designed and conducted by the Clinical Unit of Occupational Medicine, University of Trieste (Italy) and the Human Factors Research Unit, ISVR, University of Southampton (UK):

Study 1 consisted of reanalysis of the findings of previous investigations of the vascular effects of 125-Hz vibration with different magnitudes (from 1 to 176 ms^{-2} r.m.s.) and durations (from 0.03 to 1 hour) (Bovenzi, Lindsell and Griffin, 1998, 1999, 2000, 2001). The various exposure conditions were combined to obtain alternative measures of vibration dose with different time dependency:

$$dose = a^m t^n$$

where a and t are the acceleration magnitude and the duration of vibration exposure, respectively. Doses with different combinations of m = 0, 1, and 2, and n = 0, 1, and 2 (i.e. a^0t, at^0, at, a^2t, and at^2) were computed for each subject who participated in the experimental investigations described in the previous sections.

The relation between acute vascular effects and (i) vibration magnitude, (iii) vibration frequency, (iii) exposure duration, and (iv) alternative measures of vibration dose was assessed. A further aim was to investigate the acute response of finger circulation to vibration with different combinations of magnitude and duration but with the same "energy-equivalent" acceleration magnitude according to current standards for hand-transmitted vibration.

Study 2 compared the acute response of finger circulation to continuous and intermittent vibration having the same total duration of vibration exposure and the same energy-equivalent acceleration magnitude (Bovenzi, Welsh and Griffin, 2004).

The effect of intermittency was tested using a 125-Hz vibration with a constant acceleration magnitude (44 ms^{-2} r.m.s.) and a constant total exposure duration (30 minutes). Periods of regular vibration exposure were interrupted with rest periods of the same duration.

Study 3 investigated the combined effects of force and vibration on finger circulation (Bovenzi, Welsh, Della Vedova and Griffin, 2005). Push forces of three magnitudes were employed (0, 2, and 5 N). Vibration with two frequencies (31.5 and 125 Hz) and two magnitudes (2 and 8 ms^{-2} frequency weighted) were used.

2.4.1.3 Methods

Study 1

Each experiment involved ten healthy men (age range: 21 to 46 years). The measures of finger blood flow (FBF) were obtained by a strain-gauge plethysmographic technique. The FBF measurements were expressed in absolute values (ml/100 ml/min, or ml/100 ml/s) and as a percentage of the pre-exposure values (%). Different combinations of frequency, magnitude and duration of vibration were presented according to the experimental protocols.

FBF was measured in the fingers (usually the middle finger) of both the exposed and unexposed hand during vibration exposure and a recovery period of 45 minutes.

Study 2

Finger blood flow (FBF) was measured in the middle and little fingers of both hands of ten healthy men. Finger skin temperature (FST) was measured in the middle right finger. With a static load of 10 N, the middle finger of the right hand was exposed to 125 Hz at 44 ms^{-2} r.m.s. in five conditions: (i) 30 minutes continuous exposure, (ii) 2 periods of 15 minutes, separated by a 15-minute period with no vibration, (iii) 4 periods of 7.5 minutes, separated by 7.5-minute periods with no vibration, (iv) 8 periods of 3.75 minutes, separated by 3.75-minute periods with no vibration, (v) 16 periods of 1.88 minutes, separated by 1.88-minute periods with no vibration. All five exposures correspond to an 8-hour energy-equivalent frequency-weighted acceleration magnitude of 1.4 ms^{-2} r.m.s. according to International Standard ISO 5349-1 (2001). Finger circulation was measured in all four digits before the application of vibration and at fixed intervals during vibration exposure and during a 45-minute recovery period.

Study 3

Each of 10 subjects attended 11 sessions in which they experienced five successive experimental 5-minute periods: (i) no force and no vibration; (ii) force and no vibration; (iii) force and vibration; (iv) force and no vibration; (v) no force and no vibration. During periods (ii) to (iv), the intermediate phalanx of the right middle finger applied one of two forces (2 N or 5 N) on a platform that vibrated during period (iii) at one of two frequencies: 31.5 Hz (at 4 or 16 ms-2 r.m.s.) or 125 Hz (at 16 or 64 ms-2 r.m.s.). Finger blood flow was measured in the exposed right middle finger, the unexposed right little finger and the unexposed left middle fingers throughout the 25 minutes of each session.

2.4.1.4 Results

Study 1

Effects of vibration magnitude

Acute exposure to 125-Hz vibration with acceleration magnitudes of 5.5, 22, 44, or 62 m/s^2 r.m.s. (unweighted) can reduce FBF in both the vibrated and the non-vibrated finger and the degree of digital vasoconstriction is related to the magnitude of the vibration (Bovenzi, Lindsell and Griffin, 1999)

Effects of vibration frequency

Acute exposures to vibration with equal frequency-weighted magnitude (5.5 m/s^2 r.m.s.) reduce the FBF in both vibrated and non-vibrated fingers for frequencies between 31.5 and 250 Hz (Bovenzi, Lindsell and Griffin, 2000). The frequency weighting given in current standards tends to overestimate the vasoconstriction associated with acute exposures to vibration at frequencies around 16 Hz.

Effects of duration of exposure to vibration

Acute exposures to a vibration of 125 Hz with durations of 7.5, 15, and 30 minutes provoked a reduction of FBF in the vibrated finger which was significant when compared with the pre-exposure measures (Bovenzi, Lindsell and Griffin, 1998). Vibration-induced vasoconstrictor after-effects were found to increase as the duration of acute exposure to vibration increased. The findings of this study suggest that, in addition to the frequency and magnitude of the vibration stimulus, the duration of vibration exposure plays a role in the reaction of the digital vessels to acute vibration.

Dose-response patterns for finger circulation

Using vibration magnitude and exposure duration data of our published and unpublished experimental studies, it was possible to construct, for each subject, various alternative vibration 'doses', of the general form: *dose* = $a^m t^n$, where a and t are the acceleration magnitude and the duration of vibration exposure, respectively (Bovenzi, Lindsell and Griffin, 1998).

During exposure to vibration, the vasoconstriction in exposed and non-exposed fingers does not increase monotonically with increases in the magnitude or duration of the exposure. Vasoconstriction appears immediately after the onset of vibration and, if there is any subsequent variation in FBF during prolonged exposures, it may indicate reduced vasoconstriction with increased duration of exposure. Since vibration causes reductions in FBF the effects must, to some extent, depend on the vibration magnitude. Although over all conditions previously investigated there is no significant effect of vibration magnitude, the results of an experiment to investigate the effects of variations in magnitude from 5.5 to 62 m/s^2 r.m.s. (unweighted) found that there was increased vasoconstriction with increased magnitude of 125-Hz vibration. This suggests that if a dose measure is formed to predict the FBF during exposure it would reflect the magnitude of vibration but not the duration of exposure.

During recovery following exposure to vibration, FBF depends on both the duration and the magnitude of the prior exposure (as well as the frequency of vibration). Although there is increased vasoconstriction with both increased magnitude and increased duration, the a^2t relation used in current standards to accumulate exposures during the day is not an optimum predictor of changes in FBF. A measure of dose that better reflects the vasoconstriction following vibration exposure is at (or possibly at^2).

Effects of "energy-equivalent" combinations of vibration magnitude and exposure duration

For the range of vibration magnitudes investigated (44 to 176 m/s^2 r.m.s. unweighted; 5.5 to 22 m/s^2 r.m.s. when frequency-weighted according to ISO 5349), the vasoconstriction during exposure to 125-Hz vibration was independent of vibration magnitude (Bovenzi, Lindsell and Griffin, *2001*). The after-effect of vibration was different for stimuli having the same "energy-equivalent" acceleration, with greater effects following longer durations of exposure.

Study 2

The FST did not change during vibration exposure, whereas all vibration conditions produced significant reductions in FBF of the vibrated finger when compared with the pre-exposure FBF. During vibration exposure, the vibration caused a similar degree of vasoconstriction in the vibrated finger without evidence of cumulative effects during intermittent exposure. After the end of exposure to 30 minutes of continuous vibration there was a progressive decrease in the FBF, whereas there was no statistically significant reduction following exposure to intermittent vibration *(Bovenzi, Welsh and Griffin, 2004)*.

Study 3

The application of force alone caused a reduction in finger blood flow in the exposed finger, but not other fingers. There were additional reductions in finger blood flow caused by vibration, with greater reductions at the higher vibration magnitudes at both frequencies but no difference between the two frequencies when using unweighted acceleration. The vibration caused a similar vasoconstriction in vibrated and non-vibrated fingers (Bovenzi et al, 2005).

2.4.1.5 Discussion

Study 1: Acute effects of vibration on finger blood flow depend on the magnitude, frequency, and duration of vibration exposures. When vibration magnitudes and exposure durations are combined to construct alternative vibration 'doses' of the form $a^m t^n$, it may not be possible to define a measure of dose to predict the vasoconstriction during exposure. During recovery following exposure to vibration, a measure of dose that better reflects the vasoconstriction following vibration exposure is *at* (or possibly at^2).

Study 2: For the vibration stimuli investigated (exposure durations varying from 1.88 minutes to 30 minutes, with rest periods varying from 1.88 minutes to 15 minutes), the reduction of FBF during exposure was the same for continuous and intermittent vibration. The after-effect of vibration was greater following the continuous vibration exposure. Although some evidence from this study is consistent with intermittent vibration having a less severe effect than continuous vibration, this evidence is not yet conclusive.

Study 3: Modest levels of force applied by a finger can have a large effect on the finger blood flow, possibly due to the constriction of local blood vessels. The acute vascular effects of vibration cause additional reductions in finger blood flow that are not limited to the finger experiencing force and vibration. In all fingers (exposed and not exposed to vibration), the greater the magnitude of vibration, the greater the reduction in finger blood flow. In all fingers (exposed and not exposed to vibration), when the vibration was frequency-weighted according to current standards, 125 Hz vibration caused greater reductions in finger blood flow than 31.5 Hz vibration.

2.4.1.6 Conclusions

The frequency weighting given in current standards tends to overestimate the acute vascular effects induced by vibration in the low frequency range (16 – 31.5 Hz).

A dose of the product of acceleration and time (*at*) employs the relation between magnitude and duration to predict the incidence of finger blanching. In current standards, the duration of exposure is expressed in years rather than hours in the day. The use of *at* during the day (as well as over years) would make the calculation of 'dose' easier. It would also put more 'weight' on the duration of daily exposures to hand-transmitted vibration than when using the a^2t relationship underlying the current calculation of the daily A(8).

The "energy-equivalent" acceleration failed to predict the acute effects of vibration both during and following vibration exposure.

Finger blood flow is influenced by force applied by a finger, and, at least partially, by the intermittency of vibration exposure.

The pattern of the haemodynamic changes during and after vibration exposure suggests that complex vasomotor mechanisms, mediated both centrally and locally, are involved in the response of digital vessel to acute vibration.

Detailed information about the experimental findings of these laboratory studies, including Tables and Figures, is reported in Annex No. 6 to this report.

2.4.2 Acute effects of vibration on neurosensory function

2.4.2.1 Introduction

The neurological component of hand-arm vibration syndrome (HAVS) is characterized by a peripheral, diffusely distributed neuropathy with predominant sensory impairment. Epidemiological evidence suggest a greater occurrence of digital paraesthesia and numbness, deterioration of finger tactile perception, and loss of manipulative dexterity in occupational groups using vibrating tools than in control groups not exposed to hand-transmitted vibration. The awareness of the importance of sensory neuropathy has entailed an increasing interest in quantitative sensory testing for screening and diagnosis of vibration-induced neuropathy. In the scientific literature, however, there is a lack of knowledge about the relationship between the acute effects of vibration and measures of the neurosensory functions.

Four controlled laboratory experiments were set up. The first experiment addressed the acute effects of HTV on vibrotactile perception thresholds and the second experiment on thermotactile perception thresholds. In the third and fourth experiments, the acute effects of continuous and intermittent vibration on vibrotactile and thermotactile perception thresholds respectively were investigated. A more extensive description of the studies is provided in Annex 7.

2.4.2.2 Objectives

The objective of the experiments was to investigate the acute effects of hand-transmitted vibration on measures of neurological function (vibration perception thresholds and thermotactile thresholds) in order to confirm current knowledge and better define the effects of vibration magnitude, frequency and duration.

2.4.2.3 Methods

Ten healthy subjects (age between 21 and 28 years), five male and five female, with no prior history of regular use of hand-held vibrating tools in occupational or leisure activities participated in each of the studies. All subjects were non-smokers and reported no cardiovascular or neurological disorders in their dominant hand. All the experiments were performed in a room with an ambient temperature of 22ºC (± 2ºC) and with airflow less than 0.2 m/s. The subjects were asked to avoid alcohol 12 hours before testing and to avoid nicotine and caffeine consumption 1 hour before testing. After an acclimatisation period of 15 minutes, finger temperature was measured by a thermocouple attached to the distal phalanx of the examined index finger (digit 2). The finger skin temperature was maintained at 28°C or higher. If the fingers were at a lower temperature, the subjects used hand warmers to increase the temperature.

A computer-based system was used to measure vibrotactile thresholds at 31.5 Hz and 125 Hz, respectively, via the von Békésy method in a manner compliant with the methods in ISO 13091-1 (2001). Thresholds were measured on the distal phalanx of the index finger of the dominant hand. The subjects were seated in a chair in front of the instrumentation set-up and instructed to apply a downward (push) force of 0.5 N (± 0.25 N) during the tests. Subjects were instructed to press and hold the response button down as soon as they perceived a vibration sensation and to release the response button as soon as they did not perceive the vibration.

Thermal perception was measured using instruments fitted with a flat contact thermo stimulator, Peltier contact thermode. The instruments were provided by Somedic (Thermo test; Somedic, Sales AB, Sweden). When measuring the perception of coldness and warmness, the volar surface of the distal phalanges of the index finger was gently applied to the probe (25x50 mm). The perception threshold of cold and warmth was assessed by the Marstock method. The rate of the temperature change was linear and about 1°C/s. The subjects were seated in a chair in front of the instrumentation setup and instructed to apply a downward (push) force of 1 N during the tests. The subject was instructed to press a switch whenever he or she experienced the onset of a change in the sensation of temperature (cold or warm). After a response, the temperature of the thermo stimulator changed direction from warmth to cold and vice versa.

A measure of the thermal or vibrotactile perception was conducted before the different exposures to vibration. After completing pre-test the subjects were instructed to place their index, middle finger and their ring finger on a horizontal wooden platform (70x70mm) mounted on a vibrator (Ling Altec Model 40). The subjects were instructed to apply a downward force of 5 N during the entire exposure time. Immediately after the vibration exposure, the threshold measurements were conducted on the exposed index finger. The acute effect was measured continuously for the first 75 seconds and the analysis was made for a time intervals of 15 to 45s (mean 30s).

The subjects were exposed to vibration under different conditions (Table 2.20) and with a combination of different frequency, intensity, and exposure time. Furthermore, the acute effects of continuous and intermittent vibration on the perception thresholds were investigated by combinations of vibration with different periods of exposure and rest periods. The combinations were 1 period of 16-minute continuous vibration (no rest period); 2 periods of 8 min, separated by a 8-min period with no vibration (total rest period 8 min); 4 periods of 4 min, separated by 4 min periods with no vibration (total rest period 12 min); and 8 periods of 2 min, separated by 2-min periods with no vibration (total rest period 14 min). The subjects were only allowed to conduct one test per day, and the test order was distributed with a repeated measures design. Sinusoidal vibration at frequencies of 31.5 Hz and 125 Hz was generated by an IBM computer-based system. The vibration was sent via an amplifier to the vibrator, generating motion in the vertical direction. The unweighted acceleration ranged from 4.82 to 111.36 m/s^2, corresponding to frequency-weighted vibration acceleration from 2.50 to 14.14 m/s^2. The energy-equivalent frequency-weighted acceleration magnitude for an exposure time of 16 minutes ranged from 2.5 m/s^2 to 5.0 m/s^2, according to ISO 5349-1.

Computer software SAS was used for the statistical analysis. In the analysis, the measured vibrotactile thresholds at 30 s after exposure for each subject and condition were compared with the corresponding measured thresholds before the exposure to vibration (the pre-test). The difference was used as an indication of acute effect of vibration exposure on perception sensation. For the statistical analysis, repeated measures analysis of variance (ANOVA) with mixed model was used to test the hypothesis of “no difference” in the responses for the different exposure conditions.

2.4.2.4 Results

The results are summarized in Table 2.20.

The frequency of the vibration stimuli (31.5 or 125 Hz) had significant ($p<0.001$) influence on the vibrotactile thresholds but no significant ($0.667<p<0.953$) influence on total mean perception thresholds for the sensation of cold or warmth or on the neutral zone (difference between cold and warmth threshold). The increase in the vibrotactile thresholds was greater at 125 Hz compared to 31.5 Hz ($p<0.001$) and 30 s after the exposure the mean difference was about 13 dB.

The vibrotactile thresholds were significantly affected by the exposure magnitude ($p<0.001$). An increase in the equivalent frequency-weighted acceleration from 2.5 m/s^2 to 5.0 m/s^2 resulted in a mean increase in the thresholds of about 2.1 dB at 30 s after exposure. The influence of different frequency-weighted accelerations was significant for the test frequency of 31.5 Hz between the lowest and highest accelerations. The difference was about 3.6 dB at 30 s after exposure. The difference between the thresholds after exposure to other magnitudes of vibration was not significant. For the test frequency of 125 Hz, the thresholds were not significantly affected by the acceleration of prior-exposure (frequency-weighted or unweighted).

The thresholds for the cold and warmth sensation were significantly affected by the exposure magnitude ($0.001<p<0.003$) regardless of the how the exposure magnitudes were expressed (frequency-weighted, unweighted or equivalent). An increase in the equivalent frequency-weighted acceleration from 2.5 m/s^2 to 5.0 m/s^2 resulted in a mean decrease of the cold and warmth thresholds with about 0.2°C and 0.1°C respectively. For the frequency-weighted acceleration and the unweighted acceleration, no clear exposure-response relationship was found. If the acceleration is divided into two categories, low and high acceleration levels, a significant difference could be found ($p=0.005$; $p=0.006$ respectively). Higher acceleration produced a reduction in both thresholds of about 0.1°C. The neutral zone was significantly affected ($p=0.001$) by the unweighted acceleration.

Table 2.20 The mean change in vibrotactile (dB) and thermal perception thresholds (ºC) at 30 s after the vibration exposure compared with pre-test thresholds for the different experimental conditions. The standard deviations are given in parentheses.

Vibration frequency (Hz)	Frequency weighted acceleration magnitude (m/s^2)	Unweighted acceleration magnitude (m/s^2)	Exposure duration (min)	Equivalent acceleration magnitude (m/s^2)	Vibrotactile perception thresholds (dB)	Thermal perception thresholds: Warm (ºC)	Cold (ºC)	Neutral zone (ºC)
Continuous vibration								
31.5	7.07	13.62	2	2.5	7.28 (1.88)	-0.24 (1.75)	0.00 (0.61)	-0.25 (1.57)
31.5	5.00	9.63	4	2.5	7.15 (2.84)	0.10 (0.81)	-0.34 (0.79)	0.44 (0.68)
31.5	3.54	6.81	8	2.5	5.89 (2.74)	0.11 (0.45)	-0.15 (1.06)	0.26 (0.93)
31.5	2.50	4.82	16	2.5	4.61 (4.08)	-0.13 (1.23)	-0.56 (1.07)	0.43 (1.39)
31.5	14.14	27.25	2	5.0	17.1 (3.94)	-0.02 (1.02)	-0.75 (0.71)	0.72 (1.08)
31.5	10.00	19.27	4	5.0	17.74 (3.93)	-0.45 (1.47)	-1.00 (1.27)	0.55 (1.17)
31.5	7.07	13.62	8	5.0	19.67 (4.61)	0.26 (1.08)	-0.53 (0.52)	0.79 (1.38)
31.5	5.00	9.63	16	5.0	19.33 (3.78)	-0.35 (2.21)	-1.17 (1.94)	0.82 (1.56)
125	7.07	55.68	2	2.5	7.71 (3.89)	0.51 (0.94)	-0.41 (0.99)	0.92 (1.27)
125	5.00	39.37	4	2.5	6.91 (3.91)	0.21 (0.45)	-0.73 (0.78)	0.94 (1.02)
125	3.54	27.84	8	2.5	7.48 (4.68)	0.43 (0.94)	-0.47 (1.14)	0.89 (1.32)
125	2.50	19.69	16	2.5	8.17 (4.7)	-0.07 (0.87)	-0.84 (1.58)	0.77 (1.37)
125	14.14	111.36	2	5.0	19.54 (3.92)	0.18 (1.65)	-0.94 (1.34)	1.12 (0.97)
125	10.00	78.74	4	5.0	20.87 (3.89)	-0.13 (1.28)	-1.50 (1.23)	1.37 (1.28)
125	7.07	55.68	8	5.0	23.49 (2.67)	0.49 (0.55)	-0.53 (0.82)	1.02 (0.75)
125	5.00	39.37	16	5.0	21.44 (6.03)	-0.07 (0.60)	-0.86 (0.85)	0.79 (0.39)
Intermittent vibration (Periods of exposure with the same length of rest between)								
125	5.00	39.37	8+8	5.0	22.43 (5.41)	-0.15 (1.17)	-0.74 (0.94)	0.58 (0.97)
125	5.00	39.37	4+4+	5.0	19.18 (2.73)	-0.30 (1.02)	-0.47 (1.11)	0.17 (1.02)
125	5.00	39.37	2+2+	5.0	17.94 (3.95)	-0.54 (1.15)	-0.72 (1.14)	0.19 (1.11)

The exposure duration (2, 4, 8, 16 min) of the vibration stimuli had no significant influence on the vibrotactile thresholds (p=0.759). However, the exposure duration (2, 4, 8, 16 min) had a significant influence on the thresholds for cold and warmth sensations (p=0.002; p=0.003 respectively), but the neutral zone was not affected (p=0.130). There was a significant difference in thermotactile thresholds (p=0.015) between short exposure time (2 and 4 minutes) and long exposure time (8 and 16 minutes). Longer exposure time resulted in a decreased threshold of about 0.1°C.

The vibrotactile thresholds, 30 s after the exposure, were significantly different between the shortest exposure periods and the longest ($p=0.039$ and 0.018 respectively). For the other combinations of exposure and rest periods, no significant influence was found. The 2-minute exposures led to a mean temporary threshold shift about 4.5 dB lower than the 8-minute exposures.

The different combinations of exposure and rest period had no significant influence, 30 s after the exposure, on the total mean perception thresholds for the sensation of cold or warmth or on the neutral zone ($0.242<p<0.413$).

2.4.2.5 Discussion

Vibrotactile thresholds

Effect of magnitude: The magnitude of the vibration stimuli had a significant influence on the thresholds, regardless of the how the exposure magnitudes were expressed (frequency-weighted, unweighted or equivalent) and were more noticeable for larger differences between the magnitudes.

Effect of frequency: The frequency of the vibration stimuli significant affected the vibrotactile thresholds. The thresholds were greater after exposure to vibration at 125 Hz compared to 31.5 Hz.

Effect of duration: The exposure time of the vibration stimuli had no significant influence on the vibrotactile thresholds. However, the combination of exposure and rest periods had an influence on the vibrotactile thresholds. The differences were significant between the shortest exposure periods and the longest.

Thermotactile thresholds

Effect of magnitude: The thresholds for the cold and warmth sensation were significantly affected by the magnitude of the vibration stimuli, regardless of the how the exposure acceleration was expressed (frequency-weighted, unweighted or equivalent).

Effect of frequency: The frequency of the vibration stimuli had no influence on the thresholds or on the neutral zone. This is not in agreement with earlier investigations. The discrepancy may be due to a range of factors but merits further investigation.

Effect of duration: The duration of vibration exposure prior to threshold measurement had a significant influence on the thresholds for cold and warmth sensations but the neutral zone was not affected. Longer exposure time resulted in decreased thresholds. The neutral zone was not affected in the same way because the absolute levels of both the cold and warmth thresholds moved in the same direction. No significant acute effects on the thermal perception thresholds for the sensation of cold or warmth or on the neutral zone were found for different combinations of exposure durations and rest periods.

There may be several sources of bias that may have affected the results of this study such as the individual factors, number of subjects, exposure conditions and methodology. Several individual factors (such as gender, blood pressure and anthropometric parameters) might influence sensory thresholds. Results have been presented that suggest that age is the most single determinant of sensory thresholds among these parameters. The subjects in this study were young healthy males and females with no previous history of regular use of hand-held vibrating tools in occupational or leisure activities. No conclusion may be drawn on the effect on thresholds of vibration-exposed workers and also elderly subjects. The results showed differences in threshold due to gender. The gender factor was also highly related to the height of the subjects. To minimise the effect of individual factors, the statistical analyses should therefore take into account gender, height, and age. In addition, since measurement of the thresholds is conducted by obtaining subjective responses, these types of test require the full co-operation and concentration of the subjects. A limitation of this study could be the absence of an assessment of the influence on thresholds of applied push forces without exposure to vibration (5 N in this study). Initial control experiments on four subjects were conducted where no influence was found but unfortunately, these measurements were not repeated in the main study.

2.4.2.6 Conclusions

The results show that vibration divided into short periods of exposure led to lower temporary vibrotactile threshold shift compared with longer periods of exposure but the same energy-equivalent frequency-weighted acceleration. No significant acute effects were found on the thermal perception thresholds for the sensation of cold or warmth or on the neutral zone for conditions with different durations of vibration and rest periods.

2.4.3 Effects of prior exposure on vascular function

2.4.3.1 Introduction

The principal vascular disorder associated with exposure to hand-transmitted vibration is vibration-induced white finger, a type of secondary Raynaud's phenomenon (Bovenzi, 1998).

Cold provocation of the fingers and hands is a common testing procedure used in either clinical studies or epidemiological surveys to confirm objectively the existence of abnormal cold response in the digital vessels of vibration-exposed workers affected with white fingers. The measurement of finger systolic blood pressure during cold provocation is considered a useful laboratory test for quantifying the degree of cold-induced digital vasospasm in vibration-exposed workers (Bovenzi, 2002).

To assist in the implementation of uniform measuring methods and test conditions for the assessment of peripheral vascular function in vibration-exposed workers, the International Organisation for Standardisation (ISO) has recently approved the International Standard 14835-2 devoted to measurement and evaluation of finger systolic blood pressure during cold provocation (ISO, 2005). The section of the Standard dedicated to measurement procedures includes items on subject preparation, with recommendations to subjects to avoid strenuous physical exercise, smoking and caffeine for 3 h prior to examination; moreover, drinking of alcohol and intake of vasoactive medical drugs should be avoided during the twelve hours preceding the cold test. It is also recommended to avoid vibration exposure for at least 12 h prior to examination.

Researchers involved in epidemiological studies of vibration-exposed operators at workplace have often experienced that it may be hardly feasible to comply with the ISO recommendation about 12 h-avoidance of vibration exposure prior to conducting the cold test. Organisational aspects linked to work schedules or production cycles may impede to perform the cold test according to the time lag suggested by the ISO Standard.

2.4.3.2 Objectives

The aim of this study was to investigate whether exposure to hand-transmitted vibration in controlled laboratory conditions can influence the cold response of digital vessels at various time-points after the application of a vibration stimulus. Moreover, since operating vibratory tools involves contact force exerted on tool handles, the effect of force with no vibration exposure on cold-induced digital vasoconstriction was also investigated.

2.4.3.3 Methods

Ten healthy male volunteers, 8 Caucasian, 1 Asian and 1 African, gave written informed consent to participate in the investigation. All subjects were students or office workers with no history of regular use of hand-held vibrating tools in occupational or leisure activities.

Cold test

The cold test consisted of strain-gauge plethysmographic measurement of finger systolic blood pressure (FSBP) during local cooling according to the technique recommended by the International Standard ISO 14835-2 (ISO, 2005).

The results of the cold test was expressed as the change of systolic blood pressure in the right and left index fingers (test fingers) at 10°C ($FSBP_{t,10°}$) as a percentage of the pressure at 30°C ($FSBP_{t,30°}$), corrected for the change of pressure in the right and left thumb fingers (reference fingers) during the examination ($FSBP_{ref,30°}$ - $FSBP_{ref,10°}$) (ISO, 2005):

$$FSBP\%_{10°} = (FSBP_{t,10°} \times 100)/[FSBP_{t,30°} - (FSBP_{ref,30°} - FSBP_{ref,10°})] \qquad (\%)$$

Experimental procedure

The experiment was performed in a laboratory room with a mean (SD) temperature of 26.0 (SD 0.5)°C. Recommendations to the subjects about smoking, drinking of alcohol, and caffeine consumption prior to examination were according to the ISO Standard 14835-2 (ISO, 2005).

Each of the 10 subjects attended the laboratory on two occasions. In each session, they experienced nine successive experimental periods of varying durations. Table 2.21 shows the experimental design for the two conditions: with a contact force alone (condition 1) or a combination of contact force and vibration of frequency of 125 Hz and an unweighted acceleration magnitude of 64 ms^{-2} r.m.s. (condition 2).

Each of the ten subjects experienced both experimental conditions on separate days. Across the subject group, the two experimental conditions were presented in a balanced order. The experimental sessions lasted approximately 190 minutes.

The study was approved by the Human Experimental Safety and Ethics Committee of the Institute of Sound and Vibration Research at the University of Southampton (UK).

2.4.3.4 Results

Finger systolic blood pressure before exposure

The vascular measurements before exposure to either contact force alone or contact force and vibration showed no significant changes in FSBP at 30°C in either the exposed or the unexposed fingers across the two experimental sessions (p=0.12 - 0.86).

In the pre-exposure period, analysis of repeated measures by the generalised estimating equation (GEE) method showed no significant relation between FSBP at 30°C and room temperature in any finger. There was no significant difference in the air temperature of the laboratory over exposure periods (p=0.76) and across the two experimental sessions (p=0.54).

Cold test after exposure to contact force and vibration

No significant changes in the FSBP indices during local cooling ($FSBP\%_{10°}$ and R-$FSBP_{10°}$) were observed across exposure conditions and over exposure periods in either the 2nd right finger (exposed hand) or the 2nd left finger (unexposed hand) (Table 2.22).

Similar findings were observed when the results of the cold provocation test after exposure to contact force alone (condition 1) and exposure to contact force and vibration (condition 2) were analysed separately. There were no significant changes in $FSBP\%_{10°}$ (%), and R-$FSBP_{10°}$ (mmHg) at 30 and 70 minutes after exposure to either condition 1 or condition 2.

2.4.3.5 Discussion

This laboratory study was designed to investigate whether prior exposure to vibration on the day of a cold provocation test may affect the cold response of digital arteries. The vibration magnitude and duration used in this study gave rise to a daily vibration exposure, *A*(8), of 2.8 ms^{-2} r.m.s., i.e. slightly greater than the daily action value (2.5 ms^{-2} r.m.s.) established by the European Directive on mechanical vibration (European Directive 2002/44/EC, 2002).

To our knowledge, there is no previous study which investigated whether conditions of exposure to contact force and hand-transmitted vibration, as when operating vibratory tools, are likely to influence the results obtained from an objective diagnostic test that is used to detect peripheral vascular symptoms.

In this study, analysis of repeated measures of FSBP during local cooling showed no significant changes in the cold response of digital arteries over time in both the right and the left hand after 60-minute exposure of the right hand to contact force (5 N) combined with 125-Hz vibration with an unweighted acceleration magnitude of 64 ms^{-2} r.m.s. Moreover, no significant difference in cold-induced vasoconstriction of the digital arteries was found between exposure to contact force alone and combined exposure to contact force and vibration.

These findings suggest that in healthy men, recent exposure to contact force and hand-transmitted vibration does not seem to influence adversely the response of finger circulation to cold provocation. Further research is needed to investigate to what extent our experimental findings can be applied to vibration exposed workers affected with peripheral vascular symptoms.

2.4.3.6 Conclusions

This experimental study of the influence of prior vibration exposure on cold-test results in healthy men suggests that the measurement of FSBP during local cooling 30 to 70 minutes after vibration exposure is not associated with adverse effects on the cold response of digital arteries.

This finding is consistent with the suggestion included in the VIBRISKS protocol for epidemiological studies of hand-transmitted vibration (Work Package 1) that a time period of 2 hours between the last occupational exposure to tool vibration and the commencement of objective vascular testing is adequate to avoid acute circulatory effects caused by recent vibration exposure.

Detailed information about the experimental findings of this laboratory study is reported in Annex 8.

Table 2.21 Experimental design of the study: condition of exposures to contact force alone (newtons) and combination of contact force and vibration with a frequency of 125 Hz and an unweighted acceleration magnitude of 64 ms^{-2} r.m.s.

Exposure period	Time interval (min)	Condition 1		Condition 2	
		Force	Vibration	Force	Vibration
A†	0 – 30	0	0	0	0
B	30 – 40	0	0	0	0
C	40 – 50	5 N	0	5 N	0
D	50 – 110	5 N	0	5 N	125 Hz, 64 ms^{-2}
E	110 – 120	5 N	0	5 N	0
F	120 – 130	0	0	0	0
G†	130 – 150	0	0	0	0
H	150 – 170	0	0	0	0
I†	170 – 190	0	0	0	0

†Cold test with measurement of finger systolic blood pressure at 30° and 10°C

Table 2.22 Regression coefficients and robust 95% confidence intervals (estimated by a generalised estimating equations analysis with an autoregressive model) between finger systolic blood pressure (FSBP) indices during cold test at 10°C (outcome variable) and exposure condition [exposure of the right hand to contact force alone (5 N for 80 minutes) or combined exposure to contact force (5 N for 80 minutes) and 125-Hz vibration (unweighted acceleration magnitude of 64 ms^{-2} r.m.s. for 60 minutes)], exposure period, and the value of the outcome variable one measurement earlier (FSBP index $_{(t-1)}$).

Independent variables	2nd right finger (exposed hand)		2nd left finger (unexposed hand)	
	$FSBP\%_{10°}$ (%)	$R\text{-}FSBP_{10°}$ (mmHg)	$FSBP\%_{10°}$ (%)	$R\text{-}FSBP_{10°}$ (mmHg)
Intercept	43.3 (-2.7 – 89.4)	5.1 (-2.4 – 12.5)	32.7 (-9.7 – 75.1)	4.3 (-0.4 – 9.1)
Exposure period	- 2.5 (-10.8 – 5.9)	3.2 (-5.3 – 11.8)	0.4 (-3.6 – 4.3)	0.6 (-4.2 – 5.3)
Exposure condition	2.0 (-4.8 – 8.8)	- 2.3 (-9.1 – 4.5)	- 2.0 (-7.3 – 3.2)	2.6 (-3.9 – 9.1)
FSBP index $_{(t-1)}$	0.5 (0.1 – 0.9)	0.5 (0.1 – 1.0)	0.6 (0.2 – 1.1)	0.7 (0.2 – 1.1)

2.4.4 Effects of prior exposure on neurosensory function

2.4.4.1 Introduction

Prolonged occupational exposure to hand-arm vibration arising from the operation of hand-held power tools has been associated with neurological disorders. Measurement of the fingertip thermal or vibrotactile perception thresholds have been used for quantifying the neuropathy produced by hand-transmitted vibration. To minimise the effects of confounding factors on the results of the perception tests, it is often recommended to avoid vibration exposure for some period before the measurement. However, the required duration of the vibration-free period preceding the test is not standardised.

Further details of the study are reported in Annex 9.

2.4.4.2 Objectives

The objective was to investigate whether the conditions in the field are likely to influence the results obtained from the objective diagnostic tests that are used to detect symptoms (i.e. whether prior exposure to vibration on the day of the test may influence neurological function).

Three different laboratory experiments were set up. The post-stimulatory effects on vibrotactile threshold were studied in the first experiment and the effects on thermotactile perception thresholds were studied in the second experiment. In the third experiment the differences in thresholds (vibrotactile and thermotactile) during exposures to continuous vibration and intermittent vibration were studied.

2.4.4.3 Methods

The subjects, experimental procedure and statistical analyses for studying the influence on the vibrotactile and thermotactile thresholds were as described in Section 2.4.2. Threshold measurements were made continuously for the first 75 seconds, followed by 30-second measurements each minute for ten minutes. The data from the last measurement were then compared with the results from the pre-test. Differences in thermotactile perception thresholds of more than 2˚C compared with the pre-test were rejected and were followed by further measurements every 5 minutes until the difference was less than 2˚C. The measurements continued for up to 30 minutes.

2.4.4.4 Results

The frequency of the vibration stimuli (31.5 or 125 Hz) had a significant influence ($p<0.001$) on the vibrotactile thresholds after exposure. The increase in the thresholds was greater at 125 Hz compared to 31.5 Hz ($p<0.001$) and the influence was significant up to 20 minutes after exposure (Figure 2.3). The frequency had no significant influence on total mean perception thresholds for the sensation of cold or warmth or on the neutral zone.

The results show that at 10 minutes after the vibration exposure, 41% of the vibrotactile threshold tests showed a shift in the thresholds compared with the pre-test and therefore the measurement was continued. After 15 minutes, 14% of the tests still showed a shift in the thresholds and for 4% of the tests the measurements had to be continued for 30 minutes. The length of the recovery time was dependent on the frequency of the vibration stimuli. For all subjects and experimental conditions, the effect of vibration exposure on the vibrotactile threshold was significant for the first ten minutes ($p<0.0001$).

