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Special Issue: Whole-Body Vibration Injuries

Michael J. Griffin. *Predicting and controlling risks from human exposures to vibration and mechanical shock : flag waving and flag weaving*. Pages 1063-1070.

At work or in leisure activities, many people are exposed to vibration or mechanical shocks associated with risks of injury or disease. This paper identifies information that can be used to decide whether there may be a risk from exposure to hand-transmitted vibration or whole-body vibration and shock, and suggests actions that can control the risks. The complex and time-varying nature of human exposures to vibration and shock, the complexity of the different disorders and uncertainty as to the mechanisms of injury and the factors influencing injury have prevented the definition of dose–response relationships well proven by scientific study. It is necessary to wave a flag indicating when there is a need to control risks from exposure to vibration and shock while scientific enquiry provides understanding needed to weave a better flag. It is concluded that quantifying exposure severity is often neither necessary nor sufficient to either identify risks or implement measures that control the risks.**Practitioner Summary:** The identification of risks associated with exposure to vibration and mechanical shock cannot, and need not, rely solely on the quantification of exposure severity. Qualitative methods can provide a sufficient indication of the need for control measures, which should not be restricted to reducing standardised measures of exposure severity.

- **Keywords:** whole-body vibration, hand-transmitted vibration, mechanical shocks, health and safety, risks, control measures

Taneli Rantaharju, Neil J. Mansfield, Jussi M. Ala-Hiiro & Thomas P. Gunston. *Predicting the health risks related to whole-body vibration and shock: a comparison of alternative assessment methods for high-acceleration events in vehicles*. Pages 1071-1087.

In this paper, alternative assessment methods for whole-body vibration and shocks are compared by means of 70 vibration samples measured from 13 work vehicles,

deliberately selected to represent periods containing shocks. Five methodologies (ISO 2631-1:1997, BS 6841:1987, ISO 2631-5:2004, DIN SPEC 45697:2012 and one specified by Gunston [2011], 'G-method') were applied to the vibration samples. In order to compare different evaluation metrics, limiting exposures were determined by calculating times to reach the upper limit thresholds given in the methods. Over 10-fold shorter times to exposure thresholds were obtained for the tri-axial VDV (BS 6841) than for the dominant r.m.s. (ISO 2631-1) when exposures were of high magnitude or contained substantial shocks. Under these exposure conditions, the sixth power approaches (ISO 2631-5, DIN SPEC, G-method) are more stringent than a fourth power VDV method. The r.m.s. method may lead to misleading outcomes especially if a lengthy measurement includes a small number of severe impacts. In conclusion, methodologies produce different evaluations of the vibration severity depending on the exposure characteristics, and the correct method must be selected. **Practitioner Summary:** Health risks related to whole-body vibration and high acceleration events may be predicted by means of several different methods. This study compares five such methods giving emphasis on their applicability in the presence of shocks. The results showed significant discrepancies between the risk assessments, especially for the most extreme exposures.

- **Keywords:** impulse assessment, ISO 2631-1, ISO 2631-5, BS 6841, DIN SPEC 45697

Massimo Bovenzi, Marianne Schust, Gerhard Menzel, Jörg Hofmann & Barbara Hinz. *A cohort study of sciatic pain and measures of internal spinal load in professional drivers*. Pages 1088-1102.

In a prospective cohort study of 537 male professional drivers, the occurrence of sciatic pain showed stronger associations with measures of internal lumbar load expressed in terms of daily compressive dose, S_{ed} (MPa), and risk factor, R (non-dimensional), according to ISO/WD 2631-5 (2013), than with measures of daily vibration exposure calculated as either 8-h energy-equivalent frequency-weighted acceleration (ms^{-2} r.m.s.) or vibration dose value ($ms^{-1.75}$) according to the EU Directive on mechanical vibration (2002). Herniated lumbar disc, previous lumbar trauma and physical work load were also powerful predictors of the occurrence of sciatic pain over time. Psychosocial work environment was poorly associated with sciatic pain. The boundary values of risk factor (R) for low and high probabilities of adverse health effects on the lumbar spine, as proposed by international standard ISO/WD 2631-5 (2013), tend to underestimate the health risk in professional drivers. **Practitioner Summary:** In a prospective cohort study of professional drivers, measures of internal spinal load were better predictors of the occurrence of sciatic pain than the measures of daily vibration exposure established by the EU Directive (2002). Herniated lumbar disc, lumbar trauma and physical work load were also associated with sciatic pain.

- **Keywords:** back pain, biomechanics, driving, health risks, whole-body vibration

Massimo Bovenzi. *A prospective cohort study of neck and shoulder pain in professional drivers*. Pages 1103-1116.