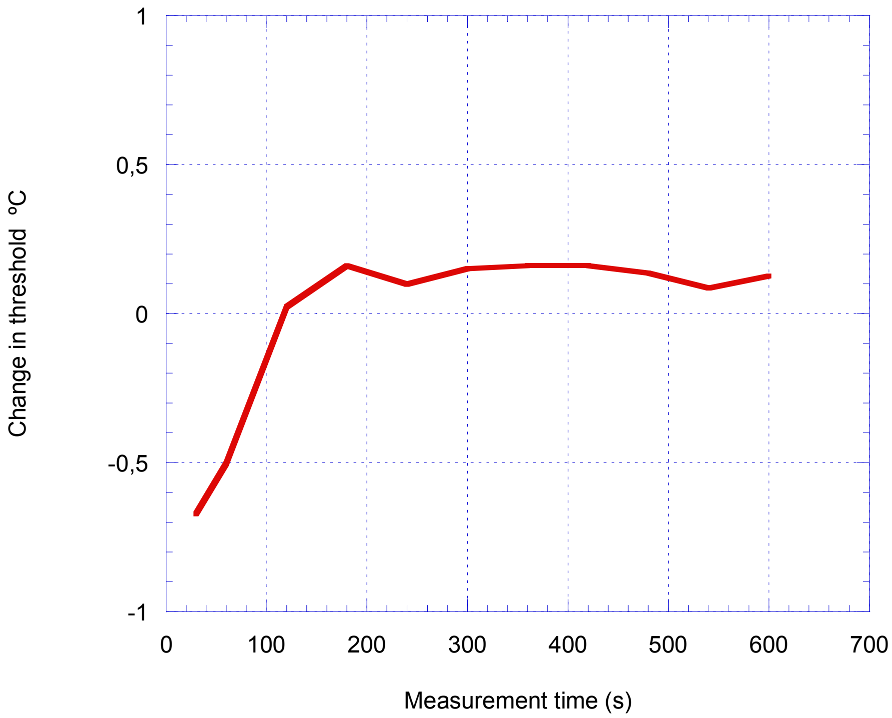

Figure 2.4 The relation between time of measurement and changes (ºC) in the mean cold threshold compared to the pre-test (mean for all experimental conditions)

The analysis showed that at 10 minutes after the vibration exposure, 14% of the thermotactile perception threshold tests had a deviation larger than 2˚C compared with the pre-test and therefore the measurement was continued. After 15 minutes, 6% still had a deviation in threshold and in two tests, the measurements had to be continued for 30 minutes before the threshold shift was eliminated. No correlation was found between the length of recovery time and type of exposure. For all subjects and experimental conditions, the effect of the vibration exposure was only significant on the cold threshold and the neutral zone for the first minute ($p<0.0001$). The warmth threshold was not significantly affected by the studied variables. Figure 2.4 shows the relationship between time of measurement and changes in the mean cold threshold (ºC) compared to the pre-test. The decrease in the threshold was in the range 0.5 - 0.7ºC. The effect was independent of exposure duration, acceleration and gender.

The vibrotactile thresholds were significantly different between the condition with the shortest exposure periods and with the longest ($p=0.048$ and $p=0.004$ respectively). For the other combinations no significant influence was found. The combinations of the different exposure types had no significant ($0.242<p<0.413$) influence on the thermotactile thresholds for the sensation of cold or warmth or on the neutral zone.

2.4.4.5 Discussion

Threshold recovery measurements show that the influence on the thresholds of prior exposure to vibration is significant for a relatively short duration of about 1 minute for the thermal perception threshold and for exposure durations of about 25 minutes for the vibrotactile perception threshold. Moreover, in a few experiments recovery took up to 30 minutes. The energy-equivalent frequency-weighted acceleration magnitude for the exposure time of 16 minutes was between 2.5 m/s^2 and 5.0 m/s^2 and the corresponding 8-

hour equivalent acceleration, A(8), according to ISO 5349-1 is 0.46 m/s^2 and 0.92 m/s^2, respectively, i.e., well below the action level (2.5 m/s^2) given in European Directive 2002/44/EC. Since, exposures in the field are often of the order of the action level, it is likely that prior exposure to vibration on the day of a test will affect the thermotactile thresholds. The test person should be given a vibration-free period before testing. Moreover, it can be concluded that work with continuous vibration exposure without rest periods implies that longer rest periods are needed. However, the subjects in this study were young healthy males and females with no previous history of regular use of hand-held vibrating tools in occupational or leisure activities. Therefore, no conclusions can be drawn on the effect of prior exposure to vibration on thresholds of vibration-exposed workers or on elderly subjects.

From this study, it can be concluded that the required minimum vibration-free period before measurement of the thermal and vibrotactile perception thresholds is 2 minutes and 30 minutes respectively. However, these time periods are without any safety margins and therefore it is likely that prior exposure to vibration on the day of a test still could influence the results. The recommendation is therefore to avoid vibration exposure 2 hours prior to the measurement of thermal perception thresholds and 4 hours prior to the measurement of tactile perception thresholds.

2.4.4.6 Conclusions

The results suggest that it is important to recognize that prior exposure to vibration on the day of a test is likely to affect vibrotactile and thermotactile thresholds. The test person should therefore be given a vibration-free period before testing. Moreover, it may be concluded that after exposure to continuous vibration exposure without rest periods, a longer rest period prior to conducting threshold tests is advisable. It is recommended that vibration exposure be avoided for at least 2 hours prior to measurement of thermotactile perception thresholds and for at least 4 hours prior to measurement of vibrotactile perception thresholds.

2.5 Biodynamic modelling of the finger

2.5.1 Objectives

The aim of this research was to model the biodynamic behaviour of a finger with the pulp in contact with a vibrating rigid plate.

2.5.2 Method

The <u>F</u>inite <u>E</u>lement <u>M</u>ethod (FEM) was chosen to achieve calculations of local internal quantities such as stresses or strains inside the finger. A first model of a forefinger cross-section has been developed. This model was limited to in-plane analysis. Thus, INRS has worked at an extension towards a 3D model for the forefinger. Real finger geometries were digitised and discretized in meshes to perform FEM calculations but difficulties were encountered in making the model stable. Consequently efforts were devoted to the response study of a forefinger 3D local model with simplified geometry. Only soft tissues between the vibrating rigid plate and the distal phalanx were considered and modelled as a parallepipedic volume with viscohyperelastic behaviour.

Further details of the study are reported in Annex 10.

2.5.3 Results

2.5.3.1 Two-dimensional model

A FE model was developed by Wu (2002) to investigate theoretically the static compression effects on the fingertip vibration modes. An in-plane FE model of the cross-section at the fingertip was formulated on the basis of the anatomical structure and the non-linear elastic material properties of the soft tissue. The fingertip vibration modes were calculated for several deformation states. Results show that modal frequencies increased with static compression force. The first task conducted by INRS was to investigate the feasibility of these calculations by using its own FE program. Thus, an in-plane model of a half-elliptical cross-section taken at the fingertip was built with adequate symmetry conditions. The model was composed of a rigid bone surrounded by viscohyperelastic soft tissues. The surface of the soft tissue was assumed to be in contact with a rigid plate, representing the vibrating machine. The rigid plate was subjected to a prescribed vertical displacement to realise a pre-constraint in the soft tissue occurring during grip of the machine or its handle. A modal analysis of the pre-stressed soft tissues was performed for several levels of compression and the mode shapes were computed. All the calculations were compared to the results obtained by Wu (2002) and identical conclusions were drawn. Effects of the static deformation state on the vibration modes were observed.

2.5.3.2 Towards a 3-dimensional Model

To extend the previous model to the whole finger, a three-dimensional model has been determined taking into account the real three-dimensional geometry. This part of the work was carried out during a 6-month student engineer training period (Karoui, 2005). The 3D model comprises the three phalanges surrounded by soft tissues. The phalange geometry files stem from the website http://www.eatonhand.com/images/spatch.htm. The outer surface of a forefinger, i.e. the skin, was digitised and numerically processed in order to include the phalanx geometry in the digitised outer finger surface. A 3D geometry model was thus obtained and prepared to be meshed.

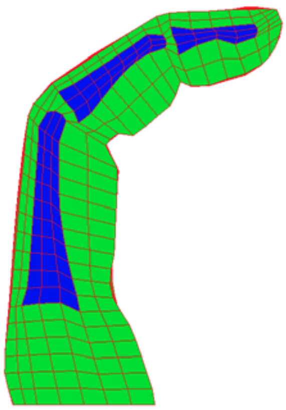

Figure 2.5 Longitudinal section of the three-dimensional forefinger mesh

Figure 2.5 shows a longitudinal section of a whole forefinger mesh. Blue parts correspond to the phalanges and green elements the surrounded soft tissues. Visco-hyperelastic constitutive equations given in Wu (2005, 2006) were used to model the soft tissue behaviour. Bones were presumed to be rigid. Therefore nodes located on bone outer surfaces were interconnected with rigid connections. Loading conditions like displacement functions were applied on these nodes in order to simulate the finger motion. A rigid cylindrical shape plate was added to take into account the machine handle. Soft tissue deformation simulations were then performed but due to many numerical problems no solution was obtained. Several reasons may explain why the calculations did not converge, the main reason being probably the use of sophisticated constitutive equations to model time-dependant (visco) non-linear (hyper) elastic behaviour of soft tissues.

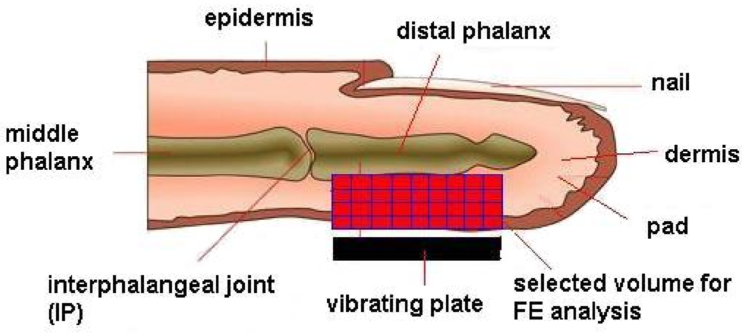

Figure 2.6 Longitudinal finger section; the area used for FE analysis is the red grid volume measuring 10 x 10 x 4 mm.

2.5.3.3 Analysis of a simplified 3-dimensional Model

In a third step, a simplified 3D model was developed and investigations were focused on the constitutive equations used to describe the viscohyperelastic deformation behaviour of soft tissues. Only soft tissues between the vibrating rigid plate and the distal phalanx were considered and modelled as a brick with viscohyperelastic behaviour (see Figure 2.6).

The model was first developed to describe time-independent non-linear elastic deformation (hyperelastic) behaviour. The displacement-force relation was determined and compared to the relation obtained by FE calculation (Fleury, 2007). The model was used to investigate the sensitivity of the material parameters on the displacement-force relation. Variation of ±2% of the value of some material parameters given in Wu (2005, 2006) led to large modifications of the displacement-force relation. The compressibility behaviour was investigated by comparing previous results with forces resulting from the same volume but confined in a rigid container. Figure 2.7 shows the comparison between confined and unconfined state and large differences are obtained during compression. This means that the material parameters chosen by Wu (2005, 2006) make the material behaviour nearly incompressible.

In a second step, the time history of the force was expressed as a function of the displacement. Time-dependent effects of the non-linear elastic deformation (viscohyperelastic) were taken into account. The finger model used previously was submitted to the following consecutive displacement loadcases:

- compression from 4 mm to 1 mm for 10 seconds;

- relaxation for 20 seconds, i.e. the deformation was kept constant;

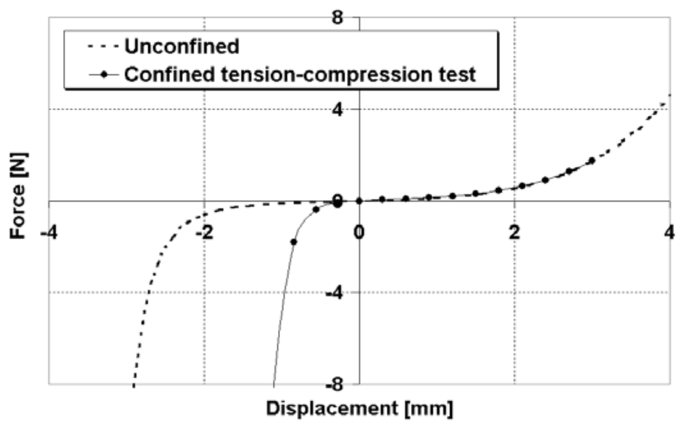

Figure 2.7 Comparison of the displacement-force relation during a tension-compression test applied on a confined and unconfined cube.

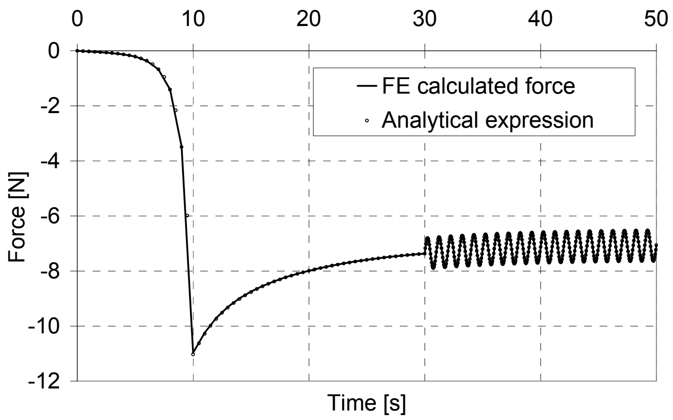

Figure 2.8 Time-history of the force; Finite Element calculations and analytical expression.

- sinusoidal excitation at frequency 1 Hz, displacement magnitude 0.01 mm.

Figure 2.8 shows the response force calculated by the finite element software compared to the calculated analytical expression given in Fleury (2007).

The analytical expression was determined and compared to the finite element results. A maximal force of 11 N was reached at 3 mm compression. The steady-state would be reached after about 30 seconds of relaxation. The force decreased from 11 to 7 N during the 20-second relaxation test. Viscosity effects are therefore significant. The driving point impedance was determined for the sinusoidal loading and decreased monotonously with the frequency. No minimum was found unlike the measurements carried out by Lundström (1984). The reason is that inertial effects were not yet taken into account at this stage of modelling.

2.5.4 Discussion and conclusions

The Finite Element Method for non-linear problems requires iterative algorithms to converge to numerical solutions. Commercial software embeds more or less advanced routines to make the calculations more robust but in all cases, no standard method is known to automatically solve non-linear problems. In the frame of this work, the materials involved (human tissues) have complex behaviours and the loading conditions (compression + relaxation + vibration) applied to the finger are also complex to deal with. The initial objective was not achieved in the sense that the developed model was not sufficiently robust and accurate to predict pressure fields in a real vibrating finger in order to have a better understanding of physiological troubles due to vibration exposure. But this work has resulted in a better understanding of the numerical problems encountered during FE calculations with viscohyperelastic behaviour used by Wu (2005, 2006) and particularly during subsequent compression, relaxation and vibration. Further work is required to obtain a simple but robust 3D model of the forefinger in order to draw comparisons with experimental results published by Lundström (1984).

2.6 Modelling of risk of exposure to hand-transmitted vibration

2.6.1 Introduction

The chronic effects of occupational exposures to hand-transmitted vibration include the development of vascular disorders (including vibration-induced white finger), neurological disorders (including impaired tactile function), and musculoskeletal disorders (including impaired grip and dexterity).

The chronic effects of hand-transmitted vibration have been previously found, or assumed, to depend on the magnitude of vibration, the frequency of vibration, the duration of exposure to hand-transmitted vibration during the day, and the number for years of exposure. Other factors, such as individual susceptibility and ergonomic factors are also suspected as being important.

Acute exposures to hand-transmitted vibration result in reduced finger blood flow during and following exposure, and elevated thresholds for tactile perception. Finger blood flow has been reported to depend on the frequency and magnitude of vibration. Vibrotactile thresholds are elevated in a manner that depends on the similarity between the frequency of vibration exposure and the frequency at which the threshold is measured, as well as the duration of exposure.

Notwithstanding the previous research, the evidence for current methods of predicting vibration-induced white finger from vibration exposures is not substantial, and there are no dose-response relationships for predicting the neurological and musculoskeletal effects of hand-transmitted vibration. Progress is being made on the acute effects of hand-transmitted vibration but the relation between the chronic and acute effects of exposure to hand-transmitted vibration is not known.

2.6.2 Objectives

One objective of the research within VIBRISKS was to interpret the data obtained from the epidemiological studies so as to describe the relationship between vibration dose and injury, and try to identify the effects of confounding variables.

The interpretation took into account previous epidemiological and experimental studies, the epidemiological studies in WP2, and the experimental data from WP3 to identify the need for new ways to estimate of vibration dose.

2.6.3 Results

From epidemiological studies conducted by UTRS in Italy and reported in Section 2.2, multivariate analysis of health and exposure data suggested dose-response relationships for both sensorineural and vascular symptoms in workers exposed to hand-transmitted vibration. There was also evidence of a dose-effect relationship for both cold-induced digital arterial hyper-responsiveness (measured using finger systolic blood pressures) and also impaired manual dexterity (measured using the Purdue pegboard).

From the Swedish studies undertaken by UMUH and reported in Section 2.2, it was concluded that the dose-response relationship for vascular disorders measured using finger systolic blood pressures was better predicted by vibration magnitude than by exposure duration or a dose measure based on both magnitude and duration. There was a dose-response relationship for thermotactile perception thresholds. There was also evidence that increased vibration magnitude increased the risk of neck pain.

<u>Vascular Responses</u>

Chronic vascular responses

In the Italian studies, statistically significant associations between finger blanching (assessed by either medical history or colour charts) and various alternative measures of daily and cumulative vibration dose indicated that daily vibration exposure expressed in terms of the unweighted acceleration, $A_{uw}(8)$, fitted the data better than those with the frequency-weighted acceleration, $A_w(8)$, as a measure of daily vibration exposure.

Several measures of vibration dose formed from combinations of vibration magnitude and duration of exposure provided significant predictors of vibration-induced white finger over the follow up period. However, measures of dose determined solely by lifetime exposure duration were either not associated with vibration-induced white finger (years of exposure) or performed worse (total hours of tool use) for the prediction of the vascular outcome. Dose measures with high powers of acceleration (i.e. $\Sigma a_i^m t_i$ with $m > 1$) appeared better at predicting vibration-induced white finger over the follow-up period than other measures of lifetime cumulative vibration exposure.

Measures of finger systolic blood pressure were indicative of finger blanching. There was a trend for increased cold response of the digital arteries with increasing finger blanching score. Workers with moderate vibration-induced white finger (blanching score 13 – 24) and severe vibration-induced white finger (blanching score > 24) showed increased cold-induced hyper-reactivity in the digital arteries when compared with the controls and workers exposed to hand-transmitted vibration but with no vascular symptoms.

Finger systolic blood pressures were also related to vibration exposure, with the unweighted acceleration, $A_{uw}(8)$, providing a better prediction than the frequency-weighted acceleration, $A_w(8)$. Vibration dose calculated from vibration magnitude and duration of exposure provided statistically significant predictions of reductions in finger systolic blood pressure at 10°C (i.e. $FSBP\%_{10°}$) in workers exposed to hand-transmitted vibration. Vibration dose determined solely by lifetime exposure duration, such as years of exposure or total hours of tool use, were less strongly associated with $FSBP\%_{10°}$. Dose measures with high powers of acceleration (i.e. $\Sigma a_i^m t_i$ with $m > 1$) performed better for the prediction of the vasoconstrictor response to cold during follow up than other measures of lifetime cumulative vibration exposure.

An investigation of the use of colour charts to assist the diagnosis of vibration-induced white finger was conducted in forestry workers and stone workers exposed to hand-transmitted vibration. Assuming the administration of colour charts as the gold standard, the sensitivity and specificity of the medical history alone to diagnose finger whiteness was 88.2% and 93.8%, respectively, at the initial cross-sectional study and 94.4% and 97.7% at the end of a follow-up study. Finger systolic blood pressures at 10°C were significantly associated with finger whiteness assessed by medical history alone ($p<0.005$) and the colour charts ($p<0.001$). However, statistical analysis suggested that use of the colour charts performed better than medical history alone for the prediction of the cold response of digital arteries. The administration of colour charts seemed to reduce the proportion of false-positive responses for finger whiteness and it was concluded that the colour charts were better predictors of digital arterial hyper-responsiveness to cold than medical history alone.

The Swedish epidemiological studies reported in Section 2.2, involved students that had graduated from vocational high schools in 2001, 2002 and in 2003 and so the prevalence of white fingers in those exposed and not exposed was low. Among the 162 males with vibration exposure, the mean finger systolic blood pressure at 10°C ($FSBP\%_{10°}$) was significantly reduced with increased the vibration exposure (maximal weighted acceleration on any tool, or maximal weighted $A(8)$, or current weighted acceleration), room temperature and gender. However, duration of exposure, or vibration doses involving combinations of exposure duration and vibration magnitude were not significantly related to $FSBP\%_{10°}$. In consequence, the results suggest that exposure duration was of greater importance than vibration magnitude. Thermal thresholds for warmth and cold showed evidence of being impaired due to vibration exposure, despite the young age of the participants, although dose-response relationships could not be established. There was evidence of increased neck pain in those exposed to vibration.

Acute vascular responses

Three experimental studies undertaken jointly by UTRS and UoS investigated acute vascular effects (i.e., changes in finger blood flow) of hand-transmitted vibration. It was found that the measure of dose (formed from the acceleration magnitude, *a*, and the duration of vibration exposure, *t*) that best reflects digital vasoconstriction following vibration exposure is $a.t$ (or possibly $a.t^2$) . The use of $a.t$ during the day (as well as over years) would make the calculation of 'dose' easier. It would also put more 'weight' on the duration of daily exposures to hand-transmitted vibration than when using the a^2t relationship underlying the current calculation of the daily $A(8)$.

For the range of vibration magnitudes investigated (44 to 176 m/s^2 r.m.s. unweighted; 5.5 to 22 m/s^2 r.m.s. when frequency-weighted according to ISO 5349), the vasoconstriction during exposure to 125-Hz vibration was independent of vibration magnitude. The after-effect of vibration was different for stimuli having the same 'energy-equivalent' acceleration, with greater effects following longer durations of exposure. The 'energy-equivalent' acceleration failed to predict the acute effects of vibration both during and following vibration exposure.

The acute vascular response to continuous and intermittent vibration with the same total duration of vibration exposure and the same energy-equivalent acceleration magnitude found the same reduction in finger blood flow during exposure with continuous and intermittent vibration. The after-effect of vibration was greater following the continuous vibration exposure, giving a hint that intermittent vibration may have a less severe effect than continuous vibration.

A study of the combined effects of force and vibration on finger circulation found that modest levels of force applied by a finger had a large effect on finger blood flow. The acute vascular effects of vibration caused additional reductions in finger blood flow that were not limited to the finger experiencing force and vibration.

Overall, these experimental studies cast doubt on the suitability of the current methods of evaluating the severity of hand-transmitted vibration and suggest that the contact force, or pressure, should be taken into account when considering the effects of hand-transmitted vibration.

Neurological Responses

Chronic neurological responses

In the epidemiological studies conducted in Italy, sensorineural symptoms (tingling, numbness, and suspected carpal tunnel syndrome) were less clearly related to measures of daily and cumulative vibration dose than vascular disorders. There was no clear preference for weighted or unweighted acceleration or any particular power when forming cumulative vibration dose. Similar to vascular symptoms, associations between sensorineural disorders and measures of lifetime exposure duration (years of exposure and total operating time with vibrating tools) were weak.

There was no statistically significant effect of ergonomic risk factors (neck-upper arm posture, hand-intensive work, or total ergonomic score) on the occurrence of vascular, sensorineural, or suspected carpal tunnel syndrome in workers exposed to hand-transmitted vibration.

The Swedish epidemiological studies found that thermal thresholds for warmth and cold showed evidence of being impaired due to vibration exposure, despite the young age of the participants, although dose-response relationships could not be established.

Acute neurological responses

Experimental studies were undertaken by UMUH in Sweden to determine the acute neurological responses (changes in thresholds for the perception of vibration and temperature) to hand-transmitted vibration. The frequency and magnitude of hand-transmitted vibration, but not the exposure duration, influenced the extent of elevations in vibration perception thresholds after the cessation of vibration. The thermal thresholds were affected by the magnitude and the duration of hand-transmitted vibration.

Manipulative dexterity and musculoskeletal findings

Studies conducted by UTRS in Italy found that manipulative dexterity, as measured using the Purdue pegboard, was lower in workers exposed to hand-transmitted vibration than in control subjects not exposed to hand-transmitted vibration. Manipulative dexterity seemed also to be affected by age and smoking, and ergonomic stress (neck-upper arm posture, hand-intensive work, total ergonomic score). After adjusting for individual characteristics and follow up time, Purdue pegboard scores for the dominant hand, non-dominant hand and both hands decreased with the increase of cumulative vibration dose and ergonomic stress

The Swedish epidemiological studies found evidence of increased neck pain in those exposed to vibration, despite the young age of the participants.

Effects of prior exposure to hand-transmitted vibration on finger systolic blood pressures, vibrotactile thresholds, and thermal thresholds.

Experimental studies investigated the extent to which the results of commonly used diagnostic indicators (finger systolic blood pressure, vibrotactile thresholds, and thermal thresholds) are affected by prior exposure to hand-transmitted vibration.

Studies undertaken in the UK jointly by UTRS and UoS concluded that in healthy men recent exposure to force at the hands and moderate levels of hand-transmitted vibration did not affect the response of finger circulation to cold provocation 30 minutes after the end of vibration.

The experimental studies by UMUH in Sweden found that 2 minutes was sufficient to recover thermal thresholds and 30 minutes was sufficient to recover vibrotactile thresholds.

The findings are of practical importance for the definition of test conditions in the field, especially the length of time required between the last occupational exposure to tool vibration and the commencement of objective vascular testing. It seems that a 30-minute rest form vibration may be sufficient, but a longer period might be appropriate in some cases.

2.6.4 Discussion

One output from the epidemiological studies is experience in using the diagnostic protocol developed during the research and presented in Section 2.1. Apart from the benefits from the individual studies, the research assisted the development of the protocol, which will be applied in studies conducted within Europe and world-wide.

The epidemiological studies are almost unique in being undertaken simultaneously using the same protocol in different countries.

In the Italian studies, two laboratory tests (i.e. finger systolic blood pressure and the Purdue pegboard), showed deterioration associated with vibration confirming their value for prospectively monitoring of vascular and sensory dysfunction in vibration-exposed workers. The colour charts showed promise as a means of improving the reporting of vascular symptoms, especially the reduction of false positive responses.

Measures of daily vibration exposure derived from unweighted acceleration magnitude gave better predictions of symptoms and signs of vibration-induced disorders than measures derived from acceleration magnitude frequency-weighted according to current standards.

Measures of vibration dose estimated from combinations of vibration magnitude and duration of exposure provided better predictions of the occurrence of upper limb disorders than doses determined solely by lifetime exposure duration (years of exposure or total hours of tool use). Dose measures with high powers of acceleration (i.e. $\Sigma a_i^m t_i$ with $m > 1$) tended to provide better fits to the data that those with lower powers. Moreover, lifetime cumulative vibration doses ($\Sigma a_i^m t_i$) derived from unweighted acceleration magnitude gave better predictions for symptoms and signs of vibration-induced disorders than measures derived from acceleration magnitude frequency-weighted.

The Swedish studies found evidence of vibration affecting finger systolic blood pressures, but in a group of young workers with little exposure the effect was only significantly related to exposure duration and not to the magnitude of vibration.

The results from the epidemiological studies have only recently been obtained and merit further analysis and consideration before firm statements are made on their interpretation. However, he present studies are not the first to conclude that the currently used frequency weighting (i.e. W_h) for evaluating vibration with respect to vascular disorders is not optimum (e.g. …). Experimental studies of the acute vascular response also show that the frequency weighting is not sufficient to reflect the changes in sensitivity with changing frequency of vibration. The evidence therefore suggests that changes to the current frequency weighting are needed.

2.6.5 Conclusions

The findings of both the experimental studies and the epidemiological surveys of workers exposed to hand-transmitted vibration suggest that improvements are possible to both the frequency weighting and the time-dependency used in current standards to predict the development of vibration-induced disorders. However, further analysis and interpretation is required before the possible form of recommended changes can be suggested.

The results confirm that the finger systolic blood pressure after cold provocation is related to vibration exposure, and that both thermal thresholds and vibrotactile thresholds are indicators of sensorineural damage caused by hand-transmitted vibration. The development of colour charts has provided a useful procedure to assist future diagnosis of vascular disorders caused by hand-transmitted vibration.

The diagnostic protocol developed during the studies is an important tool available for use world-wide to assist the design of epidemiological studies and workplace assessments in respect of hand-transmitted exposures to vibration.

3 Whole-body Vibration

3.1 Protocol for epidemiological studies of whole-body vibration

3.1.1 Introduction

Early discussions among the VIBRISKS partners led to a decision to draft a protocol for the methodology to be employed in epidemiological studies of whole-body vibration (Annex 12) and an equivalent protocol for epidemiological studies of hand-transmitted vibration (Annex 1).

The protocol for whole-body vibration was initially drafted by the leader of work package 4 in collaboration with the other partners involved in work packages 4 to 6. The protocol provided a methodology which was employed in longitudinal and case-control studies performed within work package 5 and in whole-body vibration measurements used in work package 6 as input for modelling of spinal stress. At each meeting of the partners, the protocol was reviewed and suggestions were made for revised and/or additional content. Annex 12 presents the final version of the protocol.

The various partners conducted studies with slightly differing purposes, so not all parts of this protocol are appropriate for all studies. Nevertheless, the protocol assisted the design and conduct of studies having as many similarities as possible, thereby maximising the comparison of results from the research. The protocol is likely to be useful for future studies conducted outside VIBRISKS.

3.1.2 Objectives

The objectives were to:

i) define and agree on methods for the assessments of disorders caused by whole-body vibration and alternative measures for quantifying the severity of exposure to whole-body vibration to be used in the longitudinal and case-control epidemiological studies conducted in work package 5,

ii) define and agree on a protocol for acquisition of whole-body vibration exposure data to be used in the experimental studies in work package 6.

3.1.3 Methods and results

The final protocol (Annex 12) is a document of 85 pages presented with eight sections and six appendices.

3.1.3.1 Introduction

The Introduction explains that the protocol was developed for use by partners in VIBRISKS but that it was envisaged that the document may also be useful for others conducting epidemiological and experimental studies related to whole-body vibration.

3.1.3.2 General aspects on WBV Exposure

Current standards and legislation make large assumptions on the manner in which the risks from exposures to whole-body vibration depend on the magnitude, frequency, direction, and duration of exposure. One objective of the studies within VIBRISKS, and no doubt future epidemiological studies, was to investigate the validity of the current assumptions.

The *determinants* of whole-body vibration exposure, such as information on vehicle type or machines driven, driving environment, ground surface, type of driver seat, and behavioural factors such as style and speed of driving, adjustment and use of the seat shall be noted as a part of the measurement protocol.

The vibration magnitude should be measured during representative working conditions in three orthogonal axes on the supporting seat surface beneath the ischial tuberosities of the driver in accordance with the International Standard ISO 2631. Measurement should be recorded as frequency un-weighted acceleration time histories in the x-, y- and z-direction.

The duration of the exposure should be determined by estimation of daily, weekly and yearly exposure to whole-body vibration based on data obtained from the VIBRISKS self-administered questionnaire (Appendix 4 and 5 of Annex 12) and/or as a part of the measurement protocol. If available, company records of individual exposure to whole-body vibration can be used.

3.1.3.3 Reported and observed exposure durations

It is not easy to obtain an accurate estimate of the duration of exposure to whole-body vibration. There can be differences between actual and estimated durations of exposure. For research purposes, it is desirable to obtain accurate estimates of the durations of exposures to whole-body vibration. This may require direct observation or indirect measurement of the duration of vibration exposure. The discrepancy between actual and estimated durations of exposure has not been recognized in the evolution of dose-response relationships in guidance on the risks arising from whole-body vibration. In consequence, since actual exposures are often less than estimated exposures, accurately measured exposure durations may underestimate the risk if they are compared with current guidance.

3.1.3.4 Measures of vibration dose

Appendix 2 of the protocol specifies the method of calculating 15 alternative measures of dose for exposures to whole-body vibration in the current task. Two additional measures of doses for past and leisure exposure are also specified. The measures include those in past and current whole-body vibration standards, but also include some additional measures to assist the development of a better understanding of the relative importance of vibration magnitude, vibration frequency, vibration direction, and duration of vibration exposure. These measures of whole-body vibration doses have been used in the longitudinal and case-control studies of whole-body vibration conducted within VIBRISKS.

3.1.3.5 Summary of vibration exposures and effects

Exposures to whole-body vibration and their effects are complex and often summarised by only a few measures, such as the average vibration magnitude and the prevalence of some typical symptoms.

To assist and encourage a more complete summary presentation of findings, Appendix 3 of the protocol gives a summary table that combines typical summary descriptions of the exposed population and their exposures to whole-body vibration with typical summary descriptions of relevant aspect of their health.

The summary table was evolved for the purposes of illustration within VIBRISKS, and was used by partners undertaking epidemiological studies of the effects of whole-body vibration within VIBRISKS, but it should also be useful for other epidemiological studies in the future.

3.1.3.6 Questions to be addressed by the data analysis

In addition to the tabular summary, it was decided that VIBRISKS reports of epidemiological studies on whole-body vibration should provide the following information:

1. Prevalence of musculoskeletal symptoms in the neck, shoulder, and low back (the last 7 days, the last 12 months) in the cross-sectional survey of the study population.
2. The VAS score for the musculoskeletal pains and the Roland Morris score.
3. Incidence of musculoskeletal symptoms at the follow up survey(s) of the study population.
4. Comparison of VAS and Roland-Morris scores between the cross-sectional and follow up survey(s).
5. Metrics of vibration exposure according to the protocol for dose calculations.
6. Ergonomic risk factors according to the WBV questionnaire.
7. Possible exposure-response (for symptoms) or dose-effect (for score results) relationships at the cross-sectional survey.
8. Possible exposure-response (for symptoms) or dose-effect (for score test results) relationships for the changes in the outcomes over time during the follow up period(s).
9. Contribution of the vibration and the ergonomic exposure factors (vibration dose measures and lifting postures) used to construct doses for the prediction of outcomes (symptoms and score results) over time, adjusted for personal, social and health covariates.
10. Work ability “How much time did you have to take off work due to back/leg pain? (neck, shoulder)” in the cross-sectional studies and change of work ability at follow-ups.

3.1.3.7 Questionnaires

Four questionnaires were developed within VIBRISKS and are presented in appendices to the protocol:

(i) Self-administered questionnaire for longitudinal studies – Initial Questionnaire (Appendix 4A),

(ii) Self-administered questionnaire for longitudinal studies – Follow-up Questionnaire (Appendix 4B),

(iii) Self-administered questionnaire for case-control studies – Cases (Appendix 5A),

(iv) Self-administered questionnaire for case-control studies – Controls (Appendix 5B).

All questionnaires include basic questions related to the headings: *About your self*, *Current work*, *Past work*, *Your health*, *Other symptoms and feelings*. The whole-body vibration self-administered questionnaires, Initial assessment and Follow-up, for longitudinal studies contain 17 and 16 pages. The case control study questionnaire for “cases” is 15 pages and for “controls” is 12 pages in length.

In all epidemiological studies, past and present whole-body vibration and ergonomic exposure and concomitant factors (posture, individual characteristics, climate /coldness in the cabin) must be assessed in terms of job title(s), type of vehicles used, duration of exposure, and the age during the exposure.

The VIBRISKS initial questionnaires for longitudinal studies were based on questionnaires originally developed within the Vibration Injury Network (VINET), a former EU-funded network involving the current partners. However, the questionnaires were improved from the experience of the partners. The follow-up questionnaires were newly constructed for the purposes of the longitudinal studies to be performed within VIBRISKS.

The VINET questionnaires were made available from the VINET website and have been accessed by many involved in research of vibration-exposed workers. The newly developed VIBRISKS questionnaires for longitudinal studies have also been made public on the VIBRISKS website and are currently available in English, Italian, Dutch, and Swedish.

3.1.3.8 References

The references to publications used for the development of the protocol are listed.

3.1.4 Conclusions

The evolution of the protocol provided a useful focus for discussion among partners, helping to unify understanding of the relevant issues concerned with exposures to whole-body vibration and the questioning of workers exposed to whole-body vibration. This protocol assisted the epidemiological studies conducted within work package 5, the whole-body experimental work conducted within work package 6 and the collection of data used to form an opinion on dose-response relationships.

The protocol contains valuable guidance for others wishing to undertake epidemiological studies of the effects of whole-body vibration. Just as the protocol grew out of the experience of partners within VINET, it is to be hoped that future collaboration between partners will allow the protocol to be developed further in the future.

3.2 Epidemiological surveys of workers exposed to whole-body vibration

3.2.1 Longitudinal epidemiological surveys in Italy

3.2.1.1 Introduction

Exposure to whole-body vibration (WBV) in professional drivers of industrial machines and/or vehicles is associated with an excess risk for back symptoms and disorders of the lumbar tract of the spine. Reviews of the epidemiological literature have reported that the occurrence of low back pain (LBP) and early degeneration of the lumbar spine, including intervertebral disc disorders, is greater in professional drivers than in controls groups unexposed to WBV (Bovenzi and Hulshof (1999), Burdorf and Sorock (1997), Comité Européen de Normalisation (1996), Griffin (1990) and NIOSH (1997)).

This study reports the findings of a prospective cohort survey of dose-response relationship for low back disorders in WBV-exposed drivers carried out in Italy.

3.2.1.2 Objectives

The aim of this study was to investigate the prevalence and incidence of low back pain outcomes in various groups of Italian professional drivers. Vibration measurements were performed on a representative sample of the machines and vehicles used by the various driver groups. Finally, the association between low back disorders, WBV exposure, physical load factors, and psychosocial variables was investigated while controlling for potential individual confounders recognised as risk factors for low back pain.

3.2.1.3 Methods

Study population

In the Italian survey, the study population of the cross-sectional survey (survey 1: 2003-04) included 598 male professional drivers employed in several industries and public utilities located in Lucca, Massa Carrara, Siena, and Viareggio (Tuscany Region), Chiavari (Liguria Region), Modena (Emilia Romagna Region) and Trieste (Friuli Venezia Giulia Region).

Since the cohort was of dynamic type, drivers entered and left the cohort during the first follow-up survey (survey 2: 2004-05) and the second follow-up survey (survey 3: 2005-06). In detail, 283 drivers participated in only a cross-sectional survey (145 in survey 1, 86 in survey 2, and 52 in survey 3); 321 drivers participated in one follow-up survey (109 in surveys 1 and 2, 57 in surveys 1 and 3, and 155 in surveys 2 and 3), and 317 drivers participated in two follow-up investigations (i.e. in surveys 1, 2, and 3). Overall, 921 drivers participated in the VIBRISKS study, and 638 drivers underwent at least one follow-up investigation. Reasons for leaving the cohort were change of job (23%), change of residence (15%), organisational difficulties associated with job-linked time schedules (18%), sickness on the day of the investigations (20%), refusal to participate in the follow-up studies (10%), and undetermined causes (14%).

This report provides information on the findings of the epidemiological surveys of the drivers with complete follow-up (i.e. those who participated in surveys 1, 2, and 3, n=317).

A minimum of one year of professional driving in current job was established as the basic criterion for the inclusion of drivers in the study population.

The WBV-exposed population included 76 drivers of earth-moving machines and articulated trucks employed in marble quarries, 43 drivers of fork-lift trucks and mobile cranes employed in marble laboratories, 32 drivers of fork-lift trucks, container stake trucks and freight-container tractors employed in dockyards, 32 drivers of fork-lift trucks employed in paper mills, 50 drivers of garbage trucks, garbage compactors and track-type loaders employed in public utilities, and 84 bus drivers of mini-buses and city buses.

The questionnaire

The questionnaire used in this study was originally developed within the European project VINET (*Vibration Injury Network*, http://www.humanvibration.com/EU/VINET/VINET_index.htm) The questionnaire consisted of four major sections dedicated to personal and general information, occupational history, and personal medical history. Workers were interviewed by certified occupational health personnel who were trained to conduct the interview in a standardised way. For this purpose, specific meetings were organised to test the method of administration of the questionnaire to workers.

Definition of LBP outcomes

On the basis of the items included in the medical section of the questionnaire, LBP outcomes were defined as follows:

(i) **LBP**: pain or discomfort in the low back area between the twelfth ribs and the gluteal folds (indicated in a figure), with or without radiating pain in one or both legs, lasting one day or longer in the previous seven days (7-day LBP) or the previous twelve months (12-month LBP).

(ii) **High pain intensity**: LBP in the previous 12 months associated with a pain score ≥ 5 (Von Korff scale: Von Korff *et al*, 1992).

(iii) **LBP disability**: last episode of LBP associated with a disability score ≥ 12 (Roland & Morris scale; Roland and Morris, 1983).

(iv) **Sciatic pain**: radiating pain in one or both legs in the previous 12 months.

(v) **Acute LBP**: sudden attack of low back pain producing abnormal or locked posture of the back in the previous 12 months.

(vi) **Treated LBP**: low back pain treated with anti-inflammatory drugs or physical therapy in the previous 12 months.

(vii) **Sick leave**: sick leave > 7 days due to LBP in the previous 12 months.

Measurement and assessment of vibration exposure

Vibration measurements were made on representative samples of industrial machines and vehicles (n=74) used by the professional drivers. Vibration was measured at the driver-seat interface during actual operating conditions according to the recommendations of the International Standard ISO 2631-1 (1997). From one-third octave band frequency spectra (1-80 Hz) recorded from *x*-, *y*-, and *z*-directions, frequency-weighted root-mean-square (r.m.s.) accelerations (a_{wx}, a_{wy}, a_{wz}) were obtained by using the weighting factors suggested by ISO 2631-1.

The root-sums-of-squares (sometimes referred to as the “vector sum” or “total value”) of the r.m.s. values of the weighted accelerations, a_{ws}, was calculated according to the following formula:

$$a_{ws} = [(1.4a_{wx})^2 + (1.4a_{wy})^2 + a_{wz}^2]^{1/2} \qquad (\mathrm{ms}^{-2})$$

The frequency-weighted root-mean-quad (r.m.q.) accelerations were calculated from the Vibration Dose Value (*VDV*, see below) by dividing the *VDV* by the fourth root of the exposure duration (in seconds).

The root-sums-of-quads of the r.m.q. values of the weighted accelerations, a_{wq}, were calculated according to the following formula:

$$a_{wq} = [(1.4a_{wx})^4 + (1.4a_{wy})^4 + a_{wz}^4]^{1/4} \qquad (\mathrm{ms}^{-2})$$

For each operator, questionnaire data and company records were used to estimate daily exposure to WBV expressed in driving hours, as well as the total duration of exposure to WBV in full-time driving years.

Daily vibration exposure was expressed in terms of 8-h energy-equivalent frequency-weighted acceleration magnitude (*A*(8)) according to the EU European Directive 2002/44/EC on mechanical vibration (EC, 2002):

$$A(8) = a_w (T/T_0)^{1/2} \qquad (\mathrm{ms}^{-2}\ \mathrm{r.m.s.})$$

where T is the total daily duration of exposure to the vibration a_w, and T_0 is a reference duration of 8 h.

a_w was included as either the vibration total value ($A_v(8)$), or the highest (dominant) value of the frequency-weighted r.m.s. accelerations determined on the three orthogonal axes ($A_{dom}(8)$), as required by the European Directive 2002/44/EC on mechanical vibration (EC, 2002).

Daily vibration exposure was also expressed in terms of Vibration Dose Value (*VDV*), according to the fourth power vibration dose method:

$$VDV = \left\{ \int_0^T [a_w(t)]^4 \, dt \right\}^{1/4} \qquad (\mathrm{ms}^{-1.75})$$

where $a_w(t)$ is the instantaneous frequency-weighted acceleration, and T is the duration of measurement.

The *VDV* measures were expressed as either summation over axes (VDV_{sum}), or the highest (dominant) directional component (VDV_{dom}), as required by European Directive 2002/44/EC.

Frequency-weighted acceleration of vibration and duration of exposure were used to construct measures of cumulative vibration dose estimated as:

$$dose = \sum_i [a_i^m t_i]$$

where a_i is the vibration total value of either the frequency-weighted r.m.s. accelerations (a_{ws}) or the frequency-weighted r.m.q. accelerations (a_{wq}) measured on machine *i* driven for time t_i in hours (h/d $\times$ d/yr $\times$ years).

Assessment of physical load

Heavy physical work was graded by rating the frequency of manual activities on a 3-point response scale. Awkward postures were graded by rating the duration of each posture on a 4-point time scale. A mean value of physical load variables during a typical working day was calculated for each subject. In the total sample, the average physical load index was divided into quartiles (q) which were assumed to correspond to four grades of increasing physical load: 1st q=mild load grade, 2nd q=moderate load grade, 3rd q=hard load grade, 4th q=very hard load grade.

Data analysis

The association between LBP outcomes and several independent variables over time was assessed by random-intercept logistic regression analysis. Odds ratios (OR) and 95% confidence intervals (95% CI) were estimated from the logistic regression coefficients and their standard errors. The magnitude of the likelihood ratio (LR) chi-square statistic was used to assess the “importance”, in statistical terms, of the alternative measures of vibration exposure for the prediction of the outcome. The Bayesan Information Criterion (BIC) was used as a measure of overall fit and a means to compare regression models including alternative measures of cumulative vibration dose.

3.2.1.4 Results

Vibration measurements

In marble quarries, the vibration total value (a_v) of the weighted r.m.s. accelerations averaged 0.57 to 0.69 ms^{-2} r.m.s. in earth moving machines and 0.5 to 1.1 ms^{-2} r.m.s. in transport vehicles. The lowest a_v values were measured on garbage machines (0.29-0.31 ms^{-2} r.m.s.) and on mobile cranes used in marble laboratories (0.32 ms^{-2} r.m.s.). Vibration from buses varied from 0.51 (minibus) to 0.61 ms^{-2} r.m.s. (city bus). The average a_v measured on fork-lift trucks used in marble laboratories was two to three times greater (1.1 ms^{-2} r.m.s.) than those measured on fork-lift trucks driven in dockyards (0.54 ms^{-2} r.m.s.) and paper mills (0.36 ms^{-2} r.m.s.).

Characteristics of the study groups

There were significant differences in vibration exposure between the driver groups (Tables 3.1 and 3.2). Total duration of exposure to WBV in either full-time driving years or total driving hours were significantly greater in bus drivers and drivers employed in marble quarries and paper mills compared with the other groups. Daily vibration exposure in terms of $A_v(8)$ ranged from 0.28 (drivers of garbage machines) to 0.61 ms^{-2} r.m.s. (drivers of earth moving machines), p<0.001. Similarly, daily vibration exposure in terms of VDV_{sum} ranged from 5.5 $ms^{-1.75}$ (drivers of garbage machines) to 12.4 $ms^{-1.75}$ (drivers of earth-moving machines). It should be noted that when daily vibration exposure was expressed as $A_{dom}(8)$ according to the EU Directive on mechanical vibration, no driver group exceeded, on average, the daily exposure action value established by the Directive (0.5 ms^{-2} r.m.s.). On the contrary, when daily vibration exposure was expressed as VDV_{dom}, the EU daily exposure action value (9.1 $ms^{-1.75}$) was exceeded, on average, in the marble industry and dockyards.

Vibration doses estimated as either $\sum[a_{wsi}{}^{m}t_i]$ or $\sum[a_{wqi}{}^{m}t_i]$ were significantly higher in the drivers of earth moving machines (marble quarries), fork-lift trucks (marble laboratories and dockyards) and, at least partially, buses than in the other driver groups (p<0.001).

Low back pain and individual, occupational, and psychosocial variables

Prevalence and incidence of LBP symptoms

Table 3.3 reports the point prevalence in the cross-sectional survey in 2003-2004, the prevalence over the study period 2003-2006, and the cumulative incidence over the follow-up period (2004-2006) for low back disorders in the driver population. In the cross-sectional survey, the point prevalence of the various LBP symptoms varied from 16.6% (acute LBP) to 40.1% (unspecific LBP). High pain intensity in the lower back in the previous 12 months (Von Korff pain score > 5) was reported by 28.7% of the subjects. About 19% of the subjects complained of LBP disability (Roland & Morris disability scale score ≥ 12) in the previous 12 months. Health care use for LBP (visit to a doctor, treatment) was reported by 25-30% of the subjects. Overall, low back symptoms were complained of by 64.4% of the drivers at the cross-sectional survey. Sick leave due to LBP in the previous 12 months was reported by 3.2% (> 15 days) and 12.6% (> 7 days) of the subjects. Self-reported degeneration in the lumbar disks was reported by 13.6% of the drivers. This figure was consistent with that based on MRI examination (10.1%).

Over the follow-up period during 2004-2006, the cumulative incidence of the various LBP symptoms ranged from 7.3% (acute LBP) to 47.8% (unspecific LBP). The cumulative incidence of high pain intensity and LBP disability was 28.8 and 23.8%, respectively. Two-year incidence of sick leave due to LBP was 4.9% (> 15 days) and 9.0% (> 7 days). There were 40 new cases reporting troubles in the lumbar disks (incidence 14.6%). Of those, 17 were supported by MRI examination (incidence 6.0%).

Individual variables

Univariate analysis showed that in the overall study population severe LBP outcomes (acute LBP, sciatic pain, LBP disability) tended to increase over time with the increase of age. After adjustment for age, there were no clear associations between LBP outcomes and smoking, marital status, and private car driving. An increased occurrence of some forms of LBP symptoms was found for drinking habit and level of formal education. The occurrence of acute LBP, high pain intensity, LBP disability, and sick leave due to LBP tended to increase with increasing body mass index (BMI), and significant associations were found for overweight persons (BMI > 27). Regular physical activity was associated with a lower risk of 12-month LBP, LBP disability, treated LBP, and sick leave due to LBP.

Physical variables

The various LBP outcomes were not significantly associated with previous jobs with either WBV exposure or heavy physical demands. Overall, work-related physical load factors, treated as dichotomous variables, were positively related to LBP. Awkward postures at work, such as trunk twisting while lifting loads and back bent forward or twisted while driving, showed significant associations with pain intensity and disability, treated LBP and sciatic pain.

Psychosocial variables

No clear pattern of association between LBP and psychosocial factors at work was observed in the study population. LBP in the last 7 days and the last 12 months showed significant associations with some items for job decision. Sciatic pain, LBP disability, treated LBP and sick leave due to LBP showed a positive trend, although not significant, with job dissatisfaction.

LBP outcomes in the driver groups

Assuming the driver group with the lower WBV exposure (public utilities, garbage) as an internal reference category, almost all other driver groups showed a greater incidence of

LBP outcomes over the follow-up period. When compared with the internal reference group, excess risks for 12-month LBP, sciatic pain and sick leave due to LBP were observed in the other driver groups, even though significantly increased ORs were found only for drivers employed in the dockyards. After adjustment for age and survey, significantly increased ORs for LBP disability were found in the drivers employed in marble quarries, dockyards, paper mills, and public utilities (bus).

Low back pain and vibration exposure

To assess possible exposure-response relationship for LBP outcomes in the professional drivers, measures of vibration exposure, such as $A(8)$, VDV, duration of exposure in years, and vibration doses of the form $\sum[a_i^m t_i]$, were divided into quartiles assuming the lowest quartile as the reference category.

Tables 3.4 to 3.7 report, as examples, the results of random-intercept logistic analysis for the relation over time between LBP outcomes and daily and cumulative vibration exposures, while adjusting for several covariates such as individual characteristics (age, BMI), physical load factors, psychosocial factors, back trauma, previous jobs at risk, and survey.

In general, the relation between LBP outcomes and the various measures of daily vibration exposure were poor, with the exception for LBP disability which showed a significantly increasing trend of occurrence with increase in $A_v(8)$ and VDV_{sum} (Table 3.4). Some significant associations were also observed between sciatic pain and daily driving time, $A_v(8)$, and $A_{dom}(8)$.

The occurrence of LBP in the previous 12 months was significantly associated only with $\sum[t_i]$, (Table 3.5). A trend, although not significant, of increasing ORs for 12-month LBP was observed for $\sum[a_{wqi}t_i]$.

The occurrence of sciatic pain in the previous 12 months was significantly related to all measures of cumulative vibration dose. The associations were stronger for $\sum[t_i]$, $\sum[a_{wsi}t_i]$, $\sum[a_{wqi}t_i]$ and $\sum[a_{wqi}^2 t_i]$.

Trends of an increased risk of high pain intensity and LBP disability (Table 3.7) with an increase in vibration exposure were observed for all measures of cumulative vibration dose. The occurrence of both high pain intensity in the lower back and LBP disability was mainly associated with $\sum[t_i]$, $\sum[a_{wqi}t_i]$ and $\sum[a_{wqi}^2 t_i]$.

Low back pain and other physical load factors

Owing to differences in the frequency and duration of awkward postures at work between the various driver groups, no specific posture showed an evident trend of association with LBP outcomes. Walking and standing at work, as well as sitting more than 3 h/day other than when driving, were not related to any LBP outcome.

After adjustment for potential confounders, the likelihood ratio statistic showed that the occurrence of LBP in the last 12 months was significantly associated with working with trunk bent > 40° and with driving with back bent forward or twisted. This latter was also predictive for LBP disability.

When the several physical load variables were averaged within each subject to obtain a combined physical load index (see methods), the adjusted ORs showed a clear pattern of increasing risk over time for 12-month LBP, sciatic pain, LBP disability, and treated LBP with the increase of physical load grade from mild to very hard (Table 3.8).

3.2.1.5 Discussion

In this study, we have estimated $A(8)$ using either a_v ($A_v(8)$) or the highest r.m.s. value of the dominant axis of vibration ($A_{dom}(8)$) as the measure of frequency-weighted acceleration magnitude to be included in the equation $A(8) = a_w (T/T_0)^{½}$. In each driver group of this study, $A_v(8)$ was significantly greater than $A_{dom}(8)$ (p<0.001). The EU Directive on mechanical vibration has established a daily exposure action value $A_{dom}(8)$ of 0.5 ms^{-2} r.m.s. above which the employer must implement a programme of technical and/or organisational measures intended to reduce to a minimum exposure to mechanical vibration and the associated risks (Directive 2002/44/EC, 2002). Moreover, workers exposed to WBV in excess of the action value are entitled to appropriate health surveillance. In this study, 75 drivers (23.7%) were exposed to $A_v(8)$ greater than the daily exposure action value of 0.5 ms^{-2} r.m.s., while this figure reduces to 33 drivers (10.4%) when daily vibration exposure was estimated as $A_{dom}(8)$. As a result, if $A_{dom}(8)$ is adopted as the basic indicator for the assessment of daily vibration exposure, in our study about 13% of the drivers would be excluded from health surveillance in case this latter is considered compulsory only for workers exposed to $A_{dom}(8)$ above the action value. It should be noted that most of the EU Countries have adopted the $A(8)$ criterion instead of the *VDV* criterion for the definition of daily action value and daily exposure limit value. In this study, 108 drivers (34.1%) were exposed to VDV_{dom} greater than the daily exposure action value of 9.1 $ms^{-1.75}$. This is a matter of concern for the occupational health physician because the adoption of the VDV_{dom} criterion for the definition of daily action value would result in a higher level of health protection for the drivers of this study since health surveillance would involve 34% of the drivers (VDV_{dom} criterion) vs 10% of the drivers ($A_{dom}(8)$ criterion).

The findings of this study on LBP prevalence in the various driver groups are consistent with those reported in other investigations carried out in Germany, Denmark, Finland, and other EU and North-American Countries. In this study, the cumulative incidence of LBP symptoms over the follow-up period varied from 7.3% (episodes of acute LBP) to 35% (treated LBP). The cumulative incidence of all LBP symptoms was about 48%, and that of lumbar hernia detected by means of MRI was 6%. It is difficult to compare these figures with those of other studies, because the number of reports on WBV-exposed drivers based on incident data is very limited in the literature.

The epidemiological findings of an excess risk for LBP outcomes in the WBV-exposed professional drivers of this longitudinal study seem to be consistent with the experimental findings of WBV laboratory investigations and biodynamic modelling reported in VIBRISKS WP6. Combining experimental laboratory data, field measurements of WBV, posture, and anthropometry, as well as FE-modelling based on real anatomy, an increased risk of fatigue failure of the vertebral endplate due to repeated compression may be predicted for workers driving forklift trucks in paper mills and dockyards, and forklift trucks, wheel loaders, and truck excavators in marble quarries and laboratories surveyed in this epidemiological study.

In this study, we attempted to explore some preliminary elements of dose-response relationship for LBP outcomes by pooling exposure and health data from the whole driver population. Multivariate data analysis showed that the currently recommended measures of daily vibration exposure, $A(8)$ or *VDV*, were poorly associated with most of the LBP outcomes, except for sciatic pain and LBP disability. Duration of exposure in terms of total driving hours ($\sum[t_i]$) was a better predictor of LBP than full-time driving years. Of the several measures of cumulative vibration dose computed from weighted acceleration magnitude (a_{wsi} *or* a_{wqi}) and total driving hours (*ti*), dose measures which gives equal weight to a_i and t_i, i.e. $\sum[a_{wsi}t_i]$ and $\sum[a_{wqi}t_i]$, were significantly associated with several LBP outcomes investigated in this study. Some significant associations were also found between dose $\sum[a_{wqi}^2t_i]$ and selected LBP outcomes (12-month sciatic pain, high intensity pain in the lower back, LBP disability). Based on the LR and BIC statistics, as well on the patterns of the ORs, in general lifetime exposure duration (total driving hours, $\sum[t_i]$) gave better predictions for 12-month LBP and sciatic pain than dose measures obtained by combining weighted acceleration magnitude and total exposure duration. On the other hand, dose measures of the form $\sum[a_{wqi}t_i]$ and $\sum[a_{wqi}^2t_i]$ were better predictors of LBP disability than dose determined solely by lifetime exposure duration (without consideration of the vibration magnitude).

The weak association between daily vibration exposure, *A*(8) or *VDV*, and LBP in the drivers of this study may depend on the chronic nature of low back symptoms or disorders whose appearance and development require a gradual accumulation of vibration-induced injuries over time. This may explain our findings that measures of vibration dose which include lifetime exposure duration were better predictors of LBP than a dose measure, such as *A*(8) or *VDV*, that takes into account only current daily exposure time.

In this study, non-neutral trunk postures while driving were significant predictors of LBP. A physical load index, derived from combining manual materials handling and awkward postures, was significantly related (on a log-scale) to various LBP outcomes. After adjusting for vibration exposure and other individual and work-related risk factors, the excess risk of LBP was significantly increased for hard and very hard physical load grade when compared with mild grade. These findings are consistent with those of several epidemiological studies, reviews and meta-analyses which concluded that there is a strong evidence for a positive relationship between (low) back disorders and lifting loads, frequent trunk bending and twisting, and WBV exposure at workplace (Bovenzi and Hulshof (1999), Burdorf and Sorock (1997) and Comité Européen de Normalisation (1996)).

3.2.1.6 Conclusions

This prospective cohort study suggests that professional driving in industry and public utilities is associated with an increased risk of work-related LBP(Bovenzi and Hulshof (1999), Burdorf and Sorock (1997), Comité Européen de Normalisation (1996), Griffin (1990) and NIOSH (1997)). Occupational exposure to WBV and physical loading factors at work are important components of the multifactorial origin of LBP in professional drivers. In multivariate data analysis, individual characteristics (e.g. age, body mass index) and back trauma were also significantly associated with LBP outcomes, while psychosocial work factors (e.g. job decision, job support) showed a marginal relation to LBP (Hartvigsen et al, 2004).

These findings are consistent with the prediction of spinal stress suggested by the experimental investigations conducted in VIBRISKS WP6.

The results of this prospective cohort study of vibration-exposed workers suggest that improvements are possible to the time-dependency used in current standards to predict the development of disorders caused by whole body vibration (WBV).

Even though the follow-up period of this prospective study may be considered too short for health outcomes with possible long time latency such as LBP, nevertheless our findings may contribute to improve knowledge of the exposure-response relationship between whole-body vibration and the occurrence of low back disorders, and to advance understanding of the other physical and psychosocial factors that combine to result in the progression of low back symptoms.

Detailed information about the findings of longitudinal studies of WBV exposed workers in Italy are reported in Annex 13.

Table 3.1 Measures of daily exposure to whole-body vibration (WBV) in the professional drivers at the cross-sectional survey (see text for definitions of WBV exposure). Data are given as means (standard deviations). Previous jobs with WBV exposure are given as numbers (%).

Measures of daily vibration exposure	Driver groups					
	Marble quarries (n=76)	Marble laboratories (n=43)	Dockyards (n=32)	Paper mills (n=32)	Public utilities (garbage) (n=50)	Public transport (bus) (n=84)
Daily driving time (h)	6.1 (2.7)	4.2 (3.2)	6.7 (1.4)	6.8 (1.7)	5.5 (0.9)	6.0 (0.9)[a]
$A_v(8)$ (ms^{-2} r.m.s.)	0.61 (0.19)	0.50 (0.27)	0.42 (0.06)	0.33 (0.05)	0.28 (0.04)	0.29 (0.03)[a]
$A_{dom}(8)$ (ms^{-2} r.m.s.)	0.41 (0.14)	0.41 (0.23)	0.29 (0.06)	0.26 (0.04)	0.21 (0.03)	0.26 (0.03)[a]
VDV_{sum} ($ms^{-1.75}$)	12.4 (3.3)	11.6 (4.3)	11.8 (0.7)	7.5 (0.6)	5.5 (0.5)	5.9 (0.5)[a]
VDV_{dom} ($ms^{-1.75}$)	10.9 (3.3)	10.8 (4.3)	11.5 (0.7)	7.0 (0.6)	5.1 (0.4)	5.8 (0.5)[a]
Previous jobs with WBV exposure (n)	22 (29.0)	13 (30.2)	11 (34.4)	9 (28.1)	38 (76.0)	53 (63.1)[b]

Kruskall-Wallis one-way analysis of variance: [a]$p<0.001$; chi-square test: [b]$p<0.01$

Table 3.2 Measures of cumulative (lifetime) exposure to whole-body vibration (WBV) in the professional drivers at the cross-sectional survey (see text for definitions of cumulative WBV exposure). Data are given as medians (quartiles).

Measures of cumulative WBV exposure	Driver groups					
	Marble quarries (n=76)	Marble laboratories (n=43)	Dockyards (n=32)	Paper mills (n=32)	Public utilities (garbage) (n=50)	Public transport (bus) (n=84)
Duration of exposure (yr)	14 (7 – 23)	10 (2 – 18)	13 (2 – 21)	5 (0.2 – 9)	7 (2 – 9)	18 (7 – 23)
$\sum[t_i]$ (h $\times 10^3$)	15.1 (4.8 – 27.7)	7.2 (2.4 – 15.1)	18.6 (3.8 – 30.2)	13.4 (6.0 – 23.7)	8.6 (3.0 – 11.5)	25.2 (8.1 – 32.6)[a]
$\sum[a_{wsi}t_i]$ (ms^{-2}h $\times 10^3$)	9.9 (3.6 – 21.3)	5.4 (1.9 – 9.7)	8.4 (1.7 – 13.6)	4.8 (2.2 -8.5)	2.9 (1.2 – 3.8)	8.6 (2.8 – 11.1)[a]
$\sum[a_{wsi}^2t_i]$ (m^{2}s^{-4}h $\times 10^3$)	6.9 (2.8 – 15.4)	3.0 (1.4 – 9.9)	3.8 (0.8 – 6.1)	1.7 (0.8 – 3.1)	1.0 (0.4 – 1.4)	2.9 (0.9 – 3.8)[a]
$\sum[a_{wsi}^4t_i]$ (m^{4}s^{-8}h $\times 10^3$)	3.8 (1.4 – 9.6)	2.2 (0.6 – 10.9)	0.8 (0.2 – 1.2)	0.2 (0.1 – 0.4)	0.09 (0.04 – 0.2)	0.3 (0.1 – 0.4)[a]
$\sum[a_{wqi}t_i]$ (ms^{-2}h $\times 10^3$)	14.0 (4.9 – 29.7)	7.5 (2.7 – 16.2)	17.8 (3.7 – 28.9)	8.1 (3.6 – 14.2)	3.9 (1.5 – 5.3)	12.3 (4.0 – 16.0)[a]
$\sum[a_{wq}{}^2{}_it_i]$ (m^{2}s^{-4}h $\times 10^3$)	15.7 (5.3 – 33.8)	5.6 (2.6 – 18.4)	16.9 (3.5 – 27.5)	4.9 (2.2 – 8.6)	1.9 (0.8 – 2.6)	6.0 (2.0 – 7.8)[a]
$\sum[a_{wqi}^4t_i]$ (m^{4}s^{-8}h $\times 10^3$)	18.4 (4.5 – 44.3)	7.6 (2.0 – 40.2)	15.4 (3.2 – 25.1)	1.8 (0.8 – 3.1)	0.4 (0.2 – 0.6)	1.5 (0.5 – 1.9)[a]

Kruskall-Wallis one-way analysis of variance: [a]$p<0.001$

Table 3.3 Point prevalence at baseline (2003-04), period prevalence (2003-06) and cumulative incidence (2004-06) of low back pain (LBP) symptoms in the professional drivers with complete follow up (n=317). Data are given as numbers (%).

Outcome	Point prevalence (2003-04)	Period prevalence (2003-06)	Cumulative incidence (2004-06)
LBP in the previous 7 days	55 (17.4)	89 (28.1)	34 (13.0)
LBP in the previous 12 months	127 (40.1)	184 (58.0)	57 (30.0)
Episodes of acute LBP in the previous 12 months	43 (13.6)	63 (19.9)	20 (7.3)
Episodes of sciatica in the previous 12 months	70 (22.1)	133 (42.0)	63 (25.5)
Any low back symptoms in the previous 12 months	204 (64.4)	258 (81.4)	54 (47.8)
Duration of LBP > 30 d in the previous 12 months	21 (6.6)	55 (17.4)	34 (11.5)
High pain intensity in the lower back in the previous 12 months (Von Korff pain score > 5)	91 (28.7)	156 (49.2)	65 (28.8)
Disability due to the last episode of LBP (Roland & Morris disability scale score ≥ 12)	61 (19.2)	122 (38.5)	61 (23.8)
Visit to a doctor for LBP in the previous 12 months	95 (30.0)	164 (51.7)	69 (31.1)
LBP treated with medication and/or physical therapy in the previous 12 months	79 (24.9)	162 (51.1)	83 (34.9)
LBP sick leave > 7 d in the previous 12 months LBP sick leave > 15 d in the previous 12 months	40 (12.6) 10 (3.2)	65 (20.5) 26 (8.2)	25 (9.0) 16 (4.9)
Back trauma	18 (5.7)	28 (8.8)	10 (3.3)
Lumbar discopathy (self reported) Lumbar hernia (self-reported) Lumbar hernia (MRI)	43 (13.6) 34 (10.7) 32 (10.1)	83 (26.2) 52 (16.4) 49 (15.5)	40 (14.6) 18 (6.4) 17 (6.0)

Table 3.4 Random-intercept logistic regression of low back pain in the previous 12 months on alternative measures of daily exposure to whole-body vibration (WBV) in the professional drivers (n=317) over two-year follow-up period. Odds ratio (OR) and 95% confidence interval (95% CI) are adjusted for several covariates (individual characteristics, physical load factors, psychosocial factors, back trauma, previous jobs at risk, and survey). Each measure of WBV exposure was included as a quartile based design variable, assuming the lowest quartile as the reference category. The likelihood ratio (LR) test for the measures of WBV exposure and the Bayesan Information Criteria (BIC) for comparison between models are given.

Measures of daily WBV exposure	Quartiles of measure of daily WBV exposure				LR test (χ^2, 3*df*)	BIC
	Q1	Q2	Q3	Q4		
Daily driving time (h)						
OR	1.0	1.76	1.92	2.19	5.08	1161
(95% CI)	(-)	(0.91 – 3.38)	(0.93 – 3.97)	(1.05 – 4.57)	(p=0.17)	
$A_v(8)$ (ms^{-2} r.m.s.)						
OR	1.0	0.92	1.18	0.76	3.64	1163
(95% CI)	(-)	(0.47 – 1.82)	(0.60 – 2.31)	(0.37 – 1.58)	(p=0.30)	
$A_{dom}(8)$ (ms^{-2} r.m.s.)						
OR	1.0	1.63	1.39	0.74	4.64	1162
(95% CI)	(-)	(0.84 – 3.20)	(0.72 – 2.67)	(0.35 – 1.57)	(p=0.20)	
VDV_{sum} (ms$^{-1.75}$)						
OR	1.0	1.33	1.29	0.82	2.16	1163
(95% CI)	(-)	(0.67 – 2.65)	(0.60 – 2.73)	(0.37 – 1.82)	(p=0.54)	
VDV_{dom} (ms$^{-1.75}$)						
OR	1.0	1.31	1.08	0.61	3.71	1163
(95% CI)	(-)	(0.65 – 2.62)	(0.52 – 2.28)	(0.28 – 1.33)	(p=0.29)	

Table 3.5 Random-intercept logistic regression of low back pain in the previous 12 months on alternative measures of cumulative (lifetime) exposure to whole-body vibration (WBV) in the professional drivers (n=317) over two-year follow-up period. Odds ratio (OR) and 95% confidence interval (95% CI) are adjusted for several covariates (individual characteristics, physical load factors, psychosocial factors, back trauma, previous jobs at risk, and survey). Each measure of WBV exposure was included as a quartile based design variable, assuming the lowest quartile as the reference category. The likelihood ratio (LR) test for the measures of WBV exposure and the Bayesan Information Criteria (BIC) for comparison between models are given.

Measures of cumulative WBV exposure	Quartiles of measure of cumulative WBV exposure				LR test (χ^2, 3*df*)	BIC
	Q1	Q2	Q3	Q4		
Exposure duration (yr)						
OR	1.0	1.60	1.95	1.24	2.94	1164
(95% CI)	(-)	(0.70 – 3.66)	(0.82 – 4.66)	(0.45 – 3.43)	(p=0.40)	
$\sum[t_i]$ (h)						
OR	1.0	1.20	3.90	2.29	13.9	1153
(95% CI)	(-)	(0.59 – 2.41)	(1.76 – 8.64)	(0.94 – 5.56)	(p=0.003)	
$\sum[a_{wsi}t_i]$(ms^{-2}h)						
OR	1.0	1.30	1.84	1.75	2.51	1164
(95% CI)	(-)	(0.64 – 2.62)	(0.83 – 4.06)	(0.77 – 3.98)	(p=0.47)	
$\sum[a_{wsi}^2t_i]$ (m^{2}s^{-4}h)						
OR	1.0	1.06	1.14	1.07	0.06	1166
(95% CI)	(-)	(0.53 – 2.13)	(0.52 – 2.51)	(0.48 – 2.39)	(p=0.99)	
$\sum[a_{wsi}^4t_i]$ (m^{4}s^{-8}h)						
OR	1.0	1.34	1.19	0.68	3.40	1163
(95% CI)	(-)	(0.64 – 2.83)	(0.54 – 2.60)	(0.30 – 1.52)	(p=0.33)	
$\sum[a_{wqi}t_i]$ (ms^{-2}h)						
OR	1.0	1.46	1.98	2.11	3.67	1163
(95% CI)	(-)	(0.73 – 2.93)	(0.88 – 4.47)	(0.93 – 4.82)	(p=0.30)	
$\sum[a_{wqi}^2t_i]$ (m^{2}s^{-4}h)						
OR	1.0	1.15	1.33	1.48	0.93	1166
(95% CI)	(-)	(0.57 – 2.30)	(0.60 – 2.92)	(0.66 – 3.36)	(p=0.82)	
$\sum[a_{wqi}^4t_i]$ (m^{4}s^{-8}h)						
OR	1.0	1.16	0.85	0.89	0.67	1166
(95% CI)	(-)	(0.54 – 2.50)	(0.39 – 1.88)	(0.37 – 2.10)	(p=0.88)	

Table 3.6 Random-intercept logistic regression of disability (Roland & Morris disability scale score ≥ 12) during the last episode of LBP on alternative measures of daily exposure to whole-body vibration (WBV) in the professional drivers (n=317) over one-year follow-up period. Odds ratio (OR) and 95% confidence interval (95% CI) are adjusted for several covariates (individual characteristics, physical load factors, psychosocial factors, back trauma, previous jobs at risk, and survey). Each measure of WBV exposure was included as a quartile based design variable, assuming the lowest quartile as the reference category. The likelihood ratio (LR) test for the measures of WBV exposure and the Bayesan Information Criteria (BIC) for comparison between models are given.

Measures of daily WBV exposure	Quartiles of measure of daily WBV exposure				LR test (χ^2, 3*df*)	BIC
	Q1	Q2	Q3	Q4		
Daily driving time (h)						
OR	1.0	1.11	1.60	1.63	2.46	989
(95% CI)	(-)	(0.54 – 2.30)	(0.74 – 3.44)	(0.74 – 3.58)	(p=0.48)	
$A_v(8)$ (ms^{-2} r.m.s.)						
OR	1.0	2.13	4.10	4.16	18.9	972
(95% CI)	(-)	(0.99 – 4.55)	(1.92 – 8.78)	(1.82 – 9.50)	(p<0.001)	
$A_{dom}(8)$ (ms^{-2} r.m.s.)						
OR	1.0	1.70	1.59	2.62	5.17	986
(95% CI)	(-)	(0.81 – 3.58)	(0.76 – 3.30)	(1.13 – 6.09)	(p=0.16)	
VDV_{sum} (ms$^{-1.75}$)	5.9					
OR	1.0	1.31	3.33	2.88	9.95	981
(95% CI)	(-)	(0.63 – 2.71)	(1.49 – 7.44)	(1.21 – 6.88)	(p=0.019)	
VDV_{dom} (ms$^{-1.75}$)						
OR	1.0	1.44	2.82	2.70	7.23	984
(95% CI)	(-)	(0.69 – 3.04)	(1.26 – 6.30)	(1.15 – 6.33)	(p=0.06)	

Table 3.7 Random-intercept logistic regression of disability (Roland & Morris disability scale score ≥ 12) during the last episode of LBP on alternative measures of cumulative (lifetime) exposure to whole-body vibration (WBV) in the professional drivers (n=317) over one-year follow-up period. Odds ratio (OR) and 95% confidence interval (95% CI) are adjusted for several covariates (individual characteristics, physical load factors, psychosocial factors, back trauma, previous jobs at risk, and survey). Each measure of WBV exposure was included as a quartile based design variable, assuming the lowest quartile as the reference category. The likelihood ratio (LR) test for the measures of WBV exposure and the Bayesan Information Criteria (BIC) for comparison between models are given.