In a three-year follow-up study, the occurrence of neck and shoulder pain (NSP) in terms of frequency, duration and intensity was investigated in a population of 537 male professional drivers. Over the follow-up period, the cumulative incidences for neck and shoulder pain were 31.9% and 21.4%, respectively. After adjustment for potential confounders, a measure of cumulative whole-body vibration exposure was significantly associated with all NSP outcomes. Lifting loads and work with hands above shoulder level were significantly related to shoulder outcomes, while driving with trunk bent or twisted was associated with neck pain. Limited job decision, low social support and job dissatisfaction were significant predictors of neck outcomes. Psychological distress was

associated with all NSP outcomes. The findings of this cohort study suggest that NSP outcomes are of multifactorial origin in driving occupations. **Practitioner Summary:** This prospective cohort study highlighted the multifactorial nature of neck and shoulder pain (NSP) outcomes in a population of professional drivers. Cumulative whole-body vibration exposure, physical load factors and adverse psychosocial environment at the workplace, as well as individual-related psychological distress, were significant predictors of the occurrence of NSP in the professional drivers.

- **Keywords:** whole-body vibration, health risks, musculoskeletal disorders, psychological stress, driving

Ishbir Singh, S.P. Nigam & V.H. Saran. *Modal analysis of human body vibration model for Indian subjects under sitting posture*. Pages 1117-1132

Need and importance of modelling in human body vibration research studies are well established. The study of biodynamic responses of human beings can be classified into experimental and analytical methods. In the past few decades, plenty of mathematical models have been developed based on the diverse field measurements to describe the biodynamic responses of human beings. In this paper, a complete study on lumped parameter model derived from 50th percentile anthropometric data for a seated 54- kg Indian male subject without backrest support under free un-damped conditions has been carried out considering human body segments to be of ellipsoidal shape. Conventional lumped parameter modelling considers the human body as several rigid masses interconnected by springs and dampers. In this study, concept of mass of interconnecting springs has been incorporated and eigenvalues thus obtained are found to be closer to the values reported in the literature. Results obtained clearly establish decoupling of vertical and fore-and-aft oscillations. **Practitioner Summary:** The mathematical modelling of human body vibration studies help in validating the experimental investigations for ride comfort of a sitting subject. This study clearly establishes the decoupling of vertical and fore-and-aft vibrations and helps in better understanding of possible human response to single and multi-axial excitations.

- **Keywords:** whole-body vibration biodynamics, lumped parameter model, Indian subjects, sitting posture, anthropometry

Per M.G. Jonsson, Patrik W. Rynell, Mats Hagberg & Peter W. Johnson. *Comparison of whole-body vibration exposures in buses: effects and interactions of bus and seat design*. Pages 1133-1142.

Bus and seat design may be important for the drivers' whole-body vibration (WBV). WBV exposures in buses during actual operation were assessed. WBV attenuation performance between an air-suspension seat and a static pedestal seat in low-floor buses was compared; there were no differences in WBV attenuation between the seats. Air-suspension seat performance in a high-floor and low-floor bus was compared. Relative to the pedestal seat with its relatively static, limited travel seat suspension, the air-suspension seat with its dynamic, longer travel suspension provided little additional benefit. Relative to the measurement collected at the bus floor, the air-suspension seat amplified the WBV exposures in the high-floor bus. All WBV exposures were below European Union (EU) daily exposure action values. The EU Vibration Directive only allows the predominant axis of vibration exposure to be evaluated but a tri-axial vector sum exposure may be more representative of the actual health risks. **Practitioner Summary:** Low back pain is common in bus drivers and studies have shown a relationship with whole body vibration. Relative to a pedestal seat with its limited travel seat suspension, the air-suspension seat with its longer travel suspension provided little additional benefit. Exposures were below European Union daily exposure action values.

- **Keywords:** SEAT, Seat Effective Amplitude Transmissibility, European Vibration Directive, ISO 2631-1, low back pain, WBV

Marco Tarabini, Bortolino Saggin & Diego Scaccabarozzi. *Whole-body vibration exposure in sport: four relevant cases*. Pages 1143-1150.

This study investigates the whole-body vibration exposure in kite surfing, alpine skiing, snowboarding and cycling. The vibration exposure was experimentally evaluated following the ISO 2631 guidelines. Results evidenced that the most critical axis is the vertical one. The weighted vibration levels are always larger than 2.5 m/s^2 and the vibration dose values are larger than 25 $m/s^{1.75}$. The exposure limit values of the EU directive are reached after 8–37 min depending on the sport. The vibration magnitude is influenced by the athletes' speed, by their skill level and sometimes by the equipment. The large vibration values suggest that the practice of sport activities may be a confounding factor in the aetiology of vibration-related diseases. **Practitioner Summary:** The vibration exposure in some sports is expected to be large, but has never been quantified in the literature. Results of experiments performed in cycling, alpine and water sports outlined vibration levels exceeding the EU standard limit values.

- **Keywords:** whole-body vibration, acceleration exposures, sports ergonomics, back pain

Maël Amari, Eric Caruel & Patrice Donati. *Inter-individual postural variability in seated drivers exposed to whole-body vibration*. Pages 1162-1174.