Measures of cumulative WBV exposure	Quartiles of measure of cumulative WBV exposure				LR test (χ^2, 3*df*)	BIC
	Q1	Q2	Q3	Q4		
Exposure duration (yr)						
OR	1.0	2.73	4.20	2.80	9.02	982
(95% CI)	(-)	(1.07 – 6.93)	(1.63 – 10.8)	(0.91 – 8.63)	(p=0.03)	
$\sum[t_i]$ (h)						
OR	1.0	1.15	4.28	2.63	15.2	976
(95% CI)	(-)	(0.50 – 2.65)	(1.85 – 9.89)	(1.01-6.83)	(p<0.005)	
$\sum[a_{wsi}t_i]$($ms^{-2}h$)						
OR	1.0	2.13	3.27	3.44	7.80	982
(95% CI)	(-)	(0.94 – 4.79)	(1.38 – 7.75)	(1.41 – 8.42)	(p=0.05)	
$\sum[a_{wsi}^2t_i]$ ($m^2s^{-4}h$)						
OR	1.0	1.91	2.93	4.38	10.8	980
(95% CI)	(-)	(0.84 – 4.33)	(1.21 – 7.06)	(1.77 – 10.9)	(p=0.013)	
$\sum[a_{wsi}^4t_i]$ ($m^4s^{-8}h$)						
OR	1.0	2.31	2.29	3.28	7.14	984
(95% CI)	(-)	(1.02 – 5.24)	(0.97 – 5.37)	(1.33 – 8.08)	(p=0.07)	
$\sum[a_{wqi}t_i]$ ($ms^{-2}h$)						
OR	1.0	2.62	2.44	7.07	19.7	971
(95% CI)	(-)	(1.17 – 5.89)	(0.99 – 6.0)	(2.84 – 17.6)	(p<0.001)	
$\sum[a_{wqi}^2t_i]$ ($m^2s^{-4}h$)						
OR	1.0	2.53	2.50	8.11	21.5	969
(95% CI)	(-)	(1.13 – 5.67)	(1.03 – 6.08)	(3.24 – 20.3)	(p<0.001)	
$\sum[a_{wqi}^4t_i]$ ($m^4s^{-8}h$)						
OR	1.0	1.54	3.39	4.36	12.2	979
(95% CI)	(-)	(0.65 – 3.65)	(1.43 – 8.06)	(1.69 – 11.2)	(p<0.01)	

Table 3.8 Random-intercept logistic regression of low back pain (LBP) symptoms (7-day LBP, 12-month LBP, and high pain intensity (Von Korff pain scale score ≥ 5), LBP disability (Roland & Morris disability scale score ≥ 12), treated LBP, sick leave due to LBP in the previous 12 months) on postural load index in the professional drivers over two-year follow-up period. Odds ratio (OR) and 95% confidence interval (95% CI) are adjusted for several covariates (individual characteristics, vibration exposure, psychosocial factors, back trauma, previous jobs at risk, and survey). The likelihood ratio (LR) test for postural load index is given.

Outcome	Postural load index (grade)				LR test (χ^2, 3*df*)
	Score 1 (Mild)	Score 1 – 1.9 (Moderate)	Score 2 – 2.9 (Hard)	Score 3 – 4 (Very hard)	
7-day LBP					
OR	1.0	1.67	0.94	1.09	3.18
(95% CI)	(-)	(0.84 – 3.29)	(0.44 – 2.12)	(0.55 – 2.14)	(p=0.37)
12-month LBP					
OR	1.0	1.71	2.80	2.97	12.9
(95% CI)	(-)	(0.91 – 3.20)	(1.39 – 5.66)	(1.56 – 5.67)	(p=0.005)
Acute LBP					
OR	1.0	0.72	0.93	1.0	0.76
(95% CI)	(-)	(0.29 – 1.75)	(0.35 – 2.45)	(0.43 – 2.33)	(p=0.86)
Sciatica					
OR	1.0	1.74	2.71	2.63	9.28
(95% CI)	(-)	(0.85 – 3.57)	(1.28 – 5.75)	(1.32 – 5.25)	(p=0.026)
High pain intensity					
OR	1.0	1.10	1.30	1.20	0.60
(95% CI)	(-)	(0.58 – 2.08)	(0.65 – 2.60)	(0.64 – 2.25)	(p=0.90)
LBP disability					
OR	1.0	1.62	2.02	2.11	4.80
(95% CI)	(-)	(0.78 – 3.39)	(0.93 – 4.38)	(1.03 – 4.30)	(p=0.19)
Treated LBP					
OR	1.0	1.67	2.62	2.07	7.51
(95% CI)	(-)	(0.85 – 3.30)	(1.26 – 5.42)	(1.06 – 4.04)	(p=0.057)
Sick leave due to LBP (> 7d)					
OR	1.0	1.97	1.82	1.44	2.53
(95% CI)	(-)	(0.80 – 4.87)	(0.68 – 4.88)	(0.59 – 3.52)	(p=0.47)

3.2.2 Longitudinal epidemiological surveys in Sweden

3.2.2.1 Introduction

Exposure to whole-body vibration (WBV) during driving of different types of vehicles is thought to be associated with an increased risk for developing various types of symptoms and disorders, especially in the neck, shoulders and lower back. For instance, reviews of the epidemiological literature have reported that the occurrence of low back pain (LBP) and early degeneration of the lumbar spine, including inter-vertebral disc disorders, is greater among professional drivers than in controls groups not exposed to WBV. This study reports the findings of a longitudinal epidemiological survey conducted on a group of Swedish professional forestry machine drivers. Further details of the study are reported in Annex 14.

3.2.2.2 Objectives

The objectives were to investigate:

i) the prevalence and incidence of ache and pains in different parts of the body (i.e. low back, neck and shoulders) within the last 7 days and last 12 months) and symptoms and feelings in other regions of the body (eg. elbows, arms, hands);

ii) the association between symptoms of disorders, WBV exposure, physical load factors and psychosocial variables.

3.2.2.3 Subjects and Methods

The baseline study population consists of 530 male professional drivers of forestry vehicles, such as harvesters, forwarders and mounders. During 2004 they received the VIBRISKS self-administered whole-body vibration questionnaire (Initial assessment) in which personal, occupational and health history data were asked for. Altogether 322 drivers replied (61%) among which 11 declared that they were not willing to participate. The number of forestry machine drivers included in the final baseline analysis was thus 311. During 2006 the Swedish version of the self-administered whole-body vibration follow-up questionnaire was posted to the final baseline study group. Altogether, 225 drivers replied (73%). General data for the baseline study group and the follow-up study group is shown in Table 3.9.

Individual WBV exposure doses were calculated in accordance with the protocol for calculation of dose measures for whole-body vibration (See, section 3.1).

Table 3.9 General data for the study group (Mean (±Sd)/Min/Max).

	Age (yrs)	**Length** (m)	**Weight** (kg)	**BMI**
Baseline (n=311)	45(12.2)/20/66	179(6.5)/159/198	86(12.3)/60/130	26.7(3.4)/19.6/42.4
Follow-Up (n=225)	45.1(11.8)/21.2/67.3	179.5(6.4)/160/197	86.5(11.4)/60/130	26.8(3.2/20.4/40.8

3.2.2.4 Results

Table 3.10 provides a summary of obtained data for the base-line investigation including prevalence of musculoskeletal symptoms in the neck, shoulder, and low back (the last 7 days, the last 12 months), and the VAS score for the musculoskeletal pains at the various body locations and the Roland Morris score in the cross-sectional survey of the study population. Table 3.11 provides metrics of vibration exposure doses.

Table 3.10 Population summary for the base-line study.

Population	SWEDISH FORESTRY VEHICLE DRIVERS				
Number exposed			311		
Vehicles	Harwarder	Forwarder	Mounder	Snowmobile	4 wheeler
From WBV dose calculation (m/s^2 r.m.s):					
Average $a_{x,w}$	0.25	0.5	0.7	0.7	0.7
Average $a_{y,w}$	0.4	0.8	1.1	0.7	0.7
Average $a_{z,w}$	0.3	0.6	0.6	0.8	0.8
Number indicated driving	208	170	12	16	6
Average daily duration (minutes)	404	350	34	41	19
SD daily duration	146	176	15	47	20
Max daily duration	720	780	57	180	60
Min daily duration	12	12	15	12	6
Average years of exposure for all vehicles					19.2
SD years of exposure for all vehicles					12.4
Max years of exposure for all vehicles					49.3
Min years of exposure for all vehicles					0.2
Percent with more than 1 year of occupational exposure to WBV prior to current job					22 %
From questionnaire (symptoms):					
% with low back pain in last 7 days					32.2 %
% with low back pain in last 12 months					57.9 %
VAS score for lower back					3.3/10
Roland disability scale score (response rate 41%)					3.8/24
% with neck pain in last 7 days					38.6 %
% with neck pain in last 12 months					54.3 %
VAS score for neck pain					3.8/10
% with shoulder pain in last 7 days					26 %
% with shoulder pain in last 12 months					39.5 %
VAS score for shoulder pain					3.9/10

Table 3.11 Metrics of vibration exposure according to the protocol for dose calculations (see Section 3.1).

Dose	Formula	Mean (±SD)	Unit
1	$T = \sum t_{Ti}$	30805 (22809)	h
2	$\sum a_{wsi}.t_i$	32160 (27536)	$ms^{-2}.h$
3	$\sum a_{wsi}^2 t_i$	37843 (40363)	$m^2s^{-4}.h$
4	$\sum a_{wsi}^4 t_i$	67575 (94916)	$m^4s^{-8}.h$
5	$\sum a_{wqi}.t_i$	45040 (34609)	$ms^{-2}.h$
6	$\sum a_{wqi}^2 t_i$	67288 (55575)	$m^2s^{-4}.h$
7	$\sum a_{wqi}^4 t_i$	159932 (158555)	$m^4s^{-8}.h$
8	$\left\| [(\sum a_{wsi}^2 t_i)/ (\sum t_i)]^{½} \right\|_{max}$	159932 (158555)	ms^{-2}
9	$\left\| [(\sum a_{wqi}^4 t_i)/ (\sum t_i)]^{¼} \right\|_{max}$	1.53 (0.28)	ms^{-2}
10	$Y = \left\| D_2 - D_1 \right\|_{max}$	19.2 (12.4)	y
11	$\left\| t_{d(n)} \right\|_{max}$	7.1 (2.35)	hours
12	$A(8) = \left\| (\sum a_{wsi}^2.t_{di}/T_{(8)})^{½} \right\|_{max}$	0.97 (0.37)	ms^{-2}
13	$VDV = \left\| a_{wqi}.(t_{di}.60.60)^{¼} \right\|_{max}$	18.3 (3.43)	$ms^{-1.75}$
14	$A(8) = (\sum a_{wsi}^2.t_{di}/T_{(8)})^{½}$	1.02 (0.37)	ms^{-2}

Table 3.12 shows the prevalence of low-back, neck and shoulder pain developed during the follow-up period (i.e. no case at base line but case at follow-up) or remaining symptoms at follow-up (i.e. case at base-line and still remaining a case at follow-up) in relation to vibration doses 1, 3 and 14. Table 3.13 shows the risk (Odds Ratio) of contracting symptoms of low-back, shoulder, or neck-pain at follow-up related to being a case (baseline=1) or not being a case (baseline = 0) at baseline for each quartile of vibration dose.

3.2.2.5 Discussion

The over all 7-day periods, prevalence of musculoskeletal symptom in the neck, shoulder and low back was in the cross-sectional survey of the study population 38.1%, 26.1% and 32.2% respectively. The 12-month period-prevalence was highest for low back pain (58.1%) followed by neck pain (54.3%) and shoulder pain (39.6%). A similar pattern was also found when the results were analysed in relation to vibration exposure. The risk of contracting symptoms was in no case significant but was slightly increased for shoulder symptoms (1.4) for the last 7-day period. The VAS scores for the musculoskeletal pains were only moderately increased and of comparable magnitudes of 3.3, 3.8 and 3.9 for low back pain, neck pain and shoulder pain respectively. The Roland Morris disability score was 3.8 out of 24.

When comparing the Roland-Morris score results between the cross-sectional and follow-up survey, the mean values were comparable but for individual cases a change in low values toward higher values and a corresponding change from higher values towards lower could be seen and could possibly be interpreted as a regression towards the mean. A similar pattern was revealed for the VAS pain ratings. The VAS ratings for neck pain tended to remain at the same magnitude to a large extent compared with shoulder and low back pain.

When comparing the metrics of vibration exposure according to the protocol for dose calculations the mean results of 8-hour equivalent exposure (dose 14) from the vibration exposed group was higher (1.0 m/s^2) than the present action level given by the EU-directive but below the limit value. The mean exposure duration was 19 years (dose 3) in the study population group. The analysis performed so far does not permit comparisons of and evaluations of the various exposure doses.

No exposure-response (for symptoms) or dose-effect (for score results) relationships in the cross-sectional survey were found. Although no significant risks were revealed for low-back pain, shoulder pain or neck pain, a slight risk of 1.2 to 1.7 was found for neck pain and 1.3 to 1.5 for shoulder pain for vibration dose 1. Increasing the contrasts of exposure did not result in a consistent pattern of dose-response.

The possible exposure-response (for symptoms) or dose-effect (for score test results) relation for the changes in the outcomes over time during the follow-up period showed that despite mainly “non-significant” findings and wide confidence intervals a consistent pattern was found where subjects with symptoms at base line had increased risk for symptoms at follow-up. This holds for low back, neck and shoulder pain. For vibration Dose 3, a significant risk of 4.9 to 9.2 for remaining neck pain was found. Confidence intervals were wide indicating few cases and collapsed models.

Work ability information, based on the question “How much time did you have to take off work due to back/leg pain, neck pain and shoulder pain” in the cross-sectional studies and the results from a change at follow-up revealed that most subjects remained in the same category of workability (84% for low back-pain, 91% for neck pain and 88% for shoulder pain).

The major bias of the results is due to varying and low participation rates. In the follow-up analysis, additional subjects will be added from slow responders. Due to the large number of questions the risk for missing responses and interconnected responses demands additional analysis in order to reduce missing values.

3.2.2.6 Conclusions

The overall conclusions are: i) any relation between prevalence of different symptoms and cumulated hours of exposure to WBV in forestry vehicles can not be stated; ii) drivers that were “diseased” at base line revealed an increased risk of being “diseased” at follow-up also; iii) significant risks for neck pain were found for Dose 3.

Table 3.12 Prevalence (%) of low-back, neck and shoulder pain developed during the follow-up period (i.e. no case at base line but case at follow-up) or remaining symptoms at follow-up (i.e. case at base-line and still remaining a case at follow-up) in relation to vibration doses 1, 3 and 14 divided in to quartiles.

	Low back pain last 12 months					**Neck pain last 12 months**					**Shoulder pain last 12 months**				
Dose 1		**Q0**	**Q1**	**Q2**	**Q3**		**Q0**	**Q1**	**Q2**	**Q3**		**Q0**	**Q1**	**Q2**	**Q3**
Baseline	*N*	<12928	12928 - 27063	27063 - 44694	>44694	*N*	<12928	12928 - 27063	27063 - 44694	>44694	*N*	<12928	12928 - 27063	27063 - 44694	>44694
0	*89*	35	43	35	12	*93*	35	30	25	20	*122*	25	21	32	24
1	*124*	67	68	87	76	*121*	75	66	81	82	*93*	50	62	67	68
Dose 3		**Q0**	**Q1**	**Q2**	**Q3**		**Q0**	**Q1**	**Q2**	**Q3**		**Q0**	**Q1**	**Q2**	**Q3**
Baseline	*N*	<11216	11216 - 22779	22779 - 48673	>48673	*N*	<11216	11216 - 22779	22779 - 48673	>48673	*N*	<11216	11216 - 22779	22779 - 48673	>48673
0	*89*	30	30	41	21	*93*	35	27	25	25	*122*	25	27	28	21
1	*124*	63	88	75	68	*121*	54	88	76	86	*93*	47	73	59	65
Dose 14		**Q0**	**Q1**	**Q2**	**Q3**		**Q0**	**Q1**	**Q2**	**Q3**		**Q0**	**Q1**	**Q2**	**Q3**
Baseline	*N*	<0.7253	0.7253 - 0.9363	0.9363 - 1.3810	>1.3810	*N*	<0.7253	0.7253 - 0.9363	0.9363 - 1.3810	>1.3810	*N*	<0.7253	0.7253 - 0.9363	0.9363 - 1.3810	>1.3810
0	*89*	39	33	15	38	*93*	25	18	35	35	*122*	35	26	19	24
1	*124*	64	86	71	67	*121*	70	72	77	85	*93*	50	73	65	50

(Q0=minimum value-25 percentile of dose. Q1=25 to 50 percentile of dose. Q2=50 to 75 percentile of dose. Q3=75 percentile to maximum value of dose)

Table 3.13 Risk (Odds Ratio (OR)) of contracting symptoms of low-back, shoulder, or neck-pain at follow up related to being a case (baseline=1) or not being a case (baseline = 0) at baseline and contrasted in relation to vibration exposure.

	Low back pain (last 12 months)				**Neck pain (last 12 months)**				**Shoulder pain (last 12 months)**			
Baseline	**0**		**1**		**0**		**1**		**0**		**1**	
	OR	**95% CI**	**OR**	**95% CI**	**OR**	**95% CI**	**OR**	**95% CI**	**OR**	**95% CI**	**OR**	**95% CI**
Dose 1	*N=84*		*N=113*		*N=90*		*N=112*		*N=119*		*N=89*	
Q1/Q0	0.68	0.156 - 2.98	1.3	0.369 - 4.30	1.1	0.281 - 3.95	0.73	0.202 - 2.62	1.1	0.290 - 4.26	1.6	0.419 - 5.81
Q2/Q0	0.15	0.021 - 1.02	4.1	0.947 - 17.78	0.74	0.166 - 3.34	1.3	0.277 - 6.38	1.9	0.459 - 7.52	1.8	0.399 - 7.83
Q3/Q0	0.01	0.001 - 0.152	1.6	0.371 - 7.32	0.84	0.125 - 5.61	1.5	0.245 - 8.78	1.6	0.258 - 9.42	1.9	0.378 - 9.38
Age	1.1	1.04 - 1.22	0.97	0.924 - 1.02	1.0	0.834 - 1.25	1.0	0.896 - 1.20	0.99	0.936 - 1.05	1.0	0.952 - 1.05
BMI	0.90	0.742 - 1.08	1.2	1.03 - 1.49	-	-	-	-	-	-	-	-
Dose 3	*N=84*		*N=113*		*N=90*		*N=117*		*N=119*		*N=89*	
Q1/Q0	1.1	0.246 - 4.58	3.5	0.850 - 14.70	0.84	0.235 - 3.01	9.0	1.82 - 44.09	1.1	0.307 - 3.70	3.0	0.757 - 12.07
Q2/Q0	1.4	0.290 - 6.83	2.5	0.580 - 10.53	1.0	0.237 - 4.50	4.9	1.04 - 22.96	1.1	0.319 - 4.07	1.4	0.269 - 6.90
Q3/Q0	0.57	0.090 - 3.58	1.5	0.367 - 6.18	1.3	0.254 - 6.77	9.2	1.67 - 50.78	0.85	0.181 - 3.99	1.7	0.369 - 8.07
Age	1.0	0.960 - 1.07	0.97	0.926 - 1.02	0.97	0.924 - 1.02	0.97	0.916 - 1.02	1.0	0.959 - 1.05	1.0	0.955 - 1.06
BMI	0.96	0.809 - 1.13	1.2	0.984 - 1.40	-	-	-	-	-	-	-	-
Dose 14	*N=84*		*N=113*		*N=90*		*N=117*		*N=119*		*N=89*	
Q1/Q0	0.60	0.126 - 2.90	2.6	0.723 - 9.00	0.68	0.128 - 3.54	1.1	0.345 - 3.70	0.65	0.195 - 2.18	2.9	0.822 - 10.47
Q2/Q0	0.31	0.059 - 1.62	1.5	0.452 - 5.08	2.1	0.467 - 9.72	1.6	0.424 - 5.71	0.51	0.144 - 1.82	2.3	0.618 - 8.89
Q3/Q0	1.0	0.237 - 4.52	1.0	0.279 - 3.98	1.9	0.399 - 8.92	2.1	0.523 - 8.70	0.60	0.176 - 2.05	0.86	0.218 - 3.43
Age	1.0	0.969 - 1.06	0.98	0.943 - 1.02	0.98	0.941 - 1.02	1.0	0.975 - 1.06	1.0	0.966 - 1.04	1.0	0.968 - 1.05
BMI	0.95	0.808 - 1.12	1.2	0.991 - 1.42	-	-	-	-	-	-	-	-

(Q0=minimum value-25 percentile of dose. Q1=25 to 50 percentile of dose. Q2=50 to 75 percentile of dose. Q3=75 percentile to maximum value of dose).

3.2.3 Longitudinal epidemiological surveys in the Netherlands

3.2.3.1 Introduction

Low back-pain disorders (LBP) are among the most common and costly health problems. Occupational, non-occupational, and individual risk factors play a role in the development, the duration, and the recurrence of LBP. Several critical reviews have discussed the evidence on occupational risk factors for back disorders. All these reviews conclude that there is strong epidemiological evidence for a relation between occupational exposure to whole-body vibration (WBV) and LBP. Whether this exposure is only a modest or a substantial risk factor for the onset and recurrence of LBP is still a matter of debate. In five European countries (Belgium, Germany, Netherlands, France, Denmark), LBP due to WBV is currently recognised as an occupational disease. However, high exposures and adverse effects still occur as WBV is a common occupational risk factor for LBP, affecting 4% to 8% of the workforce in industrialised countries.

This study reports the findings of a prospective cohort study on dose-response relationship for low back pain disorders in WBV-exposed drivers in the Netherlands.

Further details of the study are reported in Annex 15.

3.2.3.2 Objectives

The aim of this study was to investigate the prevalence and incidence of LBP outcomes in various groups of professional drivers in the Netherlands. Vibration measurements in a representative sample of the machines and vehicles used by the various driver groups were combined with real time observation of tasks and postures by a validated observation system, Palmtrac®. The association between LBP, WBV exposure, physical load factors, and psychosocial variables was investigated while controlling for potential individual confounders recognised as risk factors for LBP. In order to explore the evidence in the research about preventive strategies that are successful in reducing vibration magnitude in the workplace, a systematic review of the literature was carried out. The results were used to design an experimental intervention programme that was implemented in a sub-sample of the study populations.

3.2.3.3 Methods

Study population

The Dutch study population included at the start 574 male professional drivers employed in 13 different companies in agriculture, manufacturing industries, construction, public utility and transport industry throughout the country. A minimum of one year of professional driving in the current job was established as the basic criterion for the inclusion of drivers in the study population. The most important vehicles that were driven occupationally in this cohort of drivers were wheeled loaders, excavators and other earth-moving equipment, mobile cranes, lorries, lawn-mowing machines, asphalt machines, tractors, and small boats. Informed consent to the study was obtained from employers and employees at each company. At the first follow-up survey, 67 drivers were left from the original cohort. The most important reasons for drop-out were bankruptcy of one of the participating companies and retirement of some of the drivers. The response to the questionnaire study was 318 (56%) at the baseline survey and 266 (57%) at the first follow-up survey.

This report primarily provides information on the findings of the epidemiological surveys of the drivers with complete follow-up (i.e. those who participated in survey 1 and 2, n=230).

The questionnaire

Personal, occupational and health histories of the participating workers were collected by means of the Dutch version of a standardized questionnaire originally developed within the

European project VINET (*Vibration Injury Network*) and further adapted within Work Package 4 of the VIBRISKS project. All questionnaire data were stored in an Access database. The self-administered questionnaire included 42 questions and required 30-40 minutes to be completed.

Measurement and assessment of vibration exposure

Vibration measurements were made on representative samples of industrial machines and vehicles used by the professional drivers (n=49 at the baseline survey and n=45 at the first follow-up survey). Vibration was measured at the driver-seat interface during actual operating conditions according to the recommendations of the International Standard ISO 2631-1. From one-third octave band frequency spectra (1-80 Hz) recorded from *x*-, *y*-, and *z*-directions, frequency-weighted root-mean-square (r.m.s.) accelerations (a_{wx}, a_{wy}, a_{wz}) were obtained by using the weighting factors suggested by ISO 2631-1. The vibration total value (or vector sum) of the weighted r.m.s. accelerations, a_v, was calculated according to the following formula: $a_v = [(1.4a_{wx})^2 + (1.4a_{wy})^2 + a_{wz}^2]^{½}$ (ms^{-2} r.m.s.).

For each operator, questionnaire data were used to estimate daily exposure to WBV expressed in driving hours, as well as the total duration of exposure to WBV in full-time driving years. Daily vibration exposure was expressed in terms of 8-h energy-equivalent frequency-weighted acceleration magnitude ($A(8)$) according to the European Directive 2002/44/EC on mechanical vibration (EC, 2002): $A(8) = a_w\,(T/T_0)^{½}$ (ms^{-2} r.m.s.). The vibration total value and duration of exposure were used to construct measures of cumulative vibration dose:

$$dose = \sum_i [a_i^m t_i]$$

where a_i is the vibration total value of the frequency-weighted accelerations measured on machine *i* driven for time t_i in hours (h/d × d/yr × years).

Assessment of physical load, tasks and postures

The physical work demands and the tasks and postures of the drivers included in this study were assessed in two different ways: (1) with the fore-mentioned questionnaire and (2) with the PalmTrac system during observation at the workplace. The PalmTrac system is a direct observational method, originally developed at the Robens Institute (University of Surrey, UK) and further adapted by the AMC and Health/ERGOcare (Free University Amsterdam) and it allows on-site data recording of tasks, activities and postures on a palmtop. For each observed driver, data were recorded for approximately four hours. To ensure that the PalmTrac system and the WBV measurement would work simultaneously, the start of the measurements were synchronized. In addition to the questionnaire data, the PalmTrac measurements yield information about the tasks and postures more in detail. Moreover, the simultaneous measurement provides insight into the tasks, activities, and postures that are performed at the time of a minimum or maximum level in the vibration signal and this information was used in the tailoring of the intervention programme.

Systematic review of strategies to reduce WBV exposure of professional drivers

Systematic literature searches were performed of the electronic databases PubMed (biomedical literature), Embase (biomedical and pharmacological literature), ScienceDirect (science, technology, and medical literature), and Osh-Rom (occupational safety and health-related literature, including databases RILOSH, MIHDAS, HSELINE, CISDOC, and NIOSHTIC2). Searches of the databases were performed with the following search terms and their synonyms: whole body vibration, occupational and prevention. After the search, the selection criteria were refined to include only original articles: dealing with human laboratory or field studies, articles which were published between 1985 and 2005 and in which the effect on outcome values were identifiable and clearly presented. Because the goal was primarily to explore which intervention measures were successful in reducing exposure to WBV, further methodological criteria in the selection of articles were not applied.

Data analysis

The statistical analysis of the epidemiological survey was performed using SPSS 13.1 for Windows and SAS 9.1. The association between LBP outcomes and several independent variables over time was assessed by logistic regression analysis according to the transition model. Odds ratios and 95% confidence intervals (95% CI) were estimated from the logistic regression coefficients and their standard errors. The magnitude of the likelihood ratio (LR) chi-square statistic was used to assess a trend over the different quartiles of the alternative measures of vibration exposure for the prediction of the outcome.

3.2.3.4 Results

Vibration exposure

Table 3.14 shows the mean vibration magnitudes (weighted r.m.s. accelerations) of the most important vehicles that were measured at the baseline survey. Daily driving time in the participating companies varied from 3.0 hours (lawn mowing machines) to 9.8 hours (lorries in road transport). Daily vibration exposure in terms of $A_v(8)$ in the companies ranged from 0.27 (operators of small boats) to 1.20 ms^{-2} r.m.s. (drivers of wheeled loaders) (p<0.001). Similarly, daily vibration exposure in terms of VDV_{sum} ranged from 8.6 ms$^{-1.75}$ (boats) to 14.9 ms$^{-1.75}$ (drivers of earth-moving machines).

Table 3.14 Mean vibration values of the dominant vehicle categories measured.

Category vehicle	Number of vehicles measured	Ax [range] (m/s^2)	Ay [range] (m/s^2)	Az [range] (m/s^2)	Av [range] (m/s^2)
Lawn mowing machines		0,54	0,53	0,52	1.05
	9	[0,34-0,83]	[0,24-0,87]	[0,40-0,81]	[0.7-1.3]
		0,73	0,71	0,52	1.25
Shovel	8	[0,59-0,86]	[0,48-0,90]	[0,43-0,69]	[1.01-1.47]
		0,52	0,51	0,34	0.88
Tractor	3	[0,30-0,51]	[0,27-0,41]	[0,10-0,25]	[0.46-1.28]
		0,22	0,21	0,21	0.43
Wals	4	[0,07-0,37]	[0,06-0,25]	[0,08-0,34]	[0.14-0.65]
		0,26	0,26	0,39	0.65
Lorry	6	[0,21-0,30]	[0,18-0,34]	[0,26-0,57]	[0.45-0.88]
		0,05	0,04	0,06	0.10
Crane	2	[0,03-0,06]	[0,04-0,04]	[0,03-0,07]	[0.08-0.12]
		0,25	0,25	0,34	0.60
Dumper	5	[0,16-0,29]	[0,18-0,30]	[0,24-0,48]	[0.41-0.77]
		0,40	0,31	0,30	0.66
Excavator	7	[0,19-0,66]	[0,11-0,67]	[0,16-0,52]	[0.36-1.19]
		0,41	0,27	0,56	0.91
Bulldozer	2	[0,33-0,47]	[0,26,-0,27]	[0,44-0,65]	[0.82-1.0]
		0,12	0,19	0,10	0.27
Boat	2	[0,08-0,15]	[0,13-0,24]	[0,08-0,12]	[0.19-0.33]

Table 3.15 Prevalence and one-year incidence of low back pain (LBP) symptoms in the total sample of professional drivers (n=230) that responded in both surveys.

LBP outcome	Point prevalence (%) (baseline)	One-year incidence (%)
LBP in the previous 7 days	32.6	18.2
LBP in the previous 12 months	57.8	25.7
Episodes of acute LBP in the previous 12 months	36.5	9.1
Episodes of sciatica in the previous 12 months	21.7	10.4
Duration of LBP > 30 days/year in the previous 12 months	12.3	7.8
High back pain intensity in the previous 7 days (VAS score > 5)	8.3	5.6
Disability due to the last episode of LBP (Roland & Morris scale score ≥ 12)	5.7	1.7
Visit to a doctor for LBP in the previous 12 months	20.4	7.8
LBP treated with medication or physical therapy in the previous 12 months	21.3	6.5
Sick leave > 2 days due to LBP in the previous 12 months Sick leave > 7 days due to LBP in the previous 12 months	13.0 8.7	5.6 5.2

Health outcomes

Table 3.15 reports the period prevalence in 2005-2006 and the cumulative incidence over the follow-up period for LBP in the participating populations.

The period prevalence of the various LBP symptoms varied from 13.0% (sick leave of more than 2 days due to LBP) to 57.8% (overall LBP in the last 12 months). About 6% of the subjects complained about severe disability due to LBP (Roland & Morris disability scale score ≥ 12) in the last episode. However, this scale was filled in by the drivers who reported LBP in the last 7 days (n=96). Sick leave due to LBP in the previous 12 months was reported by 8.7% (> 7 days) of the subjects. Over the follow-up period (2005-2006), the incidence of the various LBP symptoms ranged from 5.6% (sick leave of more than 2 days due to LBP) to 25.7% (overall LBP in last 12 months).

Low back pain and vibration exposure

To assess possible exposure-response relationship for LBP outcomes in the professional drivers, measures of daily vibration exposure, such as $A(8)$, VDV, duration of exposure in years, and measures of cumulative vibration doses of the form $\sum[a_i^m t_i]$, were divided into quartiles assuming the lowest quartile as the reference category. Tables 3.16 and 3.17 show, as examples, the results of the logistic regression analysis for the relation over time between LBP in the last 12 months and daily and cumulative vibration exposures, while adjusting for several covariates such as age, physical load factors, and psychosocial factors. In general, the relation between the various LBP outcomes and the different measures of daily vibration exposure was inconsistent. Only daily driving time was significantly associated with most of the LBP outcomes: LBP in the last 7 months, acute LBP in the last 12 months, treated LBP, sciatica, high intensity pain and LBP disability (Roland Morris disability scale $\geq$ 12). Patterns of increased risk for sick leave > 7 days due to LBP in the previous 12 months were found for all the different measures of daily vibration exposure. Regarding the various measures of cumulative vibration doses, more significant relationships and trends with LBP outcomes were seen. Most significant relations between the defined LBP outcomes and the measures of cumulative WBV exposure are found with dose $\sum[t_i]$ and dose $\sum[a_{wsi}^2 t_i]$, however, there are also some significant relationships with the other cumulative dose measures. The occurrence of LBP in the previous 12 months was significantly associated only with $\sum[t_i]$ (Table 3.16). The occurrence of episodes of acute LBP in the previous 12

Table 3.16 Logistic regression of low back pain in the previous 12 months on different measures of daily exposure to whole-body vibration (WBV) in the professional drivers (n=230) over one-year follow-up period. Odds ratio (OR) and 95% confidence interval (95% CI) are adjusted for several covariates (age, physical load factors, psychosocial factors, back trauma, and follow-up time). Each measure of WBV exposure was included as a quartile based design variable, assuming the lowest quartile as the reference category. The likelihood ratio (LR) test for the measures of WBV exposure is given.

Measures of daily WBV exposure	Quartiles of measure of daily WBV exposure				LR test
	Q1	Q2	Q3	Q4	(χ^2, 3*df*)
Daily driving time (h)	5.0	8.0	9.4	11.0	4.28
OR	1.0 (-)	0.90	1.33	1.59	
(95% CI)		(0.54-1.51)	(0.80-2.20)	(0.81-3.10)	(0.23)
$A_v(8)$ (ms^{-2} r.m.s.)	0.28	0.45	0.56	0.74	1.76
OR	1.0 (-)	0.82	0.78	0.70	
(95% CI)		(0.47-1.43)	(0.45-1.35)	(0.41-1.20)	(0.62)
$A_{dom}(8)$ (ms^{-2} r.m.s.)	0.18	0.32	0.39	0.53	1.31
OR	1.0 (-)	0.89	0.74	0.78	
(95% CI)		(0.53-1.51)	(0.42-1.32)	(0.44-1.36)	(0.73)
VDV_v (ms$^{-1.75}$)	3.20	4.90	6.46	11.83	7.06
OR	1.0 (-)	0.50	0.69	0.88	
(95% CI)		(0.29-0.87)	(0.39-1.21)	(0.51-1.52)	(0.07)
VDV_{dom} (ms$^{-1.75}$)	3.26	4.56	5.81	10.34	1.62
OR	1.0 (-)	0.91	0.87	1.21	
(95% CI)		(0.52-1.59)	(0.51-1.47)	(0.72-2.03)	(0.65)

months was significantly related to most of the measures of cumulative vibration dose. The associations were strongest for $\sum[t_i]$, $\sum[a_{wqi}t_i]$, and $\sum[a_{wqi}^2 t_i]$.

Low back pain and other physical load factors

After adjustment for potential confounders, the occurrence of LBP in the last 12 months was significantly associated with lifting at work, lifting and bending at work, and lifting and twisting at work. A combined physical load index (derived from 4 questions from the questionnaire concerning: prolonged sitting, lifting, bending and twisting) within each subject showed a clear pattern of increasing risk over time for almost all LBP outcomes.

The results of a comparison of the assessment of the physical load, tasks and postures by real time observation (PalmTrac) with the questionnaire data in a sub sample of ten drivers of wheeled loaders revealed that the time spent ‘walking + standing’ and ‘bending’ was underestimated by more than half of the drivers. However, the time spent on ‘lifting’ was overestimated by 60% of the drivers.

Evidence on strategies to reduce WBV exposure

In the systematic review, 37 studies were included: 15 laboratory studies, 17 field studies, 4 studies laboratory/field studies and 1 intervention study. Most of the studies presented one or more factors that had a significant effect on vibration exposure. While most of the studies concentrated on factors dealing with design considerations (e.g. type of seat or cabin suspension), the results of the review showed that significant reduction of exposure can also be achieved by factors concerning ‘skills and behaviour’ (e.g. speed or driving experience).

3.2.3.5 Discussion

In accordance with many earlier studies, the results of this prospective follow-up study show that both the prevalence and the one-year incidence of LBP in a cohort of drivers of various vehicles is relatively high compared to other occupational groups (57.8% and 25.7% for prevalence and one-year incidence respectively). A considerable number of drivers in our study (52% in the baseline survey) exceeded the daily exposure action value *A*(8) of 0.5 ms^{-2} r.m.s. of the EU Directive which gives an indication that still a substantial proportion of the driving workforce may be at risk for developing LBP. In this study, several physical and postural load factors, as assessed by responses to the questionnaire, were significant predictors of LBP. The reliability of this finding may, however, be disputed as comparison of the questionnaire responses with real-time observation showed that the time spent in some unfavourable postures or tasks were underestimated while other were overestimated.The multivariate data analysis showed that the currently recommended measures of daily vibration exposure, *A*(8) or *VDV*, in general were poorly associated with most of the LBP outcomes, except for LBP last 7 months and LBP last 12 months. More significant relationships between the LBP outcomes and WBV exposure were seen when using the various cumulative dose measures, in particular for the occurrence of acute LBP in the previous 12 months. The results of the exposure-response analysis show no consistency over the whole range of LBP outcomes. This may partly be explained by the fact that the drivers in the lowest reference quartile are also exposed to WBV and by the low numbers in some categories, leading to wide confidence intervals. Pooling of the data of the different partners in this project will therefore enable an analysis with more statistical power.

3.2.3.6 Conclusions

This prospective cohort study tends to confirm that professional driving in industrial vehicles is associated with an increased risk of work-related LBP. Occupational exposure to WBV and physical loading factors at work are important components of the multifactorial origin of LBP in professional drivers. A clear exposure response pattern could not be derived from the results of this study but the pooling of the data of the different partners may give a more reliable picture. The combination of vibration measurements with real-time observations at the workplace and a systematic review on measures of vibration reduction were of help in designing and tailoring a controlled intervention study that is still ongoing.

Table 3.17 Logistic regression of low back pain in the previous 12 months on different measures of cumulative exposure in most recent job, to whole-body vibration (WBV) in the professional drivers (n=230) over one-year follow-up period. Odds ratio (OR) and 95% confidence interval (95% CI) are adjusted for several covariates (age, marital status, physical load factors, psychosocial factors, back trauma and follow-up time). Each measure of WBV exposure was included as a quartile based design variable, assuming the lowest quartile as the reference category. The likelihood ratio (LR) test for the measures of WBV exposure is given.

Measures of cumulative WBV exposure	Quartiles of measure of cumulative WBV exposure				LR test (χ^2, 3*df*)
	Q1	Q2	Q3	Q4	
Exposure duration (yr) OR (95% CI)	3.2 1.0 (-)	10.1 0.91 (0.52-1.58)	21.6 1.19 (0.66-2.13)	34.8 1.07 (0.55-2.08)	0.91 (0.82)
$\sum[t_i]$ (h $\times 10^3$) OR (95% CI)	4.6 1.0 (-)	16.7 1.26 (0.72-2.19)	34.9 2.14 (1.18-3.90)	60.7 1.48 (0.78-2.82)	6.60 (0.09)
$\sum[a_{wsi}t_i]$(ms^{-2}h$\times 10^3$) OR (95% CI)	2.8 1.0 (-)	7.7 1.20 (0.68-2.12)	16.4 1.01 (0.57-1.78)	38.2 1.04 (0.56-1.94)	0.54 (0.91)
$\sum[a_{wsi}^2t_i]$ (m^{2}s^{-4}h $\times 10^3$) OR (95% CI)	1.1 1.0 (-)	4.0 0.94 (0.54-1.64)	8.9 1.08 (0.61-1.90)	26.9 0.77 (0.43-1.40)	1.48 (0.69)
$\sum[a_{wsi}^4t_i]$ (m^{4}s^{-8}h $\times 10^3$) OR (95% CI)	0.29 1.0 (-)	1.2 0.77 (0.45-1.33)	3.3 1.12 (0.64-1.95)	14.1 0.86 (0.49-1.51)	2.07 (0.56)
$\sum[a_{wqi}t_i]$ (ms^{-2}h $\times 10^3$) OR (95% CI)	1.95 1.0 (-)	5.60 1.20 (0.68-2.10)	12.16 0.99 (0.56-1.74)	27.73 1.12 (0.61-2.07)	0.66 (0.88)
$\sum[a_{wqi}^2t_i]$ (m^{2}s^{-4}h $\times 10^3$) OR (95% CI)	0.59 1.0 (-)	2.36 0.91 (0.52-1.58)	4.94 1.21 (0.69-2.13)	14.49 0.86 (0.48-1.55)	1.78 (0.62)
$\sum[a_{wqi}^4t_i]$ (m^{4}s^{-8}h $\times 10^3$) OR (95% CI)	0.1 1.0 (-)	0.36 0.70 (0.40-1.21)	0.99 1.25 (0.71-2.19)	4.09 0.81 (0.46-1.42)	4.96 (0.18)

3.2.3.7 Longitudinal epidemiological surveys in the United Kingdom

3.2.3.8 Introduction

Many epidemiological studies and several reviews of epidemiological studies of persons exposed to whole-body vibration (WBV), especially tractor drivers, truck drivers, bus drivers, helicopter pilots and drivers of heavy off-road machines, have concluded that long-term exposure to WBV is associated with increased risk of health problems, especially low back pain (LBP).

The cause of LBP in workers exposed to WBV is often uncertain. In addition to vibration, there are many other factors that may influence LBP while driving (prolonged constrained sitting posture without physical activity, back posture during sitting, head posture, back movement, twisting of trunk while looking back, etc). In addition, physical factors (such as lifting, bending, twisting, heavy manual work, etc.), individual factors (such as gender, age, anthropometry, smoking, alcohol consumption, sport, etc.) and psychosocial factors may influence LBP.

Car drivers are exposed to a lower level of WBV than drivers of tractors, trucks, buses, helicopters and off-road machines, but have some of the other risk factors (i.e., individual factors, physical factors and psychosocial factors). Some epidemiological studies have investigated the prevalence of LBP in professional car drivers, but these studies may be considered unsatisfactory due to the lack of information about driving (duration of driving, WBV exposure, etc.).

3.2.3.9 Objectives

The objectives of this research were: (i) to report the prevalence, incidence and recurrence of LBP in populations of car drivers and compare this information with populations not exposed to daily driving, (ii) to identify any occupational factors related to exposure to WBV in car drivers that are associated with LBP, and (iii) to identify other occupational and non-occupational risk factors associated with LBP in all investigated populations.

3.2.3.10 Methods

Type of study

The survey had a longitudinal design (also called cohort design). The prospective cohort study had a cross-sectional assessment at baseline with a follow-up after one year.

Study population

The study was conducted with groups of drivers exposed to low levels of vibration and with non-drivers. The target populations were 861 taxi drivers located in the City of Southampton and 2105 persons employed by the Grampian Police (divided into groups of drivers and non-drivers).

Questionnaire

Information on risk factors and health outcomes was collected on two occasions (at baseline and at follow-up) using a self-completed postal questionnaire. The questionnaire was based on the VIBRISKS whole-body vibration questionnaire for longitudinal epidemiological studies. The questionnaire was enriched by a set of health questions selected from existing models used in earlier MRC community surveys in the UK. These questions permit an assessment of the severity and frequency of symptoms. From all participants, information was obtained about individual characteristics (e.g. age, gender, height, weight, smoking habits, sport activity, etc.), physical factors including working activities in the current job (e.g. lifting, bending, twisting, sitting or walking, driving, etc.), psychosocial factors (e.g. occupational psychosocial risk factors, psychosomatic distress, low mood, etc.), and experience of aches and pains in different parts of the body (pain in the low back, pain in the neck, pain in the shoulders) at various times (during the last 12 months, the last 4 weeks, or the last 7 days).

Measurement and assessment of whole-body vibration

Information about the type of driven vehicle and the duration of driving per week was obtained from the questionnaire. Exposure to WBV was then measured on a sample of vehicles (3 taxis and 7 police vehicles) in accord with International Standard 2631 (1997). The vehicles were driven over surfaces appropriate to normal daily driving. Fore-and-aft acceleration (*x*-axis), lateral acceleration (*y*-axis), and vertical acceleration (*z*-axis) was measured on the driver's seat pan using three accelerometers in a SIT-pad. A SIT-pad containing one accelerometer was used to measure fore-and-aft vibration between the backrest and the driver. The vertical floor vibration was measured by an accelerometer secured to the front seat rail of the driver's seat. The acceleration was low-pass filtered at 80 Hz and then digitized at 200 samples per second. The measurement of vibration commenced at a predetermined location and lasted for 20 minutes.

Additional measurements of cumulative exposure to WBV were recorded in six taxi vehicles to estimate daily exposure to vibration. The measurement was performed using a similar measurement set-up as used for the 20-minute measurements. After the measurements, drivers were asked to complete a simple questionnaire asking about the characteristics of the ride, including the duration. Information about the duration of driving was then compared with the duration the engine of the vehicle was running and the vehicle was moving (obtained from the measured vibration data) to quantify the accuracy of the driver's estimate of his driving duration.

The WBV exposure of the drivers was calculated in accord with VIBRISKS document WP4-N14. As recommended in the VIBRISKS document WP4-N14, a dose was calculated from the 'worst' axis using the highest (i.e. dominant) value of the frequency-weighted r.m.s. acceleration: $A_{\mathrm{dom}}(8)$, eVDV_{dom}. Also, the total life-time estimated vibration dose value (e$VDV_{\mathrm{Total\text{-}dom}}$) was calculated from knowledge of the type of driven vehicle, the dominant frequency-weighted r.m.s. acceleration measured in the vehicle, and the hours of driving during the average working week and the number of years of driving as reported by each drivers in the questionnaire (for this calculation it was assumed that there were 40 weeks in the year).

Apart from the lifetime vibration dose value, in accord with the VIBRISKS document WP4-N14, r.m.s. doses were calculated from the root-sums-of-squares of the r.m.s. values to obtain the weighted acceleration a_{ws}:

$$a_{\mathrm{ws}}=(1.4a^2_{\mathrm{x,w}}+1.4\ a^2_{\mathrm{y,s}}+\ a^2_{\mathrm{z,s}})^{1/2}\ (\mathrm{ms}^{-2})$$

Measurements in the *x*-axis on the backrest of the seat were not included in the calculations.

For the calculation of the dose using r.m.q. measures, the root-sums-of-quads of the r.m.q. values was used to obtain the weighted acceleration a_{wq}.:

$$a_{\mathrm{wq}}=(1.4a^4_{\mathrm{x,w}}+1.4\ a^4_{\mathrm{y,s}}+\ a^4_{\mathrm{zs}})^{1/4}(\mathrm{ms}^{-2})$$

Data analysis

In the first step of the analysis of the cross-sectional baseline of the longitudinal study, each potential risk factor for LBP (experienced on at least one day during the past 12 months) was examined using univariate logistic regression. All variables, for which the univariate test had a *p*-value less than 0.5, and age since it is a variable of known biologic importance, were considered for the subsequent multivariate logistic regression analysis. In the second step, a multivariate logistic regression analysis was performed. The first type of multivariate analysis was a standard multiple logistic regression. Separate multivariate models were used for each measure of WBV exposure. The final cross-sectional analysis of the baseline of the longitudinal study was a stepwise logistic regression. In the stepwise method, the variables with highest statistical significance were added the model one at time. Stepwise logistic regression was used to select possible risk factors (the factors remaining significantly associated with the prevalence of LBP in the stepwise regression model) to be investigated as risk factors predictive of LBP in the follow-up of the longitudinal study.

In the follow-up of the longitudinal study, all risk factors selected by stepwise logistic regression in the baseline and age were entered into a final statistical model. For each value of WBV exposure, final statistical models were formed for the 'incidence group' (participants without symptoms of LBP in the baseline of the study but with symptoms of LBP in the follow-up) and the 'persistence group' (participants reporting LBP symptoms in the baseline of the study and also reporting LBP in the follow-up) so as to investigate associations between risk factors and LBP experienced on at least one day during the past 12 months.

Detailed information on the study populations, an example of the questionnaire, the measurements of WBV and the statistical analysis are provided in Annex 16.

3.2.3.11 Results

In the cross-sectional baseline of the longitudinal study, from the total of 861 contacted taxi drivers, 209 questionnaires were used for analysis. From the total of 2105 police employees, 365 questionnaires from police drivers and 485 questionnaires from non-drivers were used for analysis. The main information (age, height, weight, years of work, and hours of work) are summarised in Table 3.18.

In the follow-up of the longitudinal study, 144 useful questionnaires were received from taxi drivers, 219 questionnaires from police drivers, and 300 questionnaires from non-drivers.

Health outcomes

In the baseline cross-sectional part of the study, 45% of the taxi drivers, 53% of the police drivers, 50% of the pooled group of drivers (combined group of taxi drivers and police drivers), and 46% of the non-drivers reported LBP during the past 12 months that lasted more than one day. In the follow-up of the study, 11% of taxi drivers, 26% of police drivers, 19% of the pooled group of drivers, and 27% of non-drivers reported an incident episode of LBP during the past 12 months that lasted more than one day. In the follow-up of the study, 67% of taxi drivers, 77% of police drivers, 74% of the pooled group of drivers, and 63% of non-drivers reported persistent episodes of LBP during the past 12 months that lasted more than one day. Tables 3.19a, 3.19b and 3.19c summarise the prevalence, incidence and persistence of various LBP symptoms and other health outcomes.

Detailed information on the occurrence of LBP symptoms and other health outcomes is provided in Annex 16.

Vibration measurement

The frequency-weighted acceleration in the *z*-axis (the dominant component of the vibration) was in the range from 0.39 to 0.47 ms^{-2} r.m.s. in the taxis and from 0.36 to 0.58 ms^{-2} r.m.s. in the police vehicles. Individual measurements of WBV in the vehicles are reported in Table 3.20.

Vibration exposures (average daily exposure and measures of cumulative exposure) were all significantly greater for the taxi drivers than the police drivers (p<0.001). For examples of daily and cumulative exposure to WBV, see Table 3.21.

Baseline cross-sectional study

In further analysis, continuous variables (i.e. age, height, weight, WBV metrics, scales of psychosocial factors) were classified into three bands (approximate thirds), with the lowest band used as a reference category.

In the univariate analysis of the baseline cross-sectional study of taxi drivers, the risk factors significantly associated with LBP during the past 12 months (variables selected for multivariate analysis in addition to exposure to WBV) were medium height (odds ratio, OR = 3.09), increased weight (OR = 2.6), lifting in the present job (OR = 2.84), physical demands in a previous job (OR = 2.1) and increased levels of all measures of psychosomatic distress (OR = 4.45 to 7.77). In the multivariate analysis adjusted for the above significant risk factors, there was a trend for increased prevalence of LBP during the past 12 months with increasing daily and cumulative exposure to WBV expressed with as $A_{sum}(8)$, $A_{dom}(8)$ and $eVDV_{dom}$. There were statistically significant increases in LBP during the past 12 months for vibration exposure in the highest band of all metrics of exposure to WBV, except total duration of taxi driving expressed in years.

In the univariate analysis of the baseline cross-sectional study of police drivers, the risk factors significantly associated with LBP during the past 12 months (variables selected for multivariate analysis in addition to exposure to WBV) were middle age (OR = 2.00), increased weight (OR = 2.54), lifting (OR = 1.84) and bending in the job (OR = 2.06), low support from colleagues (OR = 2.17) and increased levels of all measures of psychosomatic distress (OR = 1.64 to 2.47). In the multivariate analysis adjusted for the above significant risk factors, a positive increasing trend was found between increased duration of police driving expressed in years and LBP during the past 12 months (OR = 1.35 to 1.56). There was no significant association between increased prevalence of LBP and any other measure of exposure to WBV.

In the univariate analysis of the baseline cross-sectional study of the pooled group of all drivers, the risk factors significantly associated with LBP during the past 12 months (variables selected for multivariate analysis in addition to exposure to WBV) were middle age (OR = 1.57), middle stature (OR = 1.75) and high stature (OR = 1.73), increased weight (OR = 2.33), lifting (OR = 1.74), bending (OR = 1.73) and twisting (OR = 1.57) in the job, physical demands in a previous job (OR = 1.44), and increased levels of psychosomatic distress (OR = 2.11 to 3.32). In multivariate analysis adjusted for the above significant risk factors, LBP during the past 12 months tended to increase with cumulative exposure to WBV expressed with all alternative metrics. However, the only statistically significant association was between increased prevalence of LBP and taxi driving or police driving for more than 16 years (OR = 1.64).

In the univariate analysis of the baseline cross-sectional study of non-drivers, the risk factors significantly associated with LBP during the past 12 months that lasted more than one day were increased age (OR = 1.86) middle stature (OR = 1.61) and high stature (OR = 2.43), middle weight (OR = 1.68) and high weight (OR = 1.98), bending at work (OR = 1.7), and increased levels of psychosomatic distress (OR = 1.39 to 1.86).

Longitudinal study

Non-driving risk factors

Statistical analysis was not undertaken on the 'incidence group' of taxi drivers because the number of new cases was too low (n=9). In the 'persistence group' of taxi drivers, standard multiple logistic regression (without information on WBV exposure) revealed that there was significantly increased persistence of LBP during the past 12 months with increasing body height (middle stature: OR = 5.55; high stature: OR = 16.56) and increasing psychosomatic distress status (significant in the group with a high distress status: OR = 6.2).

In the incidence group of police drivers, standard multiple logistic regression revealed a significant association between increased incidence of LBP and poor psychosomatic distress status (OR = 5.44) and middle age (OR 3.21). In the persistence group of police drivers the only statistically significant association was increased persistence of LBP with poor psychosomatic distress status (OR = 4.76).

In the incidence group of the non-driving population, standard multiple logistic regression revealed that the only significant association was between increased incidence of LBP in those with poor psychosomatic distress status (OR = 3.11).

Pooling information from taxi drivers and police drivers in the multivariate analysis showed that being a police driver (OR = 2.46) and having a high psychosomatic distress status (OR = 5.27) significantly increased the risk of persistence of LBP during the past 12 months when controlling for the effect of other confounders.

In the multiple logistic regression model of the non-driving population, there was a significant association between persistence of LBP and bending at work (OR = 3.58), and being in the middle age group of participants (OR = 3.23). Analysis also revealed a non-significant trend for increased persistence of LBP with increasing height.

Driving risk factors

In the 'persistence group' of taxi drivers (where each aspect of driving information was entered into separate regression models with other confounders selected in the cross-sectional study) there was no significant association between increased persistence of LBP and any variable reflecting driving.

In the 'incidence group' of police drivers, the incidence of LBP increased significantly with increasing daily vibration exposure expressed as duration of driving in hours, $A_{sum}(8)$, $A_{dom}(8)$ and eVDV_{dom}. There were non-significant trends for increased incidence of LBP during the past 12 months with increased cumulative exposure to whole-body vibration (i.e. e$VDV_{Total-dom}$., $\sum[a_{wsi}t_i]$, $\sum[a_{wsi}{}^2t_i]$, $\sum[a_{wsi}{}^4t_i]$, $\sum[a_{wqi}t_i]$, $\sum[a_{wqi}{}^2t_i]$, and $\sum[a_{wqi}{}^4t_i]$).

In the 'persistence group' of police drivers, LBP experienced during the past 12 months increased with increasing total duration of driving expressed in years. A statistically significant increase in the persistence of LBP was found in those who had driven a police vehicle for more than 15.4 years (OR = 5.95).

Tables 3.22a to 3.22c show the results of multivariate logistic regression on the presence of LBP during the past 12 months for the alternative measures of daily and cumulative exposure to WBV in the incidence and persistence groups of drivers. More detailed information on the statistical analysis of risk factors for LBP is provided in Annex 16.

3.2.3.12 Discussion

The 12-month prevalence of LBP in the baseline cross-sectional study of taxi drivers and police drivers was similar to that found in other studies of driving populations. Generally, epidemiological studies with cross-sectional or case-control designs report 40 to 60% of professional drivers with LBP (e.g. bus drivers, truck drivers, fork-lift drivers, tractor drivers, car drivers, etc.; Magnusson *et al.*, 1996; Boshuizen *et al.*, 1992; Gallais and Griffin, 2006). In this study, the police drivers (53% in the baseline cross-sectional study) reported a higher 12-month prevalence of low-back pain than taxi drivers (45% in the baseline cross-sectional study). The non-driving population, represented by police employees who reported less than 5 hours of driving per working week, had a similar 12-month prevalence of LBP (46% in the baseline cross-sectional study) to the population of taxi drivers. The prevalence of LBP in the police non-driving population is consistent with the life-time prevalence reported in other epidemiological studies of general populations (e.g. Frymoyer *et al.,* 1983; Damkot *et al.*, 1984; Riihimäki *et al.*, 1989; Masset *et al.*, 1994). However, epidemiological studies of the general population do not always distinguish between professional drivers and those who do not drive in their job.

The greatest rate of new episodes of LBP (incidence cases) after one year of investigation was in the non-driving population (27%), followed by police drivers (26%), and taxi drivers (11%). The incidence rate of LBP in the taxi drivers is similar to the incidence of LBP reported in a study of LBP in commercial travellers (Pietri *et al.*, 1992), where a 13%

incidence rate was found among males and a 17% incidence rate among females. Although the incidence rate was higher in the non-driving population, the greatest rate of persistent LBP during the past 12 months was among the driving populations (67% in taxi drivers, 77% in police drivers, and 63% in the non-driving population). There are few longitudinal studies (cohort studies) reporting the incidence and persistence of health symptoms among professional drivers, probably because of the loss of subjects during investigation, the high cost of such studies, the high demand on time, etc.

Very approximately, there were similar rates of prevalence, incidence, and persistence of LBP during the past 12 months in police drivers, taxi drivers, and non-drivers. Comparable values of LBP outcomes suggest that the non-drivers were at a similar risk of developing LBP as the drivers.

A limitation of this study is the small number of participants (especially taxi drivers) in the first round of the study. The analysis of replies in the initial baseline cross-sectional study did not show any significant differences between those participants who replied at the initial questionnaire round and those who replied after a reminder and therefore it could be assumed that the study groups are representative samples of selected populations. In the follow-up of the longitudinal study, a higher response rate was obtained by more reminding and an incentive. To enhance the response rate, the taxi drivers were offered a small cash reward to be awarded to five drivers randomly selected from those who answered both questionnaires (baseline and follow-up study). The police employees were informed that a small donation would be paid to their local police charity for each completed questionnaire.

In previous studies of taxi drivers, the mean frequency-weighted acceleration in the *z*-axis (the dominant vibration component) was 0.31 ms^{-2} r.m.s. with a range from 0.17 to 0.55 ms^{-2} r.m.s. and from 0.26 to 0.34 ms^{-2} r.m.s (Chen *et al.*, 2003; Funakoshi *et al.,* 2004). In this study, the *z*-axis vibration on the seat was also the dominant vibration component in all measurements in both the taxis and the police vehicles. In the saloon car, which was the type of taxi driven by most taxi drivers in the City of Southampton, the frequency-weighted acceleration in the z-axis was 0.47 ms^{-2} r.m.s. In the police vehicles, the highest frequency-weighted acceleration in the z-axis was measured in one of the general purpose vehicles (0.58 ms^{-2} r.m.s.). The greater values may reflect differences in driving speeds, road surfaces, and the design of the vehicles. The present vibration measurements are broadly consistent with those reported from a previous study of exposure to WBV in vehicles in the UK.

LBP may affect the perceptions workers and their ratings of their work demands. From a review of thirteen studies investigating a possible overestimation of working tasks it has been concluded that workers with LBP tend to over-estimate their exposures to vibration (Barriera-Viruet *et al.,* 2006). In the case of taxi drivers, if the drivers did not properly distinguish between the periods when they were ‘on duty’ but waiting for passengers and the periods when the vehicle was running, there will have been errors, probably overestimation of vibration exposure duration. From a small study with 8-hour measurements of WBV it was found that a group of taxi drivers in the City of Southampton overestimated their driving exposure by 33% on average (with a range from 17% to 44%). This overestimation is based on six measurements and will be clarified by results from additional measurements now ongoing.

Various alternative indicators of the extent of exposure to WBV from taxi driving and police driving were investigated. The longitudinal study of taxi drivers did not reveal any statistically significant associations suggesting increased persistence of LBP with increased driving. In the longitudinal study of police drivers, there was a significant increase in the persistence of LBP in those who had driven for more than 15.4 years. There was significantly increased incidence of LBP in police drivers who had increased daily vibration exposure. It was not possible to investigate the incidence of LBP in taxi drivers because the number of new cases of LBP during the past 12-months was too low.

In the longitudinal study, increased psychosomatic distress was a strong predictor of the persistence of LBP experienced for at least one day during the past 12 months in all investigated driving populations (i.e. the taxi drivers and the police drivers). Increased psychosomatic distress was also a strong predictor of the incidence LBP in police non-drivers. Similar findings of the importance of psychosocial factors, such as anxiety, depression, and stressful events among individuals with LBP have been identified in other studies (e.g., Bergenudd and Nilsson, 1988; Gallais and Griffin, 2006). It is not clear the extent to which psychosocial problems are the cause of LBP or caused by LBP. There is no evidence linking psychosocial factors to the development of physical pathology of the spine, but people with distress are more likely to develop, or at least report, back pain (Waddell, 1998).

In the taxi drivers, being tall was a significant predictor of persistent LBP. Gyntelberg (1974) suggested that taller individuals are at greater risk for LBP and Heliövaara (1987) found that increased body height contributed to disc herniation. However, some studies have not found that increased body height increases the risk of LBP (see Gallais and Griffin, 2006).

Previous epidemiological studies have found that the prevalence of back problems increases with increasing age (see Gallais and Griffin, 2006). In the baseline cross-sectional study it was found that the risk of LBP was higher in the middle age group than in the older and younger age groups, which might be explained by the 'healthy worker effect' in which those with LBP tend to leave the job, resulting in less LBP with increasing age.

In the non-driving population, the risk of persistent LBP was greater in the middle age group than in the oldest and youngest age groups. A significant increase in persistent LBP was also found in the participants reporting bending at work. Similar findings of the importance of bending among individuals with LBP have been identified in other studies (e.g. Riihimäki *et al.*, 1989, Gallais and Griffin, 2006).

If there were clear positive associations between increased risk of low back pain and the duration of car driving it could not be concluded that whole-body vibration is causing low back pain. Car driving involves many factors (e.g. various postures while driving, lack of movement, forces at the feet when operating foot pedals, load from the arms, head posture, back movement, twisting whole reversing, forces during entry and exit from a car, etc.) which could influence the risk of LBP.

3.2.3.13 Conclusion

The 12-month prevalence, incidence, and persistence of low back pain (LBP) in the non-driving population was similar to the prevalence, incidence, and persistence of LBP reported by the driving populations in this study, suggesting that the driving and non-driving populations were at a similar risk of developing LBP. The 12-month prevalence of LBP among taxi drivers and police drivers was similar to that in other driving populations (i.e. bus drivers, fork-lift operators, and truck drivers).

In the taxi drivers, increased exposure to WBV was not an important risk factor for the persistence of LBP. In the police drivers, increased duration of total life-time driving (expressed in years) was a statistically significant risk factor for increased persistence of LBP, and increased daily vibration exposure (in hours) was a statistically significant risk factor for increased incidence of LBP.

In taxi drivers, police drivers, and in the non-driving population, the presence of LBP experienced for at least one day during the past 12 months was significantly associated with individual risk factors (e.g. age, height), physical factors (e.g. bending) and, mainly, psychosocial risk factors (i.e. increased psychosomatic distress status).

Table 3.18 Characteristics of the populations in the baseline cross-sectional study. Data are given as means (standard deviations) for age and anthropometric characteristics, or as numbers (%) for smoking, and physical activity.

	Study populations			
	Taxi drivers (n=209)	Police drivers (n=365)	Non-drivers (n=485)	All drivers (n=574)
Age (yr)	49.5 (10.5)	37.9 (8.4)	41.7 (10.5)	42.1 (10.8)
Height (cm)	174.6 (7.5)	178.3 (7.5)	170.9 (10.2)	177.11 (8.9)
Weight (kg)	87 (16.2)	81.5 (13)	77.1 (16.4)	83.5 (14.5)
Body mass index (kg/m^2)	28.3 (4.7)	25.6 (3.2)	26.1 (4.6)	26.5 (3.9)
Smoking (n):				
non-smokers	80 (38)	256 (70)	317 (65)	336 (59)
ex-smokers/smokers	127 (61)	108 (30)	166 (34)	235 (41)
current smokers	57 (27)	38 (10)	57 (12)	95 (17)
Physical activity (n):				
never	123 (59)	81(22)	152 (30)	204 (35)
1-2 per week	40 (19)	136 (37)	143 (30)	176 (31)
3-4 per week	28 (13)	77 (21)	80 (17)	105 (18)
> 4 per week	18 (9)	71 (20)	110 (23)	89 (16)

Table 3.19a Prevalence (in the baseline cross-sectional study) of health symptoms in the total sample of taxi drivers (n=209), police drivers (n=365), pooled group of drivers (n=574), and non-drivers (n=485).

Outcome	Taxi drivers (%)	Police drivers (%)	All drivers (%)	Non-drivers (%)
LBP in the previous 12 months	45	53	50	46
LBP in the previous 4 weeks	29	35	33	21
LBP in the previous 7 days	19	19	19	11
Episodes of acute LBP in the previous 12 months	28	33	31	31
Episodes of sciatica in the previous 12 months	14	13	13	13
Duration of LBP > 30 d/yr in the previous 12 months	16	21	19	13
High pain intensity in the lower back in the previous 7 days (Von Korf pain scale score > 5)	7	4	5	3
Disability due to the last episode of LBP (Roland & Morris disability scale score ≥ 12)	5	4	4	2
Visit to a doctor for LBP in the previous 12 months	12	12	12	11
Sick leave > 7 days due to LBP in the previous 12 months	8	3	5	2
NP in the previous 12 months	33	30	31	35
NP in the previous 4 weeks	21	17	18	18
NP in the previous 7 days	13	10	11	9
SP in the previous 12 months	28	29	29	26
SP in the previous 4 weeks	21	17	16	14
SP in the previous 7 days	13	8	10	7

Table 3.19b Incidence of health symptoms in the total sample of taxi drivers (n=144), police drivers (n=219), pooled group of drivers (n=300) and non-drivers (n=363), in the follow-up study.

Outcome	Taxi drivers (%)	Police drivers (%)	All drivers (%)	Non-drivers (%)
LBP in the previous 12 months	11	26	19	27
LBP in the previous 4 weeks	3	11	7	9
LBP in the previous 7 days	3	5	4	4
Episodes of acute LBP in the previous 12 months	10	21	16	21
Episodes of sciatica in the previous 12 months	1	2	2	4
Duration of LBP > 30 d/yr in the previous 12 months	1	5	3	4
High pain intensity in the lower back in the previous 7 days (Von Korf pain scale score > 5)	0	0	0	1
Disability due to the last episode of LBP (Roland & Morris disability scale score ≥ 12)	3	1	2	1
Visit to a doctor for LBP in the previous 12 months	3	2	2	6
Sick leave > 7 days due to LBP in the previous 12 months	1	0	1	1
NP in the previous 12 months	16	16	16	25
NP in the previous 4 weeks	11	9	10	15
NP in the previous 7 days	10	5	7	11
SP in the previous 12 months	14	24	19	19
SP in the previous 4 weeks	10	10	10	9
SP in the previous 7 days	10	4	7	8

Table 3.19c Persistence of health symptoms in the total sample of taxi drivers (n=144), police drivers (n=219), pooled group of drivers (n=300) and non-drivers (n=363), in the follow-up study.

Outcome	Taxi drivers (%)	Police drivers (%)	All drivers (%)	Non-drivers (%)
LBP in the previous 12 months	67	77	74	63
LBP in the previous 4 weeks	41	54	49	36
LBP in the previous 7 days	41	31	34	19
Episodes of acute LBP in the previous 12 months	41	46	44	44
Episodes of sciatica in the previous 12 months	16	22	20	17
Duration of LBP > 30 d/yr in the previous 12 months	25	32	29	19
High pain intensity in the lower back in the previous 7 days (Von Korf pain scale score > 5)	13	8	10	3
Disability due to the last episode of LBP (Roland & Morris disability scale score ≥ 12)	9	6	7	4
Visit to a doctor for LBP in the previous 12 months	22	19	20	18
Sick leave > 7 days due to LBP in the previous 12 months	11	6	17	4
NP in the previous 12 months	41	48	45	38
NP in the previous 4 weeks	28	29	29	21
NP in the previous 7 days	28	16	20	13
SP in the previous 12 months	34	31	32	31
SP in the previous 4 weeks	28	17	21	19
SP in the previous 7 days	28	11	17	12

Table 3.20 Frequency-weighted root-mean-square (r.m.s.) acceleration magnitude (a_w) of vibration measured in the *x*-, *y*-, and *z*-directions on the seats of taxi and police vehicles. The vibration total value of frequency-weighted r.m.s. accelerations (a_v) is calculated according to International Standard 2631-1 (1997).

		Frequency-weighted acceleration magnitude			
Type of driven vehicle	Model of driven vehicle	a_{wx} (ms^{-2} r.m.s.)	a_{wy} (ms^{-2} r.m.s.)	a_{wz} (ms^{-2} r.m.s.)	a_{ws} (ms^{-2} r.m.s.)
Taxi					
Saloon car	Skoda Octavia	0.12	0.14	0.47	0.52
Purpose build vehicle	TX1	0.14	0.16	0.44	0.5
Purpose adapted vehicle	Vauxhall Zafira	0.17	0.13	0.39	0.47
Police vehicle					
General purpose vehicles					
	Land Rover-Discovery	0.16	0.22	0.36	0.48
	Vauxhall Astra	0.22	0.18	0.58	0.67
	Ford Focus	0.15	0.19	0.38	0.48
Traffic control vehicle					
	Vauxhall Omega	0.19	0.23	0.43	0.56
	BMW 750	0.14	0.24	0.45	0.56
	Ford Mondeo	0.2	0.22	0.46	0.58
Off-road vehicle					
	Land Rover-Ranger	0.19	0.22	0.43	0.55

Table 3.21 Measures of daily and cumulative exposure to WBV in the professional drivers in the baseline cross-sectional study. Data are given as means (standard deviations).

	Driver group		
	Taxi drivers (n=209)	Police drivers (n=365)	All drivers (n=574)
Measures of daily vibration exposure			
Daily driving time (h)	7.90 (3.03)	2.92 (1.62)	4.74 (3.28)
A_{sum} (8) (ms^{-2} r.m.s.)	0.50 (0.1)	0.32 (0.09)	0.39 (0.13)
A_{dom}(8) (ms^{-2} r.m.s.)	0.43 (0.17)	0.26 (0.07)	0.32 (0.14)
VDV_{sum} (ms$^{-1.75}$)	9.27 (1.0)	7.16 (1.01)	7.92 (1.44)
VDV_{dom} (ms$^{-1.75}$)	8.34 (0.98)	6.09 (0.86)	6.92 (1.41)
Measures cumulative vibration exposure			
Exposure duration (yr)	12.27 (9.97)	11.34 (8.23)	11.68 (8.91)
$eVDV_{total\text{-}dom}$ (ms$^{-1.75}$)	54.92 (13.48)	39.35 (10.65)	46.24 (15.38)
$\sum[t_i]$ (h $\times 10^3$)	21.39 (39.49)	6.61 (6.44)	11.90 (25.17)
$\sum[a_{wsi}t_i]$(ms^{-2}h$\times 10^3$)	11.09 (20.38)	3.59 (3.39)	6.35 (13.14)
$\sum[a_{wsi}^2 t_i]$ (m^{2}s^{-4}h $\times 10^3$)	5.70 (10.51)	1.97 (1.88)	3.34 (6.78)
$\sum[a_{wsi}^4 t_i]$ (m^{4}s^{-8}h $\times 10^3$)	1.50 (2.8)	0.60 (0.58)	0.93 (1.81)
$\sum[a_{wqi}t_i]$ (ms^{-2}h $\times 10^3$)	17.16 (31.59)	4.16 (3.93)	8.94 (20.36)
$\sum[a_{wqi}^2 t_i]$ (m^{2}s^{-4}h $\times 10^3$)	13.63 (25.27)	2.66 (2.52)	6.69 (16.31)
$\sum[a_{wqi}^4 t_i]$ (m^{4}s^{-8}h $\times 10^3$)	8.62 (16.18)	1.08 (1.03)	3.85 (10.48)

Table 3.22a Taxi drivers with persistent low back pain. Logistic regression of LBP experienced for at least one day during the past 12 months on alternative measures of WBV in the population of taxi drivers in the persistent group of the one-year follow-up period. Odds ratio and 95% confidence intervals are adjusted for several covariates (age, height, previous physical demands, and psychosomatic distress).

	Subgroups of measure of WBV exposure		
	Q1	Q2	Q3
Measures of daily vibration exposure			
Daily driving time (h)	1.0	0.23	0.25
	(-)	(0.02-2.15)	(0.03-1.97)
A_{sum} (8) (ms^{-2} r.m.s.)	1.0	0.23	0.25
	(-)	(0.02-2.15)	(0.03-1.97)
A_{dom}(8) (ms^{-2} r.m.s.)	1.0	0.73	0.49
	(-)	(0.09-5.7)	(0.07-3.37)
VDV_{dom} (ms$^{-1.75}$)	1.0	0.62	0.45
	(-)	(0.08-14.89)	(0.07-2.98)
Measures cumulative vibration exposure			
Exposure duration (yr)	1.0	1.91	0.72
	(-)	(0.28-13.01)	(0.1-5.23)
$eVDV_{total\text{-}dom}$ (ms$^{-1.75}$)	1.0	1.93	1.46
	(-)	(0.23-16.06)	(0.15-13.85)
$\sum[t_i]$ (h $\times 10^3$)	1.0	9.71	1.2
	(-)	(0.77-121.97)	(0.14-10.18)
$\sum[a_{wsi}t_i]$(ms^{-2}h$\times 10^3$)	1.0	9.71	1.2
	(-)	(0.77-121.97)	(0.14-10.18)
$\sum[a_{wsi}^2 t_i]$ (m^{2}s^{-4}h $\times 10^3$)	1.0	9.71	1.2
	(-)	(0.77-121.97)	(0.14-10.18)
$\sum[a_{wsi}^4 t_i]$ (m^{4}s^{-8}h $\times 10^3$)	1.0	9.71	1.2
	(-)	(0.77-121.97)	(0.14-10.18)
$\sum[a_{wqi}t_i]$ (ms^{-2}h $\times 10^3$)	1.0	9.71	1.2
	(-)	(0.77-121.97)	(0.14-10.18)
$\sum[a_{wqi}^2 t_i]$ (m^{2}s^{-4}h $\times 10^3$)	1.0	9.71	1.2
	(-)	(0.77-121.97)	(0.14-10.18)
$\sum[a_{wqi}^4 t_i]$ (m^{4}s^{-8}h $\times 10^3$)	1.0	9.71	1.2
	(-)	(0.77-121.97)	(0.14-10.18)

Table 3.22b Police drivers with persistent low back pain. Logistic regression of LBP experienced for at least one day during the past 12 months on alternative measures of WBV in the population of police drivers in the persistent group over the one-year follow-up period. Odds ratio and 95% confidence intervals are adjusted for several covariates (age, lifting, bending, and psychosomatic distress).

	Subgroups of measure of WBV exposure		
	Q1	Q2	Q3
Measures of daily vibration exposure			
Daily driving time (h)	1.0	0.6	0.52
	(-)	(0.15-2.35)	(0.15-1.79)
A_{sum} (8) (ms^{-2} r.m.s.)	1.0	0.5	0.66
	(-)	(0.13-1.98)	(0.17-2.54)
A_{dom}(8) (ms^{-2} r.m.s.)	1.0	0.69	0.51
	(-)	(0.17-2.92)	(0.14-1.9)
VDV_{dom} ($ms^{-1.75}$)	1.0	0.56	0.42
	(-)	(0.13-2.49)	(0.11-1.64)
Measures cumulative vibration exposure			
Exposure duration (yr)	1.0	2.98	5.95
	(-)	(0.87-10.21)	(1.69-21.03)
$eVDV_{total-dom}$ ($ms^{-1.75}$)	1.0	3.05	2.12
	(-)	(0.71-13.04)	(0.61-7.44)
$\sum[t_i]$ (h $\times 10^3$)	1.0	3.85	2.44
	(-)	(0.38-38.61)	(0.8-7.43)
$\sum[a_{wsi}t_i]$($ms^{-2}h\times 10^3$)	1.0	3.62	2.34
	(-)	(0.85-15.51)	(0.67-8.19)
$\sum[a_{wsi}^2 t_i]$ ($m^2s^{-4}h \times 10^3$)	1.0	3.62	2.34
	(-)	(0.85-15.51)	(0.67-8.19)
$\sum[a_{wsi}^4 t_i]$ ($m^4s^{-8}h \times 10^3$)	1.0	3.21	2.53
	(-)	(0.75-13.72)	(0.72-8.88)
$\sum[a_{wqi}t_i]$ ($ms^{-2}h \times 10^3$)	1.0	3.62	2.34
	(-)	(0.85-15.51)	(0.67-8.19)
$\sum[a_{wqi}^2 t_i]$ ($m^2s^{-4}h \times 10^3$)	1.0	3.62	2.34
	(-)	(0.85-15.51)	(0.67-8.19)
$\sum[a_{wqi}^4 t_i]$ ($m^4s^{-8}h \times 10^3$)	1.0	3.62	2.34
	(-)	(0.85-15.51)	(0.67-8.19)

Table 3.22c Police drivers with incident low back pain. Logistic regression of LBP experienced for at least one day during the past 12 months on alternative measures of WBV in the population of police drivers in the incident group over the one-year follow-up period. Odds ratio and 95% confidence intervals are adjusted for several covariates (age, lifting, bending, and psychosomatic distress).

	Subgroups of measures of WBV exposure		
	Q1	Q2	Q3
Measures of daily vibration exposure			
Daily driving time (h)	1.0	8.24	7.69
	(-)	(1.27-53.43)	(1.58-37.4)
A_{sum} (8) (ms^{-2} r.m.s.)	1.0	10.85	9.84
	(-)	(1.64-71.63)	(1.84-52.58)
A_{dom}(8) (ms^{-2} r.m.s.)	1.0	10.85	9.84
	(-)	(1.64-71.63)	(1.84-52.58)
VDV_{dom} ($ms^{-1.75}$)	1.0	10.85	9.84
	(-)	(1.64-71.63)	(1.84-52.58)
Measures cumulative vibration exposure			
Exposure duration (yr)	1.0	1.27	0.79
	(-)	(0.38-4.23)	(0.19-3.32)
$eVDV_{total\text{-}dom}$ ($ms^{-1.75}$)	1.0	2.57	2.58
	(-)	(0.51-12.87)	(0.53-12.56)
$\sum[t_i]$ ($h \times 10^3$)	1.0	2.07	3.05
	(-)	(0.29-14.82)	(0.72-12.93)
$\sum[a_{wsi}t_i]$($ms^{-2}h \times 10^3$)	1.0	2.57	3.08
	(-)	(0.54-12.26)	(0.62-15.2)
$\sum[a_{wsi}^2 t_i]$ ($m^2s^{-4}h \times 10^3$)	1.0	2.57	3.08
	(-)	(0.54-12.26)	(0.62-15.2)
$\sum[a_{wsi}^4 t_i]$ ($m^4s^{-8}h \times 10^3$)	1.0	2.57	3.08
	(-)	(0.54-12.26)	(0.62-15.2)
$\sum[a_{wqi}t_i]$ ($ms^{-2}h \times 10^3$)	1.0	2.57	3.08
	(-)	(0.54-12.26)	(0.62-15.2)
$\sum[a_{wqi}^2 t_i]$ ($m^2s^{-4}h \times 10^3$)	1.0	2.57	3.08
	(-)	(0.54-12.26)	(0.62-15.2)
$\sum[a_{wqi}^4 t_i]$ ($m^4s^{-8}h \times 10^3$)	1.0	2.57	3.08
	(-)	(0.54-12.26)	(0.62-15.2)

3.2.4 Case-control survey in the United Kingdom

3.2.4.1 Introduction

Low back pain (LBP) is a common important cause of disability, but its aetiology is not fully understood. Epidemiological studies have implicated whole-body vibration (WBV), alongside a list of many other physical, constitutional, and psychosocial risk factors (e.g. manual work, occupational lifting and twisting, forward bending and stooping, prolonged sitting, exposure to, age, sex, height and smoking habits, mental well-being, job satisfaction and control over job demands); but these do not explain all of its descriptive epidemiology. In particular, the striking time trends in disability attributed to LBP in some countries have not been accompanied by a change in the prevalence of known risk factors.

One of the difficulties in investigation of LBP is the uncertain pathogenesis of most cases and the lack of objective diagnostic criteria. Thus, case definition in most studies has been based on subjective report of symptoms. Inevitably this opens up the possibility for bias in the assessment of risk factors. For example, people whose work is physically demanding may be more aware of back symptoms and report them more readily. An exception to the generally poor understanding of pathogenesis is prolapsed intervertebral disc (PID). PID can occur in the absence of back symptoms, and the coincidence of PID and back pain does not necessarily imply that the PID gave rise to the pain. Nevertheless, PID, and related pathology such as tears of the posterior annulus, appear to account for a substantial minority of back pain cases.

In the past, opportunities to study PID were limited because the disorder could only be diagnosed confidently by invasive surgery. More recently, the advent of magnetic resonance imaging (MRI) has meant that PID and related disc pathology can be diagnosed more easily, and there is greater understanding of the other confounding factors that need to be considered. Given the paucity of data on risk factors for objectively diagnosed PID and related disc pathology, a case-control study based on cases identified through MRI was undertaken.

3.2.4.2 Objectives

The objectives of the study were to investigate the risk factors that underlay LBP presenting to radiology services, and to compare them among subjects with and without MRI evidence of PID or related disc pathology. A particular focus was to assess how strongly the occurrence of LBP severe enough to merit MRI investigation was associated with exposure to WBV, and to which metrics of dose.

3.2.4.3 Methods

A case-control approach was used. The study population comprised all subjects aged 20-64 years normally resident in the catchment area served by the radiology services at Southampton General Hospital (SGH) - specifically, those living in certain postcodes within the Southampton area. Cases were a consecutive series of patients from the study population referred to the radiology department at SGH and two local private hospitals for MRI because of LBP over a 30-month recruitment period during 2003 - 2006. Subjects who had scans because of external trauma or non-mechanical causes of LBP were excluded. Controls were subjects from the Accident and Emergency Department of SGH who had been X-rayed during the recruitment period. Eligible controls fulfilled the same residency requirement as cases and were group matched to them by sex and 5-year age bands. Subjects having X-rays of the back following a road traffic accident were excluded. Controls had a range of diagnoses.

The recruitment procedures for cases and controls, sample correspondence and questionnaires have been published on the VBRISKS website (see also Annex 17). Questions were based on the model set developed within the VIBRISKS project. The choice and provenance of measuring instruments is set out in Annex 17, as are key decisions on the coding and classification of variables. In brief, subjects were asked about: all jobs held for more than a year; physical risk factors which loaded the back; occupational psychosocial risk factors for LBP; professional driving and exposure to WBV (vehicle types, duration and intensity); personal characteristics (e.g. height, weight, age, sex, smoking habits); and also mental health (low mood, somatising tendency), fear avoidance health beliefs, beliefs regarding work as a cause or aggravation of LBP, and propensity to consult over LBP - assessed using various standard instruments.

Exposure to WBV was assessed as in document WP4-N14. Six measures were used: (1) professional driving for ≥1 hour/day; (2) professional driving ≥3 hours at a time; (3) average hours of professional driving/week for the commonest source of exposure; (4) average hours of professional driving/week for all sources of exposure; (5) maximum r.m.s. of any machine; and (6) current r.m.s. A(8)**.** Lifetime cumulative doses were not estimated.

For cases, images of the lumbosacral spine were obtained according to routine departmental practice (see Annex 17 for details). Two hundred and thirty-three scans from SGH have been located in the X-ray library and the envelopes marked to retain them for study. Copies of a further 148 scans performed at the private hospitals have been copied to CD-ROM. These scans are currently being read by trained observers (specialists in radiology) blinded to the patient's employment and exposure history, and other questionnaire responses. The aim will be to sub-classify cases according to the presence or absence of pathology that may give rise to LBP – e.g. disc herniation (disc impairment, disc bulge, disc protrusion and disc extrusion); disc degeneration (e.g. loss of disc height, endplate changes); nerve root impingement and compression; high intensity zones and posterior annular tears; and facet joint arthropathy. Pilot work has been undertaken to define a framework of operational definitions, to train observers in a common methodology, and to assess within- and between-observer repeatability in our hands. Associations with WBV according to the presence or absence of specific findings on MRI will be examined and reported later.

The focus of this report is on two outcomes: (1) being a case (2) being in the most disabled half of cases (RMS≥ median of 11). Analysis was restricted to cases whose present episode of LBP came on in their current or most recent job and to controls who gave a current or most recent job history. Associations of each potential risk factor with the two outcomes were examined initially with adjustment for age and sex and then in standard stepwise logistic regression. In the final stage, risk factors other than driving were identified by stepwise regression and included in a multivariable model that contained a driving variable as a forced choice. Separate multivariable models were constructed for each of the six metrics of exposure to WBV. Main analyses were repeated after excluding cases recruited from the private hospitals. Associations were expressed as odds ratios (OR) with 95% confidence intervals (95% CI).

3.2.4.4 Results

Altogether, 743 cases and 2,268 controls were approached. Usable replies were received from 385 of the cases and 965 of the controls. Some subsequent exclusions were made for various reasons (mainly previous surgery to the back or lack of a current or recent job history). Finally, 271 cases and 809 controls feature in the analysis.

The median duration of LBP was 10 years, 67% reported taking time off work because of symptoms, and 84% reported sciatica. The median RMS score for the past 4 weeks was 11 (IQR 5-17). Regarding risk factors other than WBV, strong associations were seen with somatising tendency, SF-36 MH score and belief in work as a cause/aggravation of LBP. Thus, for cases overall, the OR was raised 3.8 fold in those who reported ≥2 somatic symptoms distressing vs. 0, and raised 1.8-1.9 fold in those with low mood or attributing symptoms to work; among the severe cases, associations were stronger again (12.5 and 3.5-5.4 respectively). Associations were also seen with tall stature (OR 1.6) and propensity to consult over LBP (OR 1.8-2.0), but of similar magnitude for the two outcomes. BMI, smoking status and fear avoidance beliefs were also associated with LBP, but only among the more severe cases.

In comparison with personal risks, occupational risks were only weakly associated with LBP and in many cases risks were non-significantly elevated or close to the null value. For LBP overall, however, there was a non-significant association with frequent twisting of the back (OR 1.4) and a significant association with sitting for more than 3 hours while not driving (OR 2.0), and similar associations were seen among the more severe cases. Finally, there were significant associations with low decision latitude (OR 1.3-2.1) and low support (OR 1.5-1.7).

The study included 200 professional drivers (54 cases and 146 controls), and of these 175 reported driving a single vehicle occupationally: the predominant exposure was to cars (124 reports), there being also 24 lorry drivers, 7 bus drivers, 9 drivers of forklift trucks, and 7 ambulance drivers. The median weekly exposure time for drivers was 16 hours (IQR 10-30 hours), and the median A(8) was 0.79 (0.31-3.0) m/s^{-2}, but the upper interquartile limit was 0 for both parameters when considered across the whole sample.

Few positive associations were seen between the six metrics of WBV and the two case outcomes (Table 3.23). In an analysis that adjusted for age and sex, professional driving for more than 3 hours at a time was non-significantly associated with a higher odds overall (1.3) and of severe (OR 1.5) LBP; and a non-significant increase in relative risks was found in the band with A(8) $\geq$ 0.5 - 1.15 vs. 0 ms^{-2} (OR 1.2 and 1.4), but no finding was significant at the 5% level and no exposure metric showed an exposure-response pattern. In multivariable analysis associations with professional driving for more than 3 hours/day were weakened (OR 1.1 vs. 1.3-1.5); while other associations were not much changed, the only non-significant positive associations being with A(8) $\geq$ 0.5 - 1.15 ms^{-2} and driving 3-10 vs. 0 hours/week professionally. Again, no association was significant at the 5% level and no evidence was found of an exposure-response relation.

When we repeated the analysis after excluding cases from the private hospitals (n=117) then a broadly similar pattern of results was obtained. No metric of WBV showed a significant univariate or multivariate association and in only one comparison by A(8) was an OR elevated. There was no evidence of an exposure-response relationship.

3.2.4.5 Discussion

As judged by these findings, there are strong positive associations between severe LBP referred for imaging of the lumbar spine and somatising tendency, low mood, certain beliefs about LBP and consulting attitudes, as well as moderate positive associations with tall stature, smoking, and work involving: frequent or prolonged twisting, sitting while not driving, low decision latitude and poor support from colleagues or managers. Beyond this we found very little evidence of a risk from exposure to professional driving or WBV.

In weighing the findings, a number of issues need to be considered related to incomplete response, retrospective ascertainment of exposure, timing of relevant exposures, selection of representative cases and controls, and assessment of exposures to WBV. Discussion is provided on the strengths and weaknesses of the data in Annex 17.

Our failure to observe clear relations between LBP may arise because of the relatively low prevalence of professional driving in the study population (18.5% overall) and the play of chance; but a stronger possibility is that the drivers in our study - representing a population-based sample - were less heavily exposed to WBV than in surveys of occupational cohorts. Most were drivers of cars, with relatively few other sources of exposure reported. In only 1 in 5 to 6 of our study subjects was exposed to levels of A(8) $\geq$ 0.5 m/s^{-2} and only 1 in 20 was exposed to levels of A(8) $\geq$ 1.0 m/s^{-2}. In comparison, in certain positive studies from occupational settings, average exposure levels were in the range of 0.5 – 1.0 m/s^{-2}. Our findings on sitting while not driving raise a third possibility - that previously reported associations with WBV were confounded by constrained sitting, a characteristic ingredient of professional driving. A fourth possibility is that WBV is generally associated with mild to moderate LBP, but not the severe kind studied here.

Whichever the explanation, our findings suggest that at the population level WBV is not an important cause of LBP severe enough to be referred for MRI imaging of the lumbar spine. Certain aspects of mental health and health beliefs (psychological factors) make a more important contribution in the general population.

Table 3.23 Associations with exposure to whole-body vibration in the study group

	Cases (n, %)				Controls		Univariate OR (95% CI)				Multivariate OR (95% CI)			
	All (n = 271)		**RMS ≥11 (n = 138)**		**(n, %) (n = 809)**		**All cases vs Controls***		**RMS ≥11 vs Controls***		**All cases vs Controls‡**		**RMS ≥11 vs Controls†**	
Professional driving (≥1 hr/day)														
No	217	(80.1)	109	(79.0)	663	(82.0)	1.0		1.0		1.0		1.0	
Yes	54	(19.9)	29	(21.0)	146	(18.1)	1.1	(0.7 - 1.5)	1.2	(0.7 - 1.9)	1.0	(0.6 - 1.5)	1.0	(0.6 - 1.8)
Professional driving (≥3 hrs at a time)														
No	246	(90.8)	124	(89.9)	752	(93.0)	1.0		1.0		1.0		1.0	
Yes	24	(8.9)	14	(10.1)	55	(6.8)	1.3	(0.7 - 2.1)	1.5	(0.8 - 2.9)	1.1	(0.6 - 2.0)	1.1	(0.5 - 2.4)
Average hours driven/week for the commonest exposure source														
None	217	(80.1)	109	(79.0)	663	(82.0)	1.0		1.0		1.0		1.0	
<16	26	(9.6)	16	(11.6)	67	(8.3)	1.1	(0.7 - 1.8)	1.4	(0.8 - 2.6)	1.2	(0.7 - 2.1)	1.4	(0.7 - 2.8)
≥16	22	(8.1)	12	(8.7)	73	(9.0)	0.8	(0.5 - 1.4)	0.9	(0.5 - 1.9)	0.7	(0.4 - 1.3)	0.6	(0.3 - 1.5)
Total hours driven/week, all sources														
Not a regular driver	217	(80.1)	109	(79.0)	663	(82.0)	1.0		1.0		1.0		1.0	
3 -10	18	(6.6)	11	(8.0)	43	(5.3)	1.2	(0.7 - 2.1)	1.5	(0.7 - 3.0)	1.3	(0.7 - 2.6)	1.6	(0.7 - 3.7)
>10 - 20	14	(5.2)	8	(5.8)	39	(4.8)	1.0	(0.5 - 1.9)	1.2	(0.5 - 2.7)	0.8	(0.4 - 1.7)	0.9	(0.3 - 2.3)
>20 - 40	12	(4.4)	6	(4.4)	40	(4.9)	0.8	(0.4 - 1.6)	0.9	(0.3 - 2.1)	0.8	(0.4 - 1.6)	0.7	(0.2 - 2.2)
>40 - 81	4	(1.5)	3	(2.2)	18	(2.2)	0.6	(0.2 - 1.8)	1.0	(0.3 - 3.4)	0.5	(0.1 - 1.8)	0.6	(0.1 - 2.4)
Current r.m.s. A(8) (ms^{-2})														
0	217	(80.1)	109	(79.0)	663	(82.0)	1.0		1.0		1.0		1.0	
>0 -< 0.5	4	(1.5)	2	(1.5)	20	(4.8)	0.6	(0.2 - 1.8)	0.6	(0.1 - 2.7)	0.8	(0.2 - 2.5)	0.5	(0.1 - 2.7)
0.5 - 1.15	32	(11.8)	19	(13.8)	77	(9.5)	1.2	(0.7 - 1.8)	1.4	(0.8 - 2.5)	1.1	(0.7 - 1.9)	1.4	(0.7 - 2.8)
>1.15	12	(4.4)	7	(5.1)	41	(5.1)	0.8	(0.4 - 1.6)	1.0	(0.4 - 2.4)	0.6	(0.3 - 1.4)	0.6	(0.2 - 1.7)

Figures may not sum to 100% due to missing values. Each row variable was analysed in a separate regression model. RMS = Roland Morris score.
* OR adjusted for age (in three bands) and sex.

‡ Adjustment was made for: age, sex, somatising tendency, beliefs about causation of LBP, attitudes to consulting over LBP, number of other sites with pain, work with arms above shoulder height, sitting while not driving (see Annex 17 for details).

† Adjustment was made for: age, sex, height, somatising tendency, mental health, beliefs about causation of LBP, attitudes to consulting over LBP, number of other sites with pain, sitting while not driving (see Annex 17 for details).

3.3 Biodynamic modelling and whole-body vibration experimental work

3.3.1 Introduction

The complex relationships between whole-body vibration exposure (WBV) and health risk have been discussed recently (Seidel, 2005). Variable postures, age and anthropometric characteristics were identified as important factors that co-determine the effects of occupational WBV on health. These factors are not sufficiently considered by current evaluation procedures. International Standard 2631-1 (1997) provides a Health Guidance Caution Zone without quantitative information that would permit an allocation of a certain exposure condition within that zone, taking into consideration associated factors, for example, posture and/or stature. International Standard 2631-5 (2004) considers solely age by a quantitative correction of the predicted ultimate strength of lumbar vertebrae. Both standards do not provide quantitative guidance concerning effects on different levels of the lumbar spine and relevance of vibration input via backrest, feet and hand support in three directions for health.

A linear FE-model was developed within the research project F 5162 of the German Federal Institute for Occupational Safety and Health (FIOSH). The prediction of intra-spinal forces by suited dynamic finite element (FE-) models can bypass the difficulties linked with complicated separate quantifications of many different relationships and/or effects of factors by simulating the whole chain between vibration inputs in different directions to parts of a specific human body and the outputs of compressive and shear forces acting on different levels of the lumbar spine. A sufficient solution requires validated anatomy-based dynamic FE-models, whereas phenomenological models are not suited for this purpose. The range of applicability depends on the ability of the FE-models to reflect different postures and statures.

3.3.2 Objectives

The study aimed at the extension of the existing anatomy-based FE-model and its adaptation to different postures. Human experiments had to be performed as a basis for this extension and in order to validate the model together with other partners. An analysis of anthropometric characteristics of European drivers was intended to scale FE-models for this population. Another task was the development of a practicable tool that permits the application of FE-modelling to routine calculations.

3.3.3 Methods

Two experimental studies were performed. In the first study 13 subjects were exposed to single-axis vibration in X-, Y-, and Z-axes at three vibration magnitudes, dual-axis vibration in X- and Y-axes as well as three-axis vibration in X-, Y-, and Z-axes simultaneously at two vibration magnitudes. The excitation axes are marked by capitals, but measuring directions by lower-case letters (e.g. ax X means acceleration measured in x-direction during the excitation in X-axis). The subjects were exposed to random whole-body vibration (nearly flat spectrum from 0.25 to 30 Hz for 60 s) at unweighted root-mean-square (r.m.s.) accelerations of 0.26 ms^{-2}, 0.83 ms^{-2} and 1.57 ms^{-2}. In the second study, eight subjects were exposed to three magnitudes of single-axis vibration in the X, Y, and Z-axes and of three-axis vibration in X-, Y-, and Z-axes simultaneously. The subjects were exposed to random whole-body vibration (nearly flat spectrum from 0.25 to 20 Hz for 65 s) at unweighted r.m.s. accelerations of 0.45 ms^{-2}, 0.90 ms^{-2} and 1.80 ms^{-2}. A force plate (Kistler 9396 AB) capable of measuring forces in three directions simultaneously was mounted at the seat surface in order to measure forces in the fore-and-aft (x) direction, lateral (y) direction and vertical (z) direction. The feet were support by a second force plate (Kistler 9281 B12, SN 124804, 60x40x20 cm). The time series of the measured forces were corrected by subtracting the product of the mass of the plate resting on the force sensors and the acceleration measured at the seat plate for all conditions tested. Accelerations in three translational directions (*x*, *y*, and *z*) were measured at each force plate using six capacitance accelerometers (ENDEVCO 7290A-10) mounted on two special blocks for them (ENDEVCO 7990 block). Three translational one- or three-axial accelerometers mounted on a bite-bar (material: titan) to measure head motion were full bridge piezo-resistive (strain gauge) type accelerometers (two EGAXT3-M-10 and one EGAXT-10, Entran). The bite bar was held by the teeth via an individually-produced bite plate. Translational and rotational head accelerations were measured in three directions and around three axes, respectively. The data acquisition was performed by a WaveBook (WBK16, Iotech). A motion analysis system (Qualisys) was used to register the movements of body points (spinal process of C7, acromion process, elbow joint, wrist, pelvic, iliac crest, hip joint, knee joint, and ankle). The forces in the three translational directions were related to the input accelerations in the same direction and location. The apparent mass is defined as the complex ratio of force amplitude and acceleration amplitude in the same direction (*x, y, z*) as a function of frequency. The apparent mass was calculated by dividing the cross-spectral density function between the force and the acceleration by the power spectral density of the seat acceleration using a MatLab routine. The experimental set-up is shown in Figure 3.1.

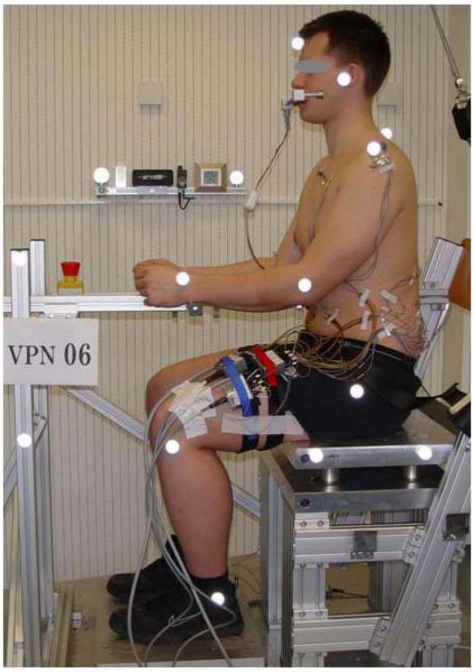

Figure 3.1 Subject sitting on a rigid

The linear FE-model was extended and verified by comparisons with experimentally determined apparent mass data. The model was adapted to five different postures (model groups) derived from data obtained by partners and scaled with respect to 10 combinations of body mass and height derived from representative anthropometric characteristics of European drivers that 90 percent of the driver population. Thus, a total of 50 FE-models resulted.

3.3.4 Results

The mean curves of the modulus determined by usual averaging show a clear dependence on the vibration magnitude for the single-axis vibration. The different amounts of shifts towards the lower frequencies with increasing vibration magnitudes are proportional to the differences in the levels of exposure intensities. The values of the coherency functions were in the range 0.6 to 0.99 with the lower values at the higher frequencies. The mean peak moduli tend to increase slightly across the intensities and directions. The main peak frequencies decreased with the increasing vibration magnitude. The results during the dual- and three-axis excitations showed that the apparent mass functions in the three measuring directions shifted to lower frequencies when the number of excitation axes increased from one to two or three (Hinz et. al, 2006). This phenomenon could have been caused by an increase of the vibration magnitude of the vector sum. The coherencies were in the same order as during the single axis excitation.

In order to compute the model outputs for the combined vibration excitations measured by partners at the contact points buttocks, back, hands and feet, the existing models and Matlab-files were extended. In the FE-model, additional calculation steps for the horizontal (X- and Y-axis) excitations with adapted boundaries for the four contact points were added. Due to the significant difference between experimental data and the simulation data for z-axis excitation, an adaptation of the model was necessary. The higher resonance values of the measurements indicated that the initial damping of the model was too high. For the

Figure 3.2 Photo of a driver of a forwarder and adapted FE-model.

modulus a very good correlation was achieved; the phase had a constant offset, but the characteristic matched very well. For the x-axis excitation, the simulation results corresponded very well to the measured data and therefore no model adaptation was performed. The existing model was adapted for five typical postures of drivers of different machines chosen by WP5 partners UMUH and University Trieste. Figure 3.2 shows an example. The 50 models were simulated by transfer functions with the results serving as basis for the software design. Thus, for each model a three-dimensional matrix exists with the transfer functions for the different percentiles, excitation points and excitation directions with 10x4x3 cells. The results of each model were stored in a separate binary Matlab file.

Software was programmed within Matlab by which - based on input accelerations at the four contact points of the model to the environment (buttock, back, hands, feet) - the resulting forces within the lumbar spine for arbitrary input accelerations can be determined. ASCII-files were used for the data input from field measurements and output of intra-spinal forces. For easy handling of the software, a graphical user interface was designed, by which the user can control all necessary inputs. The output of model calculations contains compressive and shear forces predicted for six lumbar levels (from T12/L1 to L5/S1) in the time and frequency

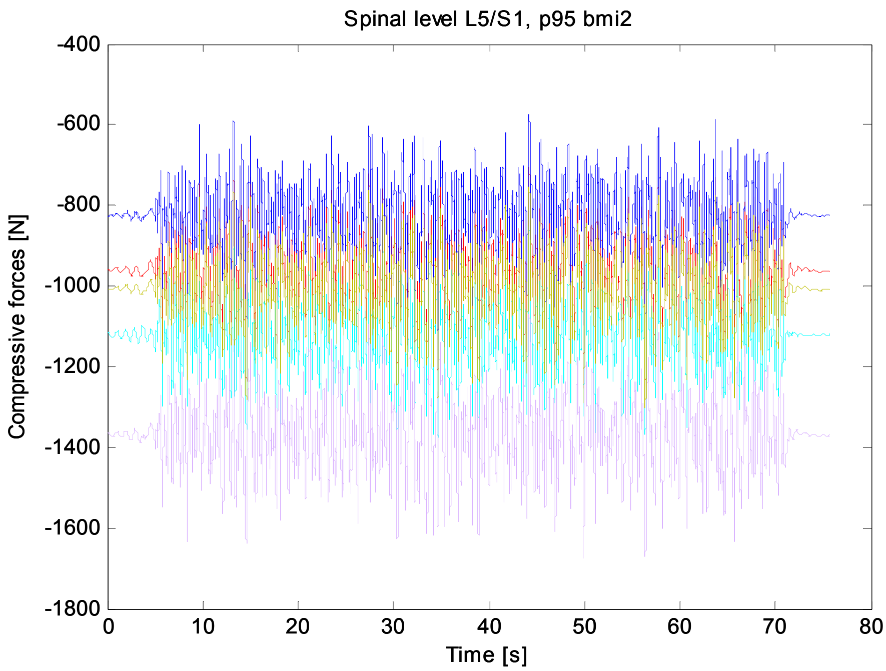

Figure 3.3 Compressive forces (exposure white noise) calculated for the spinal level L5/S1, the 95th percentile of body mass, body mass index >2.61 g/cm^2, with 5 different models/postures: Red – model group1, turquoise – model group 2, purple – model group 3, blue – model forwarder, curry – model harvester.

domain. Figure 3.3 shows time series of compressive forces as an example. The output of model calculations can be used for further data processing in order to assess a possible health risk for the lumbar spine.

3.3.5 Discussion

The results of the static and dynamic shares of the spinal forces at six spinal levels showed strong influences of the factors stature and posture. The consequences of the variability caused by posture and anatomy were illustrated by different static forces caused by five various postures and anthropometric characteristics. Considering all conditions, the maximum forces in all three conditions can reach the triple of minimal once. A more detailed analysis of the static compressive forces shows different influences of the factors. The ratio of the maximum to minimum forces caused by the spinal level within each posture is relatively small, around 1.16 and 1.21 for all percentiles and body mass indices. The stature was found to have the strongest influence: the ratios between the 5th percentile of body mass at body mass index (BMI) $\leq$2.61 g/cm^2 and the 95th percentile at BMI >2.61 g/cm^2 were in the range between 1.89 and 2.06 within each posture. Based on these differences between the static compressive forces it can be assumed that the consideration of variable static forces is an essential prerequisite for a successful prediction of spinal forces. Also the dynamic shares of the forces, characterized by the peak-to-peak values reflect the variability of statures and postures. The maximum differences calculated for white noise input accelerations expressed as ratios amounted to 2.68 for the compressive force, to 1.92 for the for-and-aft shear forces, and to 1.72 for the lateral forces. Consideration of the postures and anatomy by assignment to different classes improves the validity of stress predictions and risk assessments. The average high BMI of European drivers can be considered as an additional risk factor. The results clearly demonstrated significant effects of posture and anthropometric characteristics on the predicted intra-spinal forces, thus indicating the necessity to consider the posture and stature of drivers with any risk assessment. For the first time, the implementation of finite-element modelling permits the consideration of anthropometric characteristics and postures with the routine calculation of forces acting on lumbar discs and due to whole-body vibration, posture and individual stature.

3.3.6 Conclusions

The objective to develop a practical method for the prediction of spinal stress during selected exposures to whole-body vibration, based on a combination of postural forces and vibration exposures was successfully realized. The results of the laboratory experiments could be used to develop and verify a predictive model of spinal load. The modelling software can be regarded as a well-suited instrument for the future examination of exposure-effect relationships characterized by a new quality, i.e., the consideration of human factors, like stature and posture that can essentially modify this relation.

Further details of the study are provided in Annex 18.

3.4 Prediction of spinal stress in drivers

3.4.1 Introduction

The prediction of spinal stress is a prerequisite for a quantitative assessment of the health risk of the lumbar spine. Repetitive peak compressive forces are assumed to be responsible for fatigue failure of vertebral endplates. Up to now, the detrimental effect of shear forces cannot be quantified. The processing of predicted compressive forces in the time domain enables the calculation of a dose measure characterising the probability of fatigue failure. One procedure for the quantification of health risk described in ISO 2631-5 (2004) is based on the erroneous assumption that three compressive force components exist arising independently and separately from spinal accelerations in x-, y-, and z-axis, and that the peak values of these components can be used to calculate a dose that characterizes the compressive stress. This procedure ignores the fact that only one time series of compressive force exists as a result of the superposition of different components. Hence, any sufficient dose of peak values can be based on one time series only and not on peak values of several non-existing components. Variable postures, anthropometric characteristics, spinal geometry, and individual spinal tolerance were identified as important factors that co-determine the effects of occupational whole-body vibration (WBV) on health.

The European Directive 2002/44/EC (2002) gives an extremely high limit value for WBV in z-direction without any limitation of an energy-equivalent evaluation. The consequence is a very dubious assessment of health effects, especially for WBV containing high peak values and/or short daily exposure times.

Further details of the study are reported in Annex 19.

3.4.2 Objectives

The aims of this study were (1) to use dynamic FE-models for the prediction of intra-spinal forces caused by real exposure conditions measured in European countries, (2) to use these predictions for an evaluation procedure reflecting the risk of fatigue failure considering anthropometric characteristics of European drivers, and (3) to compare the results of this new evaluation procedure with assessments based on current standards and the Directive 2002/44/EC (2002).

3.4.3 Methods

The prediction of spinal stress in drivers was performed by simulated FE-modelling as described in Sections 3.3.3 and 3.3.4. Compressive and shear forces were calculated for the 5th percentile (body mass of European drivers) with a BMI $\leq$ 2.61 g/cm^2 and 95th percentile with a BMI > 2.61 g/cm^2 and for a total of 36 exposure conditions. A special program 'riscm3t.m' read the spinal stress values, i.e., the time series of the compressive force calculated for the exposure condition by one out of 50 models representing different statures and postures. The same program calculates a long-term dose expressed as risk factor R which is identical to the equivalent stress, i.e. the normalized static compressive stress with a value of $\geq$1 causing endplate failure. In order to specify the conditions for dose calculation, the user can select an exponent for the dose calculation, the disc level of interest (from T12/L1 to L5/S1), an equation for the calculation of the ultimate strength, and the size of the endplate area. A careful analysis of published data on the size of endplate areas was summarized in a table together with new representative unpublished data as assistance for the user. The user selects further the static compressive force for the corresponding model from a table provided by FIOSH, and specifies the number of exposure conditions, duration of each measurement, the daily exposure time, the number of days with exposure per year, the duration of the long-term exposure in years and the age at the end of exposure. The health-risk assessment, based on the spinal stress in drivers, includes the following steps: (a) Transformation of the dynamic and static compressive forces (in N) into dynamic and static compressive stresses (in MPa); (b) Determination of subsequent peak-to-peak values of internal cyclic stress. Subsequent peak-to-peak compressive forces acting on the lumbar discs, i.e. increasing (from plus to minus) and decreasing (from minus to plus) dynamic amplitudes are counted. Hence, peaks below the static stress are included, and the number of peak-to-peak values is twice as much compared with a counting method that would consider either upwards or downwards directed peaks only. In order to be comparable with results from laboratory tests on fatigue failure counting full sinusoidal cycles, and the usual lifetime prediction methodology in mechanics, each peak-to-peak amplitude and the number of peak-to-peak values calculated for one day of exposure or longer were divided by 2. The condition to count peak-to-peak amplitudes only between zero-crossings eliminates smaller peak-to-peak amplitudes that exist between two subsequent zero-crossings, i.e., either above or below the static internal load; (c) Calculation of the dynamic compressive stress dose for the specified exposure and disc level using an exponent of 6; (d) Calculation of the daily dynamic compression dose for the specified exposure and disc level. This daily compression dose does not consider the extent of the simultaneously acting static compressive stress that could be taken into account, e.g., by Goodman's law. The static compressive stress is considered in the calculation of the Risk factor R. A simple assessment of adverse health effect at lifetime exposure based on this dose is not recommended, since it will cause misjudgements due to the missing consideration of the individual age and individual compressive static stress; (e) Calculation of the Risk factor R (or 'equivalent stress') for the specified disc level.

The following parameters were chosen for the results section: Disc level L4/L5; ultimate strength [MPa] = -0.067184 (b) + 6.765024 with b = age in years for 50% of the general population, or reduced by 1.5 MPa for 95%; size of the endplate area 16 cm^2; duration of exposure measurement 140 s, daily exposure time 14400 s, 240 days of exposure per year, 45 years of exposure, end of exposure at age 65.

3.4.4 Results

The static compressive forces varied to a large extent between about 423 N (L5/S1, 5th percentile, BMI $\leq$2.61, model group 1 forklifts) and 1547 N (L3/L4, 95th percentile, BMI >2.61, model group 3 truck excavator), thus causing compressive stresses between 0.26 and

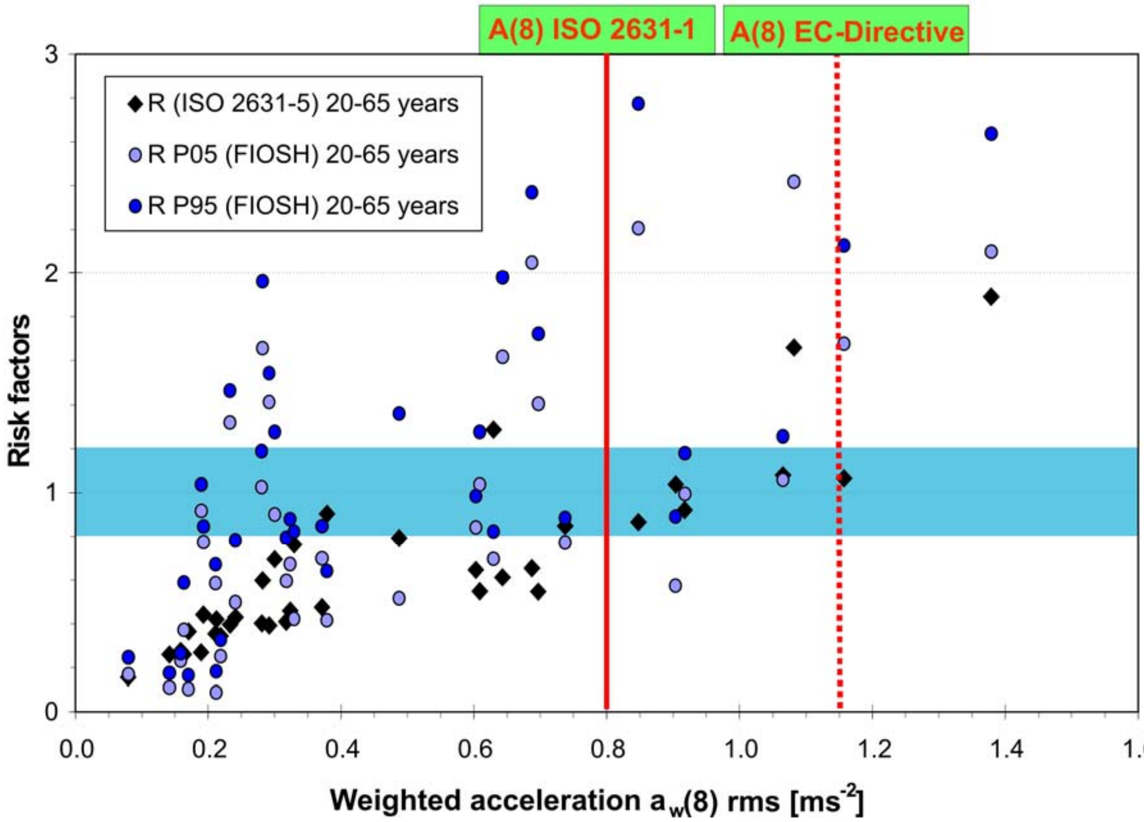

Figure 3.4 Comparison of risk assessments for 36 exposure conditions, R – factor defined in ISO 2631-5 without specification of posture, anthropometric characteristics and disc level. R P05 – risk factor for the lumbar level L4/L5 of drivers with a body mass of the 5th percentile and body mass index ≤ 2 .61 g/cm^2, R P95 – risk factor for the lumbar level L4/L5 of drivers with a body mass of the 95 percentile and body mass index > 2.61 g/cm^2. Abscissa – A(8) values of the dominant axis.

0.97 MPa, respectively, if a size of 16 cm^2 is assumed for the endplate area. The number and amplitude of peak-to-peak dynamic forces differed also considerably depending on the exposure conditions, anthropometric characteristics and posture (model group). The predicted dynamic compressive forces were predominantly larger for heavier persons with a higher BMI. Maximum dynamic positive peak shear forces in x-axis of 510 N (level L4/L5, 5^{th} percentile, BMI $\leq$ 2.61) and 741 N (level L5/S1, 95^{th} percentile, BMI > 2.61 g/cm^2) were predicted at exposures 'Forwarder2transportNoCargo'. Maximum peak-to-peak shear forces in y-axis of 478 N and 1211 N were calculated at the same exposure and for models of the 95^{th} percentile with BMI >2.61 g/cm^2.

Figure 3.4 shows the calculated risk factors for parameters listed in the last paragraph of Section 3.4.3 in dependence of the A(8) values given on the abscissa. There are four exposure conditions with risk factors (FIOSH-approach) above 1 for both percentiles, in spite of A(8)-values below the action value of the EC-directive. Another three conditions caused R-factors above 1 only for the 95^{th} percentile and BMI >2.61224 g/cm^2, whereas the R-factors for the 5^{th} percentile and BMI $\leq$2.61224 g/cm^2 were smaller than 1. These results illustrate the significance of a consideration of anthropometric characteristics. Obviously, the new risk assessment method leads to different results that often contradict the assumptions underlying the EC-directive and international standards.

3.4.5 Discussion

The combination of predicting spinal stress with a risk assessment referring to fatigue failure can be used to judge the combined effects of WBV, the biological variability, and/or posture. It offers the possibility to predict the health risk for different shares of the exposed population as a contribution to subsequent decisions on tolerated risks. Unlike ISO 2631-5 (2004), the FIOSH approach can consider additionally significant variables like posture, body mass, body height, BMI, size of the disc area, disc level, and variable ultimate strength covering either 50 or 95% of the general population. The consideration of different significant variables enables a more sophisticated assessment to identify health risks arising from exposure conditions and/or personal characteristics. Both, the variable static compressive force resulting from posture and anthropometric characteristics, and the variable ultimate strength can cause large differences between assessments for the same exposure condition. Up to now, no comparable evaluation procedure was known.

The results disagree with the predictions of spinal stress according to ISO 2631-5. Several reasons can explain the differences: (1) The spinal stress predicted by FE-models was different from that predicted by the simplistic and fundamentally wrong method of ISO 2631-5. The effects of the latter are non-predictable, because they vary with the phase relations between the spinal responses in different directions calculated according to ISO 2631-5; (2) A variable static stress was predicted instead of the "constant c representing the static stress due to gravitational force" in ISO 2631-5. The general assumption of only 0.25 MPa as static stress that 'can be normally used for driving posture' would lead to a significant underestimation of health risk in many cases.

The new procedures for an assessment of health risk do not intend to provide a quantitative risk assessment for internal stresses caused by shear forces, bending and torsion, because reliable strength data for such stresses, especially for dynamic repetitive loads are missing. One might consider peak-to-peak shear forces exceeding 30 percent of the provisionally estimated final strength limits of about 2000 N as potentially harmful. Since the maximum sum of predicted static and dynamic positive shear peak forces in x-direction could reach more than 50% of the ultimate shear strength, fore-and-aft shear forces should be considered in the future as an important possible damaging mechanism. A closer inspection of relationships between exposure data tested and predicted effects shows that often horizontal accelerations in the *y*-axis seem to be responsible for a tendency to underestimate the health risk by ISO 2631-1 (1997) as compared with model calculations. This is a surprising fact, because the multiplying factor k = 1.4 for this axis (ISO 2631-1, 1997) indicates already a stronger effect. Further research is urgently needed to clarify how WBV in this axis should be weighted in order to reflect the health risk adequately. There are further relevant factors that would increase the variability of health risk. The size of the vertebral endplate was kept constant, although the normal variation was estimated near ± 2cm^2. The ultimate strength for compressive stress was predicted without any variation, although a significant variability can be assumed. The postures reflected by the FE-models vary moderately and do not yet include exceptional conditions like a bent-forward posture.

The new risk assessments definitely contradict the limit value set by the Directive 2002/44/EC (2002). The high risk factors of several exposures with r.m.s.-values below the health guidance caution zone (ISO 2631-1) may help to explain results of epidemiological studies that described an increased health risk due to WBV with low magnitudes and could not verify a safe limit. The missing systematic consideration of anthropometric characteristics, posture and age during the exposure are further factors probably explaining the missing simple relationships between exposure and long-term effects in former epidemiological studies.

3.4.6 Conclusions

The consideration of the normal variability of all factors determining the exposure-effect relationships would lead to even larger ratios between risk factors for the same WBV-exposure than those based on the FE-model calculations and reported in the results section. Therefore, the assessment of single cases may require considerably larger latitude than that indicated by current standards. This conclusion is important for prevention and interpretation of results of epidemiological studies. The differences between the new and conventional methods of risk assessment illustrate the possible danger arising from the application of an average exposure-effect relationship to any individual case.

3.5 Modelling of risk of exposure to whole-body vibration

3.5.1 Introduction

The chronic effects of occupational exposures to whole-body vibration are believed to include increased risks of low back pain. However, unlike the chronic effects of hand-transmitted vibration there are no specific injuries known to be caused by whole-body vibration and dose-effect guidance is not yet available.

The chronic effects of whole-body vibration may be assumed to depend on the magnitude of vibration, the frequency of vibration, the duration of exposure to whole-body vibration during the day, and the number for years of exposure. Other factors, such as individual susceptibility and ergonomic factors are also suspected as being important.

Experimental studies of whole-body vibration have produced information on biodynamic responses to vibration, subjective responses, physiological responses, and performance effects. The manner in which some of these acute responses depend on the magnitude, frequency, and duration of exposure to whole-body vibration, and some personal characteristics, have been reported.

Although there are strong grounds for suspecting that whole-body vibration can be harmful, the evidence for specific exposures to vibration causing injury is not yet substantiated. Notwithstanding the lack of certainty, the EU Machinery Safety Directive places requirements for measuring vibration on machinery suppliers and the EU Physical Agents (Vibration) Directive (European Directive 2002/44/EC, 2002) places limitations on the exposure of workers to whole-body vibration at the workplace.

3.5.2 Objectives

One objective of the research within VIBRISKS was to obtain and interpret data from the epidemiological studies so as to advance understanding of the relationship between exposure to whole-body vibration and the probability of any injury, and to identify the effects of confounding variables.

The interpretation presented below is based on knowledge from previous epidemiological and experimental studies, the epidemiological studies conducted in WP5, and the modelling studies in WP6. The research makes it possible to identify whether there is a need for new ways to estimate risks from exposure to whole-body vibration.

3.5.3 Methods

The epidemiological studies conducted in Italy, The Netherlands, Sweden, and the UK, provided information on factors associated with low back pain in various environments (see Section 3.2).

The modelling studies (in Section 3.3) and the predictions of risk developed from the models (Section 3.4) provided an alternative procedure for estimating the strain arising from exposures to whole-body vibration and shock.

3.5.4 Results

Epidemiological studies

In Italy, UTRS commenced with a baseline cross-sectional survey of 598 professional drivers employed in various industries and public utilities. Over two subsequent follow-ups, some drivers entered and some left the cohort. In summary, 283 drivers participated in only a cross-sectional survey, 321 drivers had one follow-up survey, and 317 drivers had two follow-up investigations. In total, 921 drivers participated in the VIBRISKS study in Italy, with 638 drivers undergoing at least one follow-up investigation. The studies found evidence consistent with professional driving in industry and public utilities being associated with increased risk of work-related low-back pain. Occupational exposure to whole-body vibration and physical loading factors at work appeared to be important components of the multi-factorial origin of low-back pain in professional drivers. In multivariate data analysis, individual characteristics (e.g. age, body mass index) and back trauma were also significantly associated with low-back pain, while psychosocial work factors (e.g. job decision, job support) showed only a marginal relation to low-back pain.

The study undertaken by AMC in the Netherlands included at the start 574 male professional drivers employed in 13 different companies in agriculture, manufacturing industries, construction, public utility, and transport industry throughout the country. The follow-up study found that both the prevalence and the one year incidence of low-back pain were high compared to other occupational groups. A considerable number of drivers in the study exceeded the daily exposure action value $A(8)$ of 0.5 ms^{-2} r.m.s. of the EU Physical Agents (Vibration) Directive (European Directive 2002/44/EC, 2002), suggesting that a substantial proportion of the drivers were at risk. Several physical and postural load factors, as assessed by responses to the questionnaire, were significant predictors of low-back pain, although a comparison of the questionnaire responses with real time observations found that the time spent in some unfavourable postures or tasks were underestimated while other were overestimated. The multivariate data analysis showed that the currently recommended measures of daily vibration exposure, $A(8)$ or *VDV*, were poorly associated with most of the low-back pain outcomes, except for sick leave due to low-back pain. More significant relationships between the low-back pain outcomes and WBV exposure were seen when using the cumulative dose measures, in particular for the occurrence of acute low-back pain in the previous 12 months. So far, the exposure-response analysis has found no consistency over the whole range of low-back pain outcomes, but further analysis is in progress. Overall, the findings tend to confirm that professional driving of industrial vehicles is associated with an increased risk of work-related low-back pain, and that there is an association with both whole-body vibration and physical loading.

In Sweden, UMUH studied a baseline population of 530 male professional drivers of forestry vehicles who received the self-administered VIBRISKS whole-body vibration questionnaire. A total of 322 drivers replied and, of these, 311 were sent the follow-up questionnaire and 225 drivers replied. No significant relationships were found with vibration exposure at the cross-sectional survey for low-back pain, shoulder pain or neck pain but a risk of 1.2 to 1.7 was found for neck pain and 1.3 to 1.5 for shoulder pain for total exposure in hours (i.e. dose 1). Over the follow-up period, there was a consistent pattern for those with symptoms of low-back pain, neck pain and shoulder pain at the baseline to have increased risk of these symptoms at follow-up.

In the UK, UoS conducted a longitudinal study with two groups of drivers exposed to low levels of vibration and a group of non-drivers. The target populations were 861 taxi drivers located in the City of Southampton and 2105 persons employed by the Grampian Police (divided into groups of drivers and non-drivers). The 12-month prevalence, incidence, and persistence of low-back pain in the non-driving population was similar to the prevalence, incidence, and persistence of low-back pain reported by the driving populations, suggesting that the driving and non-driving populations were at a similar risk of developing low-back pain. Furthermore, the 12-month prevalence of low-back pain among taxi drivers and police drivers was similar to that previously reported in other driving populations (e.g., bus drivers, fork-lift operators, and truck drivers). In the taxi drivers, increased exposure to whole-body vibration was not an important risk factor for the persistence of low-back pain. In the police drivers, increased duration of total life-time driving (expressed in years) was a statistically significant risk factor for increased persistence of low-back pain, and increased daily vibration exposure (in hours) was a statistically significant risk factor for increased incidence of low-back pain. In taxi drivers, police drivers, and in the non-driving population, the presence of low-back pain experienced for at least one day during the past 12 months was significantly associated with individual risk factors (e.g. age, height), physical factors (e.g. bending) and, mainly, psychosocial risk factors (i.e. increased psychosomatic distress status). Although from this study it is not possible to exclude whole-body vibration as a risk factor for low back pain in taxi driving and police driving, vibration is clearly not the dominant cause of any low back pain in these drivers. A similar risk of low back pain was present in non-drivers. This suggests that whole-body vibration does not need to be identified as a risk for driving similar to that undertaken by taxi drivers and police drivers who participated in the UK study.

In the UK, the UoS also undertook a case-control study to investigate the risk factors for low-back pain among those presenting to diagnostic radiology services, and to compare them among subjects with and without MRI evidence of prolapsed inter-vertebral disc or related disc pathology. The study was designed to assess how strongly the occurrence of low-back pain severe enough to merit MRI investigation was associated with exposure to whole-body vibration, and to which metrics of vibration dose. Analysis was undertaken on 271 cases and 809 controls. The analysis revealed strong positive associations between severe low-back pain referred for imaging of the lumbar spine and somatising tendency, low mood, certain beliefs about low-back pain and consulting attitudes, as well as moderate positive associations with tall stature, smoking, and work involving: frequent or prolonged twisting, sitting while not driving, low decision latitude and poor support from colleagues or managers. There was little evidence of a risk from exposure to professional driving or whole-body vibration. The absence of evidence of clear relations between whole-body vibration and low-back pain may be a consequence of the few professional drivers in the population (18.5%) and relatively low vibration exposures. Alternatively, the findings allow the possibility that previously reported associations with whole-body vibration were confounded by the effects of constrained sitting, a characteristic of professional driving. Overall, however, the findings suggest that at the population level whole-body vibration is not an important cause of low-back pain severe enough to be referred for MRI imaging of the lumbar spine. Mental health and health beliefs (psychological factors) are more influential contributors in the general population referred for MRI imaging of the lumbar spine.

Modelling and predicting risk of low-back pain

Research undertaken by FIOSH in Germany extended an existing anatomically-based finite-element (FE) model of the human spine to different postures. Biodynamic experiments were conducted to measure the apparent mass and transmissibility of the body in specific postures and the results compared with those obtained by partners UMUH in Sweden and the UoS in the UK. An analysis of anthropometric characteristics of European drivers was used to scale the FE-model.

The FE model predicted that both static and dynamic forces at six spinal levels were strongly influenced by subject stature and subject posture, with the maximum static forces three times the minimum static forces. It was concluded that static forces must be considered when predicting dynamic spinal forces. The high average body mass index of European drivers increased the predicted forces and may be an additional risk factor. The predicted large effects of posture and anthropometric characteristics on the intra-spinal forces indicate that the posture and the stature of drivers must be considered in any procedure for predicting the risk low-back pain in vibration environments. The finite element modelling permitted for the first time the inclusion of anthropometric characteristics and postures when calculating forces acting on the lumbar discs from the combination of whole-body vibration, posture, and individual stature.

FIOSH used dynamic FE-models to predict the intra-spinal forces caused by example vibration exposures measured by the other partners (UTRS, AMC, UMUH and UoS). Taking into account the anthropometric characteristics of European drivers, they predicted the risk of fatigue failure and compared the results with assessments based on current standards and the EU Physical Agents (Vibration) Directive (European Directive 2002/44/EC). The static compressive forces varied greatly (between about 423 N and 1547 N, corresponding to compressive stresses between about 0.26 and 0.97 MPa) depending on the spinal location and the body posture. The peak-to-peak dynamic forces differed considerably according to the vibration exposure conditions, anthropometric characteristics, and postures. Overall, the results illustrated the importance of considering anthropometric characteristics and produced results that often contradict the assumptions underlying the EU Physical Agents (Vibration) Directive and International Standard 2631-5 (2004).

Unlike ISO 2631-5 (2004), the FIOSH approach includes posture, body mass, body height, BMI, size of the disc area, disc level, and variable ultimate strength covering either 50 or 95% of the general population. The variable static compressive force resulting from posture and anthropometric characteristics, and the variable ultimate strength can cause large differences between assessments for the same vibration exposure. The procedure for predicting spinal stress by the simplistic method in ISO 2631-5 appears to be incorrect in several ways. The model predictions also suggest that the risks form lateral vibration would be underestimated by ISO 2631-1 (1997), notwithstanding the multiplying factor of 1.4 for this axis. This highlights the need for further research related to the weighting of non-vertical vibration.

Risk assessments derived from the new model strongly contradict the EU exposure limit value and, when using r.m.s. values, predict a high risk below the health guidance caution zone in ISO 2631-1. Differences between the predictions of the new model and conventional methods of risk assessment arise partly from the inclusion of postural and individual factors and illustrate the danger of applying average exposure-effect relationships to individual cases.

3.5.5 Discussion

One output from the whole-body vibration research is the protocol developed for epidemiological research on whole-body vibration, as presented in Section 3.1, especially the newly improved questionnaires and definitions of alternative measures of vibration dose. Apart from advances arising from the individual epidemiological studies, the development of the protocols should benefit future studies conducted within and outside Europe.

The VIBRISKS epidemiological studies are unique in being undertaken simultaneously using the same questions in different countries. This allows the findings of the studies to be compared. The UTRS studies in Italy indicated that occupational exposure to whole-body vibration and physical loading contributed to low-back pain in professional drivers, with individual characteristics (age and body mass index) and back trauma also associated with low-back pain. The findings from the Italian epidemiological studies appear consistent with the prediction of spinal stress suggested by the predictive modelling of risk developed by FIOSH and reported in Sections 3.4 and 3.5. The AMC studies in the Netherlands produced a similar conclusion: professional driving of industrial vehicles was associated with increased risk of work-related low-back pain, and there was an association with both exposure to whole-body vibration and physical loading. With lower levels of vibration, the longitudinal study undertaken by the UoS in the UK suggested that car drivers are not at a high risk of developing low-back pain from driving. However, there was some evidence that the incidence of low-back pain was related to the hours of driving in the day and that the persistence of low back pain was related to years of driving. Although vibration was not shown to be a significant factor in the development of low-back pain, some other factors (especially psychosocial factors) were found to have highly significant associations with low-back pain in both drivers and non-drivers. The UoS case-control study in the UK produced similar findings, with low-back pain sufficient for referral for MRI investigations related to psychological factors but not to vibration exposure.

The results from the epidemiological studies have only recently been obtained and merit further analysis and consideration before firm statements are made on their final interpretation. However, the results suggest that improvements are needed to the r.m.s. method of predicting risk as employed in the EU Physical Agents (Vibration) Directive (European Directive 2002/44/EC). From all studies it is clear that the risks to the low-back are complex and multi-factorial and cannot be predicted solely from measurements of vibration exposure. Especially important are postural factors that have been shown to greatly influence the spinal forces and also influence the risks of low back pain.

The duration of the VIBRISKS project meant that the epidemiological research was restricted to one or two follow-up studies, limiting the power of the studies. It is hoped that it will be found possible to continue the monitoring of some of the groups beyond the end of VIBRISKS. Notwithstanding the short duration, the findings make some significant contributions to understanding of the exposure-response relationships between whole-body vibration and the occurrence of low back disorders. They also advance understanding of other physical and some psychosocial factors that combine to result in the development or progression of low back symptoms.

3.5.6 Conclusions

The results of the studies give a strong indication that improvements are needed to the method of predicting risks to the low-back from exposure to whole-body vibration. However, further research is required before specific changes can be recommended.

The results from the epidemiological and modelling studies should assist national and international bodies and institutions involved in guidelines, directives, and standards related to the safety and health of workers exposed to whole-body vibration from industrial vehicles and machines. The studies have advanced knowledge of the complex multi-factorial dose-effect relationships for low-back pain. Individual occupational health physicians, occupational safety and health organisations involved in monitoring the health effects of whole-body vibration, and academic researchers involved in epidemiological research should also find the research findings helpful.

In addition to the epidemiological, experimental, and modelling research, the diagnostic protocol developed during the studies is an important tool available for use world-wide to assist the design of epidemiological studies and workplace assessments in respect of hand-transmitted exposures to vibration.

Beyond the preliminary findings as summarised in this report, further analysis is being undertaken that will result in the publication of full findings in appropriate scientific journals.

Annex 20 reports on the pooling of longitudinal survey data on workers exposed to WBV in Italy, Sweden, the Netherlands, and the United Kingdom.

4 Occupational safety and health guidelines

4.1 Introduction

Mechanical vibration arises from a wide variety of processes and operations performed in industry, mining and construction, forestry and agriculture, and public utilities. Hand-transmitted vibration occurs when the vibration enters the body through the hands, e.g. in various work processes where rotating or percussive power tools or vibrating workpieces are held by the hands or fingers. Whole-body vibration occurs when the human body is supported on a surface which is vibrating, e.g. in all forms of transport and when working near some industrial machinery.

Article 2 of the Directive 2002/44/EC (2002) of the European Parliament and of the Council on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (vibration), defines "hand-arm vibration" as "*the mechanical vibration that, when transmitted to the human hand-arm system, entails risks to the health and safety of workers, in particular vascular, bone or joint, neurological or muscular disorders*", and "whole-body vibration" as "*the mechanical vibration that, when transmitted to the whole body, entails risks to the health and safety of workers, in particular lower-back morbidity and trauma of the spine*".

According to the 3rd European Survey on Working Conditions, about 23.6% of all workers interviewed during the survey reported being exposed to mechanical vibration in the workplaces of the European Union. Of those, 10.3% were exposed all or almost of the time, 6.5% around ¾ or ½ of the time, and 6.8% around ¼ of the time (Paoli and Merllié, 2001).

In Europe, craft workers, machine operators, agricultural workers, work force involved in elementary occupations, and armed forces are the occupations with the greatest exposure to vibration from hand tools, machinery, and vehicles.

Exposure to harmful vibration at the workplace can induce several complaints and health disorders, mainly in the upper limbs and the lower back.

4.2 Objectives

In the context of the implementation of the EU Directive on mechanical vibration, this report provides guidelines for the protection and health surveillance of vibration-exposed workers. A brief review on the long-term health effects caused by occupational exposure to hand-transmitted vibration is also presented.

4.3 Health effects of mechanical vibration

4.3.1 Hand-transmitted vibration

Prolonged exposure to hand-transmitted vibration (HTV) from powered processes or tools is associated with an increased occurrence of symptoms and signs of disorders in the vascular, neurological and osteoarticular systems of the upper limbs (Bernard (1997), Bovenzi (1997, 1998), CEN Tech. Report 12349 (1996), Griffin (1990)). The complex of these disorders is called *hand-arm vibration syndrome* (HAV). The *vascular component* of the HAV syndrome is represented by a secondary form of Raynaud's phenomenon known as vibration-induced white finger; the *neurological component* is characterised by a peripheral, diffusely distributed neuropathy with predominant sensory impairment; the *osteoarticular component* includes degenerative changes in the bones and joints of the upper extremities, mainly in the wrists and elbows. An increased risk for upper-limb muscle and tendon disorders, as well as for nerve trunk entrapment syndromes, has also been reported in workers who use hand-held vibrating tools. The vascular and osteoarticular disorders caused by HTV are included in a European Schedule of Recognised Occupational Diseases [2003/670/CE, Annex I, items

505.01 e 505.02] It is estimated that 1.7 to 5.8% of the workers in the European Countries, U.S. and Canada are exposed to potentially harmful HTV (Commission Recommendation 2003/670/EC, 2003).

4.3.2 Whole-body vibration

Long-term occupational exposure to intense whole-body vibration (WBV) is associated with an increased risk for disorders of the lumbar spine and the connected nervous system (Bernard (1997), Bovenzi and Hulshof (1999), CEN Technical Report 12349 (1996), Griffin (1990) and Seidel and Heide (1986). With a lower probability, the neck-shoulder, the gastrointestinal system, the female reproductive organs, the peripheral veins, and the cochleo-vestibular system are also assumed to be affected by whole-body vibration. However, there is a weak epidemiologic support for vibration-induced disorders of organ systems other than the lower back. It has been estimated that 4 to 7% of all employees in the U.S., Canada and some European Countries are exposed to potentially harmful WBV. In some Countries (e.g. Belgium, France, Germany, The Netherlands, Denmark), (low) back disorders occurring in workers exposed to WBV are, under certain conditions regarding intensity and duration of exposure, considered to be an occupational disease which can be compensated.

4.4 Protection and health surveillance of vibration-exposed workers

The prevention of injuries or disorders caused by mechanical vibration in the workplace requires the implementation of administrative, technical and medical procedures.

In most cases only a combination of administrative, technical and medical actions will lead to an effective prevention of vibration-induced disorders.

Health surveillance is mentioned as the cornerstone of occupational health services in many documents on occupational health services. The International Labour Office (1997) has defined occupational health surveillance as ‘the ongoing, systematic collection, analysis, interpretation and dissemination of data for the purpose of prevention’. Surveillance is seen as essential to the planning, implementation and evaluation of occupational health programmes and control of work-related ill health and injuries and the protection and promotion of workers' health.

Individual health surveillance can be carried out as a health status assessment at different moments in a worker's career: pre-employment, periodical, at return to work after sick leave or at the termination of employment or retirement. In this report, health surveillance is restricted to pre-employment and periodical health examinations. Workers' health surveillance can be best defined as any medical examination that is carried out at otherwise healthy workers with the aim to maintain or improve the worker's health. The results of health surveillance should be used to protect and promote the health of the individual, collective health at the workplace, and the health of the exposed working population. Moreover, a worker’s health surveillance programme must ensure professional independence and impartiality of the health professionals, workers’ privacy and confidentiality of individual health information.

Health surveillance may consist of pre-employment medical screening and subsequent clinical examinations of vibration-exposed workers at regular intervals. Medical preventive programs should be managed by certified occupational health personnel.

The European Directive 89/391/EEC (article 14, paragraph 1) states that: "*to ensure that workers receive health surveillance appropriate to the health and safety risks they incur at work*, *measures shall be introduced in accordance with national law and/or practices*".

According to the European Directive 2002/44/EC on mechanical vibration (article 8, para. 1), “*health surveillance, the results of which are taken into account in the application of* *preventive measures at a specific workplace, shall be intended to prevent and diagnose rapidly any disorder linked with exposure to mechanical vibration. Such surveillance shall be appropriate where:*

(i) *the exposure of workers to vibration is such that a link can be established between that exposure and an identifiable illness or harmful effects on health;*

(ii) *it is probable that the illness or the effects occur in a worker's particular working conditions;*

(iii) *there are tested techniques for the detection of the illness or the harmful effects on health.*

In any event, workers exposed to mechanical vibration in excess of the values stated in Article 3(1)(b) and (2)(b) shall be entitled to appropriate health surveillance", (i.e. daily exposure action value $A(8)$ 2.5 ms^{-2} r.m.s. in case of exposure to hand-transmitted vibration, or $A(8)$ 0.5 ms^{-2} r.m.s. in case of exposure to whole-body vibration).

One of the objectives of VIBRISKS is the development of common procedures for HTV health surveillance, including the development of improved methods for the detection and diagnosis of disorders. In this context, protocols for the health surveillance of workers exposed to HTV have been developed. The protocols are to provide tools for assessing health effects in the upper limbs that can be used for health surveillance in the workplace, and in epidemiological research. The tools that have been developed include guidelines for health surveillance, questionnaires for initial assessment and periodic medical examinations at regular intervals, and the definition of a battery of objective tests for the assessment of vibration-induced disorders.

The protocols and diagnostic tools for health surveillance in workers exposed to hand-transmitted vibration are described in details in Annex 21 (Deliverable D21/22) of this report.

4.5 Aims of health surveillance in case of exposure to mechanical vibration

In the field of occupational exposure to mechanical vibration, the aims of health surveillance are:

(i) to inform the workers on the potential risk associated with vibration exposure;

(ii) to assess worker's health status and fitness for work;

(iii) to diagnose vibration-induced disorders at an early stage;

(iv) to give preventive advice to employers and employees;

(v) to control the long-term effectiveness of preventive measures.

The employers should provide a health monitoring program for all workers occupationally exposed to vibration according to the provisions of the EU Directive and in accordance with national laws and/or practice (Art. 8, para. 1). The EU Directive on mechanical vibration establishes that health surveillance is compulsory for workers exposed to vibration exceeding the daily exposure action values. Moreover, the Directive requires that the employer shall take immediate action to reduce exposure if the daily exposure limit values have been exceeded.

Appropriate facilities for the health surveillance of the vibration-exposed workers should also be provided by the employers. The management of a health surveillance program for workers exposed to vibration should be under the supervision of a physician with a speciality in occupational medicine or at least with a certified training in occupational health ("competent doctor"). Practical routine procedures for the application of the health surveillance program may be carried out by allied health professionals with experience in occupational health problems. The workers should be informed by the health care staff that their personal and health data will be confidentially treated and preserved.

Pre-placement medical assessment and periodic clinical examinations at regular intervals shall be conducted for each worker exposed to mechanical vibration in excess of the daily exposure action values established by the EU Directive. Moreover, health surveillance is appropriate when there is evidence for the conditions listed in article 8 (para. 1) of the Directive.

It should be noted that no one sign or symptom is specific of vibration-induced injuries and that the clinical features of the disorders may be found in several other diseases. As a result, the occupational health physician should consider various clinical and laboratory tests in order to perform a differential diagnosis when the case history and the physical examination suggest the presence of symptoms or signs possibly related to occupational exposure to vibration.

Health surveillance of vibration-exposed workers shall be conducted according to the principles and practice of occupational medicine and the ethical issues recommended by the International Commission on Occupational Health (ICOH, 1997) (see appendix after Section 4.9).

4.6 Health surveillance for workers exposed to mechanical vibration

4.6.1 Pre-placement medical examination

A pre-placement medical examination should be offered to each worker who will be exposed to mechanical vibration on the job. The main purposes of pre-placement health assessment are (i) to make the worker aware of the hazards connected with the exposure to vibration, (ii) to obtain baseline health data for comparison with the findings of subsequent periodical health examinations, and (iii) to verify the presence of pathological conditions which may increase the risk of adverse health effects due to exposure to mechanical vibration.

The pre-placement medical evaluation shall include the case history, a complete physical examination and, if necessary, screening tests and special diagnostic investigations according to the clinical judgement of the physician (further details are provided in Annex 21).

4.6.2 Periodic medical examination

The pre-placement examination should be followed by periodic health re-assessment with a regular interval according to the national legislations. Periodic medical examination shall be made available to all workers exposed to mechanical vibration in excess of the daily exposure action value indicated by the EU Directive 2002/44/EC (i.e. $A(8)$ 2.5 ms^{-2} r.m.s. for hand-transmitted vibration, $A(8)$ 0.5 ms^{-2} r.m.s. for whole-body vibration).

At the periodic medical examination, any change in work practices with exposure to vibration should be reported in follow-up questionnaires (see at http://www.humanvibration.com). Moreover, any illness or injury occurred since the last examination, any symptom possibly related to vibration exposure, as well as the findings of the physical examination should be also reported (further details are given in Annex 21).

The reported findings for the individual should be compared with previous examinations.

Grouped, anonymous, data should be compiled periodically and reported to management and representatives of employees.

4.7 Avoidance of vibration exposure

Avoidance or reduction of vibration exposure for workers affected with disorders possibly related to mechanical vibration should be decided after considering the severity of symptoms, the characteristics of the entire working process, and other aspects related to the company's medical policy and the legislation of the country (Faculty of Occupational Medicine, 2000).

Since symptoms and signs associated with vibration exposure may improve when vibration exposure is ceased, the occupational health physician may discuss with the employee and the employer the possibility of his/her re-placement in working practices without exposure to vibration.

It should be noted that the EU Directive on mechanical vibration (Directive 2002/44/EC, Art. 8, para. 3) establishes that "*where, as a result of health surveillance, a worker is found to have an identifiable disease or adverse health effect which is considered by a doctor or occupational health-care professional to be the result of exposure to mechanical vibration at work:*

(a) the worker shall be informed by the doctor or other suitably qualified person of the result which relates to him personally. He shall, in particular, receive information and advice regarding any health surveillance which he should undergo following the end of exposure;

(b) the employer shall be informed of any significant findings from the health surveillance, taking into account any medical confidentiality;

(c) the employer shall:

- *review the risk assessment carried out pursuant to Article 4,*
- *review the measures provided for to eliminate or reduce risks pursuant to Article 5,*
- *take into account the advice of the occupational health care professional or other suitably qualified person or the competent authority in implementing any measures required to eliminate or reduce risk in accordance with Article 5, including the possibility of assigning the worker to alternative work where there is no risk of further exposure, and*
- *arrange continued health surveillance and provide for a review of the health status of any other worker who has been similarly exposed. In such cases, the competent doctor or occupational health care professional or the competent authority may propose that exposed persons undergo a medical examination*".

4.8 Treatment

4.8.1 Hand-transmitted vibration

Medical treatment of the hand-arm vibration syndrome is usually of limited benefit.

No controlled clinical trial has been conducted in vibration-exposed patients to assess the effectiveness of pharmacological agents commonly used for the treatment of Raynaud's phenomenon, such as calcium channel antagonists, α_1-adrenoreceptor antagonists, antifibrinolytics, prostanoids or nitroglycerin paste applied to affected digits. In case series reports, the calcium channel blocker nifedipine was the most frequently used drug, but its long-term effectiveness on the relief of vibration-induced vasospastic symptoms is not known. Moreover, calcium channel antagonists may be associated with side effects such as hypotension, swelling, headache and blushing.

Digital sympathectomy or pharmacologically-induced regional nerve blockage are associated with temporary benefit even in patients with trophic cutaneous changes in severe Raynaud's phenomenon. These invasive practices are rarely justified in persons affected with VWF.

Workers suffering from white fingers should be instructed to wear adequate clothing and suitable gloves to keep their hands, feet and body dry and warm, mainly when travelling or working with vibrating tools. Anti-vibration gloves, as defined in ISO 10819 [1996], can be beneficial to reduce vibration exposure. Other measures (use of chemical heat packs, breaks in a warm environment, abstaining from smoking) may be also useful to reduce the frequency of finger blanching attacks.

At present, there is no specific treatment regimen for the neurological component of the hand-arm vibration syndrome.

Carpal tunnel-release surgery may be effective in vibration-exposed workers affected with CTS, even though it has been reported that the prognosis may be less favourable than in patients not exposed to HTV, mainly in those cases in which CTS symptoms coexist with other vibration-induced neurological disorders such as digital neuropathy. Conservative treatments for CTS (splinting, nonsteroidal anti-inflammatory medication, local corticosteroid injection) have been proven to be effective in mild form of nerve impairment when associated with reduction of activities at home and work which can exacerbate symptoms.

The medical management of musculoskeletal symptoms caused by working with vibrating tools is similar to that adopted for work-related neck and upper limb disorders associated with exposure to adverse ergonomic stressors at the workplace. A primary goal of treatment strategy is to avoid the development of a chronic pain syndrome which can make the worker unable or unwilling to return to work. In this context, the occupational health physician shall take into account the several individual, medical, physical, and psychosocial variables that may play a role in the etiopathogenesis of the musculoskeletal symptoms complained by the worker. Randomised trials have suggested that intensive muscular training, chiropractic treatments, learning and behavioural therapies, and/or biofeedback techniques can result in substantial improvement of pain and function in the upper limbs of workers with specific and non-specific musculoskeletal syndromes (Hagberg, 2002).

4.8.2 Whole-body vibration

The management of low back pain at workplace is one of the major challenges for the occupational health professional. Since work is only one of the component of the multifactorial origin of LBP disorders, the occupational physician should take into account the broad variety of individual, medical, physical, psychosocial and organisational risk factors which can concur to the onset and aggravation of LBP symptoms in the injured worker (Faculty of Occupational Medicine, RCP (2000) and Waddell and Burton (2000)).

Imaging studies have revealed non-specific findings in the great majority of persons affected with LBP and, conversely, degenerative changes in the lumbar vertebrae and disks have been found in asymptomatic subjects. Hence, the management of the worker with LBP should include educational interventions with the aims to provide information and advice to employees and employers, to reassure the patient about the benign prognosis of LBP, to overcome fear avoidance beliefs, and to promote self-care.

There is strong scientific evidence that “back or abdominal belts” or “back supports” do not reduce work-related low back injuries and sickness absence.

The primary goals of treatment are to relieve pain, to restore function, and to encourage patients to become active early and gradually in ordinary and work activities in order to prevent the risk of chronic pain and disability. There is strong evidence that the longer a worker is off work with LBP, the lower their chances of ever returning to work (Spitzer *et al*, 1987).

Guidelines for the occupational health management and treatment of LBP suggest a combination of pharmacological therapy, active and progressive exercise and physical fitness programme, multidisciplinary rehabilitation, and organisational interventions by the employers/supervisors to facilitate return to work. There is moderate evidence that a combination of measures is more effective than a single method of treatment alone (Faculty of Occupational Medicine, RCP (2000)).

There is general agreement that bed rest as a treatment for simple (low) back pain is not recommended. For acute or recurrent LBP with or without referred leg pain, bed rest for 2-7 days is worse than placebo or ordinary activity. Prolonged bed rest may lead to chronic disability and increasing difficulty in rehabilitation.

Pharmacological treatment of LBP includes analgesics, anti-inflammatory drugs, muscle relaxants, and antidepressant drugs. These pharmacological agents are effective for simple (low) back pain, while their benefits for nerve root pain are inconsistent. Adverse effects (e.g. gastrointestinal and neurological problems) should be also considered. Long-term treatment with narcotics or sedatives should be avoided because their significant adverse side effects.

Rehabilitation programmes include manipulation, some forms of "back school", and progressive active back exercises accompanied by cognitive behavioural therapy. Manipulative treatment within the first six weeks of onset of acute or recurrent low back pain seems effective in patients who need additional help with pain relief or who are failing to return to normal activities, but the evidence is inconclusive. A Cochrane review of randomised trials of various exercises for persistent LBP (strengthening, general stretching, McKenzie passive stretching exercises, conventional physical therapy) showed that exercise programmes have some positive effects on the recovery of pain and disability as compared with placebo or usual care, but no difference in the outcomes of the different exercise programmes was found (van Tulder *et al*, 2000).

Occupational health guidelines for the management of LBP recommend that workers having difficulty to return to work within 2 - 12 weeks, should refer to a gradually increasing exercise programme or a multicomponent rehabilitation programme, which should be implemented within an integrated occupational health and safety system.

In summary, available data suggest that intensive multidisciplinary programmes combining medical, behavioural and rehabilitative components are associated with improvement of (low) back pain, reduction of functional disability and decrease in sick leave, even though there is no clear evidence for their long-term effects. In addition to these strategies, the management of LBP in an occupational setting should require organisational interventions on several aspects of the work system (time schedules, tasks, technology, environment and industrial relations). As pointed out by a Working Group of the Faculty of Occupational Medicine (2000): "*A major feature of the occupational (as opposed to clinical) guidance is the concept that work organisation and communication between workers and supervisors/management are important elements of occupational health management; education of both workers and employers is seen as important*" (Waddell and Burton, 2000).

4.9 Conclusions

The VIBRISKS project has developed common procedures for health surveillance of workers to hand-transmitted vibration and whole-body vibration, including the development of improved methods for the detection and diagnosis of disorders. In this context, protocols for the health surveillance of workers exposed to either HTV or WBV have been developed. The protocols are to provide tools for assessing health effects in the upper limbs (HTV exposed workers) or in the lower back (WBV exposed workers) that can be used for health surveillance in the workplace, and in epidemiological research. The tools that have been developed include guidelines for health surveillance, questionnaires for initial assessment and periodic medical examinations at regular intervals, and the definition of a battery of objective tests for the assessment of vibration-induced disorders.

The full document on Occupational Safety and Health Guidelines is included in Annex 21.

Appendix

Ethical issues recommended by the International Commission on Occupational Health (ICOH):

- The objectives and the details of the health surveillance must be clearly defined and the workers must be informed about them. The validity of such surveillance must be assessed and it must be carried out with the informed consent of the workers by an occupational health professional approved by the competent authority. The potentially positive and negative consequences of participation in screening and health surveillance programmes should be discussed with the workers concerned.
- The results of examinations, carried out within the framework of health surveillance must be explained to the worker concerned. The determination of fitness for a given job should be based on the assessment of the health of the worker and on a good knowledge of the job demands and of the worksite. The workers must be informed of the opportunity to challenge the conclusions concerning their fitness for their work that they feel contrary to their interest. A procedure of appeal must be established in this respect.
- The results of the examinations prescribed by national laws or regulations must only be conveyed to management in terms of fitness for the envisaged work or of limitations necessary from a medical point of view in the assignment of tasks or in the exposure to occupational hazards. General information on work fitness or in relation to health or the potential or probable health effects of work hazards, may be provided with the informed consent of the worker concerned.

Conditions of execution of the functions of occupational health professionals

- Occupational health professionals must keep good records with the appropriate degree of confidentiality for the purpose of identifying occupational health problems in the enterprise. Such records include data relating to the surveillance of the working environment, personal data such as the employment history and health-related data such as the history of occupational exposure, results of personal monitoring of exposure to occupational hazards and fitness certificates. Workers must be given access to their own records.

5 General Conclusions

5.1 Work Package 1

The first activity of Work Package 1 was the development of a draft diagnostic protocol. This was further developed throughout the research project and now provides an important tool available world-wide to assist the design and conduct of epidemiological studies and workplace assessments of exposures to hand-transmitted vibration. The diagnostic protocol provides not only the definition of tests for diagnosing the hand-arm vibration syndrome, it also provides colour charts to improve patient reports of finger blanching, criteria for the diagnosis of carpal tunnel syndrome in persons exposed to hand-transmitted vibration, clinical tests for the diagnosis of upper limb disorders, criteria for the clinical diagnosis of neck and upper limb musculoskeletal disorders, guidance on differences between reported and observed exposure durations, alternative measures of vibration dose, uniform means of summarising vibration exposures and their effects, and newly improved self-administered and clinically administered questionnaires for cross-sectional and follow-up studies. The document provides a unique combination of useful information for future research as well as a guide to the studies conducted within Work Package 2.

The final activity of Work Package 1 was the interpretation of results obtained from the epidemiological studies of the chronic effects of hand-transmitted vibration in Italy and Sweden in relation to the results of experimental studies of acute effects conducted in the UK and Sweden. The findings among vibration-exposed workers confirm that improvements are possible to both the frequency weighting and the time-dependency used in current standards to predict the development of vibration-induced disorders. However, further analysis and interpretation of results is required before the possible form of changes can be suggested. The findings confirm that the measurement of finger systolic blood pressure after cold provocation is related to vibration exposure, and that both thermal thresholds and vibrotactile thresholds are indicators of sensorineural damage caused by hand-transmitted vibration. The newly developed colour charts was shown to be a useful procedure for the diagnosis of vascular disorders caused by hand-transmitted vibration.

5.2 Work Package 2

In the prospective cohort study of vibration-exposed workers carried out in Italy (UTRS), the relationships between measures of daily and cumulative exposures to hand-transmitted vibration (taking account of vibration magnitude, exposure duration and frequency of vibration) and the development of neurological, vascular, and musculoskeletal disorders in the upper limbs have been investigated.

Over the study period 2003-2006, the point and period prevalence and the cumulative incidence of peripheral sensorineural and vascular symptoms were found to be significantly greater in the vibration-exposed groups than in control groups. An increased risk for musculoskeletal symptoms of the upper extremities was also observed in the HTV-exposed workers

Multivariate analysis of health and exposure data showed that after adjustment for potential confounders there was evidence for a dose-response relationship for sensorineural and vascular symptoms in the HTV-exposed worker groups. There was also evidence for a dose-effect relationship for cold-induced digital arterial hyperresponsiveness and for impairment to manual dexterity over time.

The cohort investigated in Sweden (UMUH) consisted of young males and females attending vocational high schools (construction, auto mechanics and restaurant workers). They had a fairly short vibration exposure, mostly a couple of years in duration. Even though vibration exposure was low, significant associations were found between indices of peripheral vascular and sensory dysfunction and some measures of daily and cumulative vibration dose. Moreover, vibration exposure and awkward neck postures were associated with neck pain among young male workers. An excess risk attributable to interaction between vibration exposure and awkward neck postures was also observed. This young cohort gives a unique opportunity for future studies aimed at investigating the natural history of vibration-induced disorders over time and at implementing administrative, technical and medical measures for prevention purposes.

The experimental studies of the effects of age and gender on vascular function (finger systolic blood pressure after local cooling) and sensory function (thermotactile and vibrotactile thresholds) carried out in UK (UoS) have provided valuable information about laboratory testing procedures and normative values that may assist clinicians and occupational health physicians in the interpretation of the findings of clinical and epidemiological studies of the hand-arm vibration syndrome.

The prospective cohort studies conducted within VIBRISKS Work Package 2 have provided advanced knowledge of the possible exposure-response and dose-effect relationships for vascular and sensorineural disorders induced by occupational exposure to hand-transmitted vibration. The findings of these studies of vibration-exposed workers have also suggested that improvements are possible to both the frequency weighting and the time-dependency used in current standards to predict the development of vibration-induced disorders.

5.3 Work Package 3

The aims of WP3 were to investigate the acute effects of hand-transmitted vibration on measures of vascular (finger blood flow, finger systolic blood pressure) and neurological functions (vibration perception thresholds and thermotactile thresholds) in order to better define the effects of vibration magnitude, frequency and duration.

It was shown that the “energy-equivalent” time-dependency failed to predict adverse vascular and sensorineural effects of vibration both during and following vibration exposure. Vascular experiments suggest that exposures to intermittent vibration might be less hazardous than exposure to the continuous vibration with the same energy but without breaks in exposure. The acute vascular effects of vibration cause reductions in finger blood flow that are additional to the reductions caused by force and are not limited to the finger experiencing force and vibration. The vibration magnitude and exposure time affect the cold and warmth thresholds, but the frequency of the vibration stimuli does not.

The results of an experimental study of the influence of prior vibration exposure on the cold test results suggest that in healthy men recent exposure to contact force and moderate levels of hand-transmitted vibration does not affect the response of finger circulation to cold provocation. On the other (hand), prior exposure to vibration on the day of a test is likely to influence the results obtained for determining the vibrotactile and thermotactile thresholds.

A 3D model of the biodynamic behaviour of a finger with the pulp in contact with a vibrating rigid plate was designed with the aim of developing a model for the prediction of vibration propagation through human tissues and for calculating internal mechanical properties. Such a model is expected to assist the understanding of the vascular and neurological effect of vibration. However, the modelling work met with many numerical problems and further work is required to obtain a simple but robust 3D model of the forefinger.

5.4 Work Package 4

The first activity of Work Package 4 was the development of a draft protocol for the conduct of whole-body vibration epidemiological studies. This protocol was further developed throughout the research project and now provides a useful tool available world-wide to assist the design and conduct of epidemiological studies and workplace assessments of exposures to whole-body vibration. The protocol define methods for the assessments of disorders caused by whole-body vibration, such as initial and follow-up self-administered questionnaires, and alternative exposure dose measures for quantifying the severity of exposure to whole-body vibration that have been used in the longitudinal and case-control epidemiological studies conducted in WP5. The protocol also defines methods for acquisition of whole-body vibration exposure data that have been used in the experimental studies in WP6 as input for FE-modelling of spinal stress.

Data from the longitudinal studies conducted in Italy, the Netherlands, Sweden and the UK within WP5 have been merged in to a common data base which is available for partners. FE-modelling has been conducted and predictive risk for spinal injury has been calculated at different exposure conditions to be compared the health outcomes in WP5.

Health surveillance guidelines for whole-body vibration have been developed which include common procedures that can be applied by occupational health workers across Europe for minimizing risk, screening exposed individuals and management of individuals with symptoms of mechanical vibration injuries.

5.5 Work Package 5

Task 5.1: Dose-response studies of WBV exposed workers

All the involved partners (UTRS, UoS, UMUH, and AMC) completed at least two surveys in the contract period. The data were analyzed by both univariate and multivariate analysis on baseline and follow-up data and by a longitudinal analysis with a logistic regression analysis technique according to a transition model. From the results it can be concluded that in general rather high prevalences and incidences of LBP were found within the involved professional driver groups. Physical load factors, and in some studies adverse psychosocial aspects, were associated with an increased risk of LBP. The results of the individual partners with respect to exposure to WBV show a less clear pattern. The Italian and the Dutch results more or less tend to confirm a trend of a higher risk of LBP with a higher cumulative WBV exposure dose. However, the currently recommended measures of daily vibration exposure, *A*(8) or *VDV*, were in general poorly associated with most of the LBP outcomes. In the studies performed in Sweden and in the UK, no relationship or an unclear relationship between exposure to WBV and LBP was found. All results have been presented in the Final Technical Report. The analysis of the pooled data from the partners is still in progress.

Tasks 5.2: Case control study of low back pain and intervertebral disc pathology in UK

The study comprised altogether 385 cases and 965 controls. No dose measure of WBV showed a significant univariate or multivariate association with intervertebral disc pathology and no evidence of an exposure-response relationship was found. However, there was a relatively low prevalence of professional driving in the study population (18.5% overall) and the drivers in this study - representing a population-based sample - were less heavily exposed to WBV than in the surveys of occupational cohorts. The findings suggest that at the population level, WBV is not an important cause of LBP severe enough to be referred for MRI imaging of the lumbar spine.

5.6 Work Package 6

The combination of experimental studies, acquisition of field data on posture and anthropometry of European drivers, and finite element modelling was a very successful approach and enabled the development of a new practical method for the prediction of spinal stress due to whole-body vibration. Posture and body stature are important factors that must not be neglected with the evaluation of the health risk associated with occupational vibration exposure. The normal variability of these factors requires an adequate variety of mathematical models in order to reflect sufficiently all exposure-effect relationships occurring in real life. The predictions of compressive stress can be used to quantify the health risk with consideration of the age during the exposure and individual geometry of the lumbar spine. A new method for the evaluation of whole-body vibration with respect to health was developed. The application of the results has shown that the limit value set by the Directive 2002/44/EC (2002*)* should be revised, because a high health risk was predicted for many exposure conditions below this limit. The high risk factors of several exposures with r.m.s. acceleration below the health guidance caution zone (ISO 2631-1) can help to explain findings of epidemiological studies. Future research is urgently needed in order to examine the health effects of shear forces arising from predominantly horizontal vibration. The application of the results will improve the prevention of injuries related to whole-body vibration in drivers.

6 Exploitation & Dissemination

6.1 Publications in peer-reviewed journals

The following papers describing work carried out by VIBRISKS participants as part of the project have been published in, or submitted to, peer-reviewed journals:

1. Ahlstrand C, Ekman A, Elam M, Hagberg M (2007) The influence of applied pressure on the thermal perception thresholds in index finger. Submitted to International Archives of Occupational and Environmental Health.

2. Angotzi G, Bramanti L, Tavarini D, Gragnani M, Cassiodoro L, Moriconi L, Saccardi P, Pinto I, Stacchini N, Bovenzi M (2005) World at work: Marble quarrying in Tuscany. Occup. Environ. Med., 62, 417-421

3. Bovenzi M, Welsh A J L, Griffin M J (2004) Acute effects of continuous and intermittent vibration on finger circulation. Int. Arch. Occup. Environ. Health, 77, 255-263

4. Bovenzi M, Della Vedova A, Negro C (2005) A follow up study of vibration induced white finger in compensation claimants. Occup. Environ. Med., 62, 237-242

5. Bovenzi M, Rui F, Negro C, D'agostin F, Angotzi G, Pinto I, Stacchini N, Gatti S, Rondina I, Bramanti L, Festa G, Montinaro I, Bianchi S (2006) An epidemiological study of low back pain in professional drivers. Journal of Sound and Vibration, 298, 514-539.

6. Bovenzi M, Welsh A J L, Della Vedova A, Griffin M J (2006) Acute effects of force and vibration on finger blood flow. Occup. Environ. Med., 63, 84-91.

7. Bovenzi M, Welsh A J L, Griffin M J (2006) Effect of prior exposure to hand-transmitted vibration on cold response of digital arteries. Int. Arch. Occup. Environ. Health. Published online.

8. Bovenzi M, D’Agostin F, Rui F, Negro C (2007) A longitudinal study of finger systolic blood pressureand exposure to hand-transmitted vibration. Submitted to International Archives of Occupational and Environmental Health.

9. Burdorf A, Hulshof C (2006) Effects of exposure to whole-body vibration on low back pain and its consequences for sickness absence and associated work disability. Journal of Sound and Vibration, 298, 480-491.

10. Burström L, Lundström R, Sjödin F, Lindmark A, Lindkvist M, Hagberg M, Nilsson T (2007) Acute effects of vibration on thermal perception threshold. Submitted to International Archives of Occupational and Environmental Health.

11. Gallais L, Griffin M J (2006) Low back problems among car drivers: a review of studies published 1975 to 2004. Journal of Sound and Vibration, 298, 499-513.

12. Gerhardsson L, Burström L, Hagberg M, Lundström R, Nilsson T (2007) Hand symptoms among young adults in relation to vibrotactile and monofilament tests. Submitted to International Archives of Occupational and Environmental Health.

13. Griffin M J (2007) Negligent exposures to hand-transmitted vibration. Submitted to International Archives of Occupational and Environmental Health.

14. Griffin M J (2007) Measurement, evaluation, and assessment of peripheral neurological disorders caused by hand-transmitted vibration. Submitted to International Archives of

Occupational and Environmental Health.

15. Hagberg M, Burström L, Ekman A, Vilhelmsson R (2006) The association between whole body vibration exposure and musculoskeletal disorders in the Swedish work force is confounded by lifting and posture. Journal of Sound and Vibration, 298, 492-498.

16. Hagberg M, Burström L, Lundström R, Nilsson T, Volkmann R (2007) Finger systolic blood pressure among young adults in relation to gender and hand-transmitted vibration. Submitted to International Archives of Occupational and Environmental Health.

17. Hinz B, Blüthner R, Mezel G, Rützel S, Seidel H, Wölfel P (2006) Apparent mass of seated men - Determination with single-axis and multi-axis excitations at different magnitudes. Journal of Sound and Vibration, 298, 704-724.

18. Lundström R, Nilsson T, Hagberg M, Burström L (2007) Grading of sensorineural disturbances according to the Stockholm workshop scale using self-reports - A proposal. Submitted to International Archives of Occupational and Environmental Health.

19. Negro C, Rui F, D'Agostin F, Bovenzi M (2007) Use of color charts for the diagnosis of finger whiteness. Submitted to International Archives of Occupational and Environmental Health.

20. Nilsson T, Burström L, Hagberg M, Lundström R (2007) Thermal perception thresholds among young adults exposed to hand-transmitted vibration. Submitted to International Archives of Occupational and Environmental Health.

21. Noorloos D, Tersteeg L, Tiemessen I J H, Hulshof C T J, Frings-Dresen M H W (2007) Does Body Mass Index Increase the Risk of Low Back Pain in a Population Exposed to Whole Body Vibration? Submitted to Applied Ergonomics.

22. Pinto I, Stacchini N (2006) Uncertainty in the evaluation of occupational exposure to whole-body vibration. Journal of Sound and Vibration, 298, 556-562.

23. Rui F, D'Agostin F, Negro C, Bovenzi M (2007) A longitudinal study of manipulative dexterity in vibration-exposed workers. Submitted to International Archives of Occupational and Environmental Health.

24. Seidel H, Pöpplau B M, Morlock M M, Püschel K, Huber G (2007) The size of lumbar vertebral endplate areas - prediction by anthropometric characteristics and significance for fatigue failure due to whole-body vibration. Submitted to International Journal of Industrial Ergonomics.

25. Seidel H, Hinz B, Hofmann J, Menzel G (2007) Intraspinal forces and health risk caused by whole-body vibration - predictions for European drivers and different field conditions. Submitted to International Journal of Industrial Ergonomics.

26. Seidel H, Hinz B, Hofmann J, Menzel G (2007) The significance of anthropometric parameters and postures of European drivers as data base for FE-models to calculate spinal forces during whole-body vibration. Submitted to International Journal of Industrial Ergonomics.

27. Seah S A and Griffin M J (2007) Normal values for thermotactile and vibrotactile thresholds in males and females. Submitted to International Archives of Occupational

and Environmental Health.

28. Tiemessen I J, Hulshof, C T J, Frings-Dresen, M H W (2007) An overview of strategies to reduce whole-body vibration exposure on drivers: A systematic review. International Journal of Industrial Ergonomics, 37, 245-256.

29. Tiemessen I J H, Hulshof C T J, Frings-Dresen M H W (2007) Direct observational assessment of physical work demands in whole-body vibration measurements yields important information for preventive activities. Submitted to Journal of Sound and Vibration.

30. Wahlström J, Burström L, Hagberg M, Lundström R, Nilsson T (2007) Musculoskeletal symptoms and associations with exposure to hand-arm vibration and ergonomic stressors among young men. Submitted to International Archives of Occupational and Environmental Health.

31. Welsh A J L and Griffin M J (2007) Normal values for finger systolic blood pressures in males and females. Submitted to International Archives of Occupational and Environmental Health.

6.2 3rd International Conference on Whole-body Vibration Injuries, Nancy, France: 7-9 June 2005

VIBRISKS partners INRS (France) in conjunction with UMUH (Sweden) organised the 3rd International conference on Whole Body Vibration Injuries in Nancy from 7 to 9 June. There were 57 papers presented to 150 participants from 14 different countries all around the world. A selection of 24 reviewed papers presented at the conference has been published in the Journal of Sound and Vibration, 298(3), 2006.

The following seven papers presented by VIBRISKS participants describe work carried out as part of the project. Abstracts of these papers can be viewed on the results page of the VIBRISKS web site (www.humanvibration.com/vibrisks):

1. Bovenzi M, Rui F, Negro C, D'agostin F, Angotzi G, Pinto I, Stacchini N, Gatti S, Rondina I, Bramanti L, Festa G, Montinaro I, Bianchi S. An epidemiological study of low back pain in professional drivers.

2. Hagberg M, Burström L, Ekman A, Vilhelmsson R. The association between whole body vibration exposure and musculoskeletal disorders in the Swedish work force is confounded by lifting and posture.

3. Hinz B, Blüthner R, Mezel G, Rützel S, Seidel H, Wölfel P Apparent mass of seated men - Determination with single-axis and multi-axis excitations at different magnitudes

4. Justinova L, Griffin M. Low back problems among car drivers: a review of studies published 1975 to 2004.

5. Pinto I, Stacchini N. Uncertainty in the evaluation of occupational exposure to whole-body vibration.

6. Burdorf A, Hulshof C. Effects of exposure to whole-body vibration on low back pain and its consequences for sickness absence and associated work disability.

7. Tiemesen I, Hulshof, C, Frings-Dresen M. Assessment of the physical work demands in a vibration exposed population by use of palmTRAC.

6.3 Diagnosis of Injuries Caused by Hand-transmitted Vibration - 2nd International Workshop, Göteborg, Sweden: 6-7 September 2006

The 2nd International Workshop on Diagnosis of Injuries Caused by Hand-transmitted Vibration was held in Göteborg on 6th and 7th September 2006. The workshop was sponsored by VIBRISKS and organised by partner UMUH in Göteborg, Sweden, with assistance from UoS and UTRS. There were 22 papers presented at the International Workshop, 15 of which were presented by VIBRISKS participants and described work carried out as part of the project.

There were 22 papers presented at the International Workshop, 15 of which were presented by VIBRISKS participants and describe work carried out as part of the project. Abstracts of these papers can be viewed on the results page of the VIBRISKS web site (www.humanvibration.com/vibrisks):

1. Bovenzi, M, Griffin, M, Hagberg, M (2006) Diagnosis of Injuries Caused by Hand-transmitted Vibration - 2nd International Workshop, Occupational and Environmental Medicine, 114.

2. Ahlstrand C, Ekman A, Elam M, Hagberg M. The influence of applied pressure on the thermal perception thresholds in index finger.

3. Bovenzi M, D'Agostin F, Rui F, Negro C. A longitudinal study of finger systolic blood pressure and exposure to hand-transmitted vibration.

4. Burström L, Lundström R, Sjödin F, Lindmark A, Lindkvist M, Hagberg M, Nilsson T. Acute effects of vibration on thermal perception threshold.

5. Gerhardsson L, Burström L, Hagberg M, Lundström R, Nilsson T. Hand symptoms among young adults in relation to vibrotactile and monofilament tests.

6. Griffin M J. Negligent exposures to hand-transmitted vibration.

7. Griffin M J. Measurement, evaluation, and assessment of peripheral neurological disorders caused by hand-transmitted vibration.

8. Hagberg M, Burström L, Lundström R, Nilsson T, Volkmann R. Finger systolic blood pressure among young adults in relation to gender and hand-transmitted vibration.

9. Lundström R, Nilsson T, Hagberg M, Burström L. Grading of sensorineural disturbances according to the Stockholm workshop scale using self-reports - A proposal.

10. Negro C, Rui F, D'Agostin F, Bovenzi M. Use of color charts for the diagnosis of finger whiteness.

11. Nilsson T, Burström L, Hagberg M, Lundström R. Thermal perception thresholds among young adults exposed to hand-transmitted vibration.

12. Rui F, D'Agostin F, Negro C, Bovenzi M. A longitudinal study of manipulative dexterity in vibration-exposed workers.

13. Seah S A and Griffin M J. Normal values for thermotactile and vibrotactile thresholds in males and females.

14. Wahlström J, Burström L, Hagberg M, Lundström R, Nilsson T. Musculoskeletal symptoms and associations with exposure to hand-arm vibration and ergonomic

stressors among young men.

15. Welsh A J L and Griffin M J. Normal values for finger systolic blood pressures in males and females.

6.4 Other conference presentations

Presentations describing work carried out as part of the VIBRISKS project have also been made by partners at other international conferences:

1. Bovenzi M, Vedova A D, Negro C (2004) A Follow Up Study of Vibration-Induced White Finger in Compensation Claimants. 10th International Conference on Hand-arm Vibration, Las Vegas, USA.

2. Bovenzi M, Rui F, D'Agostin F, Negro C (2006) I compiti del Medico Competente alla luce della Direttiva Europea 2002/44/CE sulle vibrazioni meccaniche e del Decreto applicativo 187/2005 [The role of occupational health physician in the implementation of the European and Italian regulations on mechanical vibration at work]. In proceedings of the 69th National Congress of the Italian Society of Occupational Medicine, Montesilvano (PE) 23-25 October 2006, Italy, pp 241-244.

3. Bovenzi M (2006) Esposizione a vibrazioni trasmesse al corpo intero: il progetto europeo VIBRISKS [Occupational exposure to whole-body vibration: the European VIBRISKS project] In proceedings of the national Conference dBA 2006, Modena 12-13 October 2006, Italy, vol. 1, pp 149-180.

4. Gallais L, (2006) Exposure of taxi drivers to whole-body vibration. 41st UK Conference on Human Response to Vibration, Qinetic, Farnborough.

5. Griffin M J, Lewis C H, Bovenzi M, Lemerle P, Lundström R (2004) Risks of Occupational Exposures to Hand-transmitted Vibration: VIBRISKS. 10th International Conference on Hand-arm Vibration, Las Vegas, USA.

6. Justinova L (2004) Back problems among car drivers: a summary of studies during the last 30 years. 39th UK Conference on Human Response to Vibration, Ludlow.

7. Justinova L (2005) Risk factors associated with low back pain among taxi drivers. 40th UK Conference on Human Response to Vibration, Health and Safety Executive, Liverpool.

8. Tiemessen I, Hulshof C, Frings-Dresen M. (2006) Low back pain due to whole-body vibration in professional drivers. Paper presented at the 28th ICOH International Congress on Occupational Health, Milan June 11-16.

9. Tiemessen I J H, Hulshof C T J, Frings-Dresen M H W (2006) Assessment of vibration and other physical work demands at the work site: A longitudinal study. Paper presented at the IEA 2006 16th World Congress on Ergonomics, Maastricht July 10-14.

6.5 Provision of information to the occupational health community

Partner UTRS (Italy) provides training to the technicians and the occupational health physicians of the Occupational Health Units of the National Health Service. In Italy the operators of these Units must control the application of EU legislation for health and safety at the workplace and must advise manufactures, employers and employees how to implement preventative measures. The information is being disseminated during regular, annual, meetings or seminars which take place in the most important Units in the country. For example, the Laboratory of Physical Agents, AUSL 7, Siena (subcontractor to UTRS) organised a Workshop on 10 – 11 November 2004, which was attended by about 80 occupational health physicians, technicians and nurses coming from the Italian Regions involved in the VIBRISKS project. The objectives of the workshop were:

- To summarize the current state of knowledge regarding risks of vibration exposures at work.
- To update labour inspectors and occupational physicians on the European vibration directive, which should be promulgated in Italy in June 2005.
- To identify practical tools for risk assessment and prevention, including the VIBRISKS questionnaires for health surveillance.
- Training of NHS personnel for the administration of the VIBRISKS HTV and WBV questionnaire and to perform objective tests (cold test with FSBP measurement, muscle strength, manipulative dexterity).
- To update participants on the preliminary results of the VIBRISKS surveys in Tuscany, and future work plans.

Guidelines developed by UTRS for the assessment of vibration exposure and for medical surveillance of HTV and WBV workers have been adopted officially by the Italian Society of Occupational Medicine and Industrial Hygiene, and a manual has been published (*Bovenzi M, Angotzi G, Apostoli P, Negro C, Versini W. Linee Guida per la prevenzione dei disturbi e delle patologie da esposizione a vibrazioni meccaniche negli ambienti di lavoro. Linee Guida per la formazione continua e l'accreditamento del medico del lavoro. Maugeri Foundation books, Volume 5. PI-ME Editrice, Pavia 2003. ISBN 88-7963-158-6*).

AMC (Dr Hulshof) is responsible for the teaching programme on vibration and health for occupational health physicians in training at the Netherlands School of Public and Occupational Health (NSPOH) in Amsterdam. The preliminary results and experiences within the VIBRISKS project have already been used in the courses of last two years. Besides this, Dr Hulshof and Mr Tiemessen have given lectures on the VIBRISKS project at a regional CME-meeting of the Netherlands Society of Occupational Medicine (NVAB) and at two annual scientific meetings of the Association of Occupational Hygienists.

AMC (Mr Tiemessen) has given presentations about findings of the VIBRISKS project at the 28th ICOH Congress in Milan in June 2006 and at the International Ergonomics Association (IEA) Triennial Conference in Maastricht in July 2006. The results will also be forwarded to the ICOH Scientific Committee on Noise and Vibration. Dr Hulshof is a member of this committee and he also chairs the ICOH Scientific Committee on Health services *Research and Evaluation in Occcupational Health*. The guidelines on health surveillance, developed within the VIBRISKS project, will also be published on the website of this last committee.

The Swedish partners (UMUH) organised a course for senior occupational medicine specialists from university hospitals in Sweden, with 40 participants, at the National Board of Occupational Safety and Health Sweden in Stockholm (March 9, 2005). The course was arranged to disseminate information from VIBRISKS, especially the use of the protocols and questionnaires developed by the project.

A one-day course on 'Surveillance and Diagnosis of Hand-arm Vibration Syndrome' (5 September 2006) was run by the Sahlgrenska Academy at Göteborg University, with assistance from VIBRISKS partners UoS and UTRS, on the day before the 2nd International Workshop on HTV injuries (see Section 6.3). The course covered pathophysiology, health surveillance, risk assessment, clinical assessment, quantitative testing, case management, cost-benefits for the occupational health care business, and examples of checklists and protocols from EU countries.

6.6 Development of national and European guidance

Most of the VIBRISKS partners are members of relevant committees of their national standardisation bodies, the European Committee for Standardization (CEN), or the International Organisation for Standardization (ISO). Their participation in the work of these standardisation committees has allowed quick communication of the results and resources arising from the VIBRISKS project.

UoS and INRS participated in an EC-funded project to develop '*Guides for good practice with a view to implementation of Directive 2002/44/EC on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (vibrations)*'. This project, co-ordinated by the UoS, references procedures developed within VIBRISKS.

AMC has developed a national information guide on hand-transmitted and whole-body vibration to accompany the implementation of the EU Directive 2002/44/EC in the Netherlands, under the auspices of the Ministry of Social Affairs and Employment (*Van Drimmelen D E, Hulshof C T J (2005) Arbo-Informatieblad Trillingen. AI-36. Ministerie van Sociale Zaken en Werkgelegenheid. Den Haag, Sdu Uitgevers bv. ISBN: 90 12 10853 5*). Dr Hulshof is the chair of the Dutch National Standard Committee (NEN) on the effects of vibrations and shock on humans. At the last meetings he has already reported and discussed the progress of the VIBRISKS project. The results will also made available for the members of the committee.

FIOSH have used the results of VIBRISKS for the support of the German Ministry of Work and Social affairs during the process of the implementation of the EU-directive in national regulations. FIOSH is also promoting the methods to estimate the spinal stress and to predict the health risks developed within the VIBRISKS project to national experts in Standardisation (NALS C7) and in ISO TC108 SC4 (effects of whole-body vibration).

UoS have used procedures developed within VIBRISKS to assist the Department of Work and Pensions establish a procedure for compensating workers suffering from the neurological aspects of the hand-arm vibration syndrome.

6.7 Dissemination to industry

For the purpose of their intervention study, AMC has developed and tested in the project an informative leaflet for employees and a brochure for employers. Preliminary versions of these information guides were presented and discussed with Arbouw, the national occupational health branch organisation in construction industry. After the finishing of the intervention study this material will be made available also for occupational health professionals and other branch organisations.

Members of UMUH (Sweden) have links with manufacturers of tools and off-road vehicles, and have disseminated information from VIBRISKS during a course for purchasers and production engineers arranged by a major manufacturer of vibratory tools (Atlas Copco) at three different locations in Sweden during April 2005 (Sundsvall, Stockholm and Göteborg).

7 Policy Related Benefits

7.1 Community added value and contribution to EU policies

Methods of measuring, evaluating, and assessing the severity of exposures to hand-transmitted vibration and whole-body vibration in current standards are not primarily based on epidemiological evidence or understanding of the mechanisms of vibration-induced injury. Notwithstanding these limitations, the EU Machinery Safety Directive and the EU Physical Agents (Vibration) Directive use the standards to quantify the vibration of tools and machines, limit exposures to vibration at work, and identify when health surveillance is required.

The VIBRISKS project sought to improve the understanding needed to minimise risks from vibration-induced injuries. The findings from the experimental and epidemiological studies show that improvements are possible to both the frequency weightings and the time-dependency currently used to predict the development of vibration-induced disorders from hand-transmitted vibration and whole-body vibration. Further analysis and interpretation, which are currently underway, are needed before new recommendations can be made. The VIBRISKS project also developed protocols, including questionnaires, for the future epidemiological studies needed for a further advance in understanding in the area.

7.2 Contribution to Community social objectives

The VIBRISKS project has contributed to the prevention and control of vibration-induced disorders by disseminating new methods, results and experience from the project to: (i) occupational health professionals (see Section 6.5), (iii) national, European, and International standards committees (see Section 6.6), and (iii) employers and their workers (see Section 6.7).

The VIBRISKS protocols for diagnosing vibration-induced injuries and the VIBRISKS guidelines for the health surveillance of persons exposed to hand-transmitted vibration or whole-body vibration can be applied by occupational health workers across Europe to minimise risk and manage those exposed.

In the long term, improved prevention will reduce disability, the cost of welfare payments, and the costs of medical care, as well as increase the quality of life for vibration-exposed individuals.

7.3 Economic development, scientific and technological prospects

Results from the project have been published in peer-reviewed international journals (see Section 6.1) and presented at international conferences (see Sections 6.2 to 6.4). More publications will follow in the near future. Some of the longitudinal epidemiological studies are expected to continue for years to come and will lead to publications in the distant future.

Two international meetings, the 3rd International Conference on Whole-body Vibration Injuries (held in Nancy in 2005) and the 2nd International Workshop on the Diagnosis of Injuries Caused by Hand-transmitted Vibration (held in Göteborg in 2006) were sponsored by the project and featured presentations describing research carried out as part of VIBRISKS (see Sections 6.2 and 6.3).

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9 List of annexes

Annex No.	Related Final Technical report section	Title	Partner Responsible
1	2.1	Protocol for epidemiological studies of hand-transmitted vibration	UoS (ISVR)
2	2.2.1	Longitudinal epidemiological surveys in Italy of workers exposed to hand-transmitted vibration	UTRS
3	2.2.2	Longitudinal epidemiological surveys in Sweden of workers exposed to hand-transmitted vibration	UMUH
4	2.3	Normal values for finger systolic blood pressure in males and females	UoS (ISVR)
5	2.3	Normal values for thermotactile and vibrotactile thresholds in males and females	UoS (ISVR)
6	2.4.1	Experimental studies of acute effects of hand-transmitted vibration on vascular function	UTRS
7	2.4.2	Experimental studies of acute effects of hand-transmitted vibration on neurosensory function	UMUH
8	2.4.3	Effects of prior exposure to hand-transmitted vibration on vascular function	UTRS
9	2.4.4	Effects of prior exposure to hand-transmitted vibration on neurosensory function	UMUH
10	2.5	Biodynamic modelling of the finger	INRS
11	2.1	Measurement, evaluation and assessment of peripheral neurological disorders caused by hand-transmitted vibration	UoS (ISVR)
12	3.1	Protocol for epidemiological studies of whole-body vibration	UMUH
13	3.2.1	Longitudinal epidemiological surveys in Italy of drivers exposed to whole-body vibration	UTRS
14	3.2.2	Longitudinal epidemiological surveys in Sweden of drivers exposed to whole-body vibration	UMUH
15	3.2.3	Longitudinal epidemiological surveys in the Netherlands of drivers exposed to whole-body vibration	AMC
16	3.2.4	Longitudinal epidemiological surveys in the United Kingdom of drivers exposed to whole-body vibration	UoS (ISVR)
17	3.2.5	Whole-body vibration case-control study of low back pain and intervertebral disc pathology	UoS (MRC)
18	3.3	Whole-body vibration experimental work and biodynamic modelling	FIOSH
19	3.4	Prediction of spinal stress in drivers from field measurements	FIOSH
20	3.5	Pooling of longitudinal epidemiological surveys of drivers exposed to whole-body vibration in Italy, Sweden, the Netherlands and the United Kingdom	UMUH
21	4	Common procedures that can be applied by occupational health workers across Europe for minimizing risk, screening exposed individuals and management of individuals with symptoms of mechanical vibration injuries	UTRS/AMC