Long-term occupational exposure to whole-body vibration (WBV) is a cause of low back pain for seated drivers. Poor and long-term seated postures are considered as a cofactor in the risk. It depends on the vehicle's ergonomics and tasks. Differences in posture may also be observed between operators doing identical tasks. An experiment has been performed in order to simultaneously measure posture and WBV for 12 drivers in 3 vehicles (loader, dumper and excavator) during controlled tasks. The inter-individual postural variability has been evaluated. The positions and movements of the body were measured with the CUELA system (computer-assisted recording and long-term analysis of musculoskeletal loads). Significant differences were observed between the three vehicles in the WBV, positions and movements of the body. Significant postural differences were observed between drivers (EN 1005-4 2005). Individual strategies for performing a task were also identified. **Practitioner Summary:** Posture is considered as a cofactor in the risk of low back pain for seated drivers exposed to whole-body vibration. Combined measurements revealed significant postural differences between drivers doing identical tasks. Depending on individual driving strategies, driver's body segments could be significantly deviated from neutral body postures (EN 1005-4 2005).

- **Keywords:** whole-body vibration, drivers, low back pain, posture, exposure

K.N. Dewangan, S. Rakheja, Pierre Marcotte & A. Shahmir. *Effects of elastic seats on seated body apparent mass responses to vertical whole body vibration*. Pages 1175-1190.

Apparent mass (AM) responses of the body seated with and without a back support on three different elastic seats (flat and contoured polyurethane foam (PUF) and air cushion) and a rigid seat were measured under three levels of vertical vibration (overall rms acceleration: 0.25, 0.50 and 0.75 m/s^2) in the 0.5 to 20 Hz range. A pressure-sensing system was used to capture biodynamic force at the occupant-seat interface. The results revealed strong effects of visco-elastic and vibration transmissibility characteristics of seats on AM. The response magnitudes with the relatively stiff air seat were generally

higher than those with the PUF seats except at low frequencies. The peak magnitude decreased when sitting condition was changed from no back support to a vertical support; the reduction however was more pronounced with the air seat. Further, a relatively higher frequency shift was evident with soft seat compared with stiff elastic seat with increasing excitation. **Practitioner Summary**: The effects of visco-elastic properties of the body-seat interface on the apparent mass responses of the seated body are measured under vertical vibration. The results show considerable effects of the coupling stiffness on the seated body apparent mass, apart from those of excitation magnitude and back support.

- **Keywords:** biodynamic response, cushion seats, visco-elastic properties, sitting conditions, body mass effect, elastic body-seat interface

Marianne Schust, Gerhard Menzel, Jörg Hofmann, Nazim Gizem Forta, Iole Pinto, Barbara Hinz & Massimo Bovenzi. *Measures of internal lumbar load in professional drivers – the use of a whole-body finite-element model for the evaluation of adverse health effects of multi-axis vibration*. Pages 1191-1206.

The present study aimed to (1) employ the method for evaluation of vibration containing multiple shocks according to ISO/CD 2631–5:2014 (Model 1) and DIN SPEC 45697:2012 in a cohort of 537 professional drivers, (2) deliver the results for a re-analysis of epidemiological data obtained in the VIBRISKS study, (3) clarify the extent to which vibration acceleration and individual variables influence risk values, such as the daily compressive dose S_{ed} and the risk factor R, and (4) compare the results with *in vivo* measurements and those obtained in previous studies with similar models. The risk factor R was influenced by the acceleration, lifetime exposure duration, sitting posture, age at the start of exposure and body mass/body mass index in order of decreasing effect. Age and annual and daily exposure duration had only a marginal effect. The daily compressive dose S_{ed} and the risk factor R showed weak linear association with the daily vibration exposure $A(8)$ and the vibration dose value VDV. The study revealed high shear forces in the lumbar spine. **Practitioner Summary:** In a re-analysis of an epidemiological study of professional drivers, a software tool available with standards DIN SPEC 45697:2012 and ISO/CD 2631–5:2014 Model 1 was used to calculate the risk to the lumbar spine in terms of daily compressive dose S_{ed} and risk factor R. The tool was found to be suitable for risk assessment in a large cohort.

- **Keywords:** whole-body vibration, health risk, biodynamic, lumbar spine

Chi Liu, Yi Qiu & Michael J. Griffin. *Finite element modelling of human-seat interactions: vertical in-line and fore-and-aft cross-axis apparent mass when sitting on a rigid seat without backrest and exposed to vertical vibration*. Pages 1207-1219.

Biodynamic models representing distributed human-seat interactions can assist seat design. This study sought to develop a finite element (FE) model representing the soft tissues of the body supported by seating and the vertical in-line apparent mass and the fore-and-aft cross-axis apparent mass of the seated human body during vertical vibration excitation. The model was developed with rigid parts representing the torso segments, skeletal structures (pelvis and femurs) and deformable parts representing the soft tissues of the buttocks and the thighs. The model had three vibration modes at frequencies less than 15 Hz and provided reasonable vertical in-line apparent mass and fore-and-aft cross-axis apparent mass. The model can be developed to represent dynamic interactions between the body and a seat over a seat surface (e.g. dynamic pressure distributions and variations in seat transmissibility over the seat surface). **Practitioner Summary:** The three-dimensional FE model of the human body represents the in-line apparent mass

and cross-axis apparent mass measured on a seat. With deformable soft tissues it can assist seat design by representing dynamic human-seat interactions, such as pressure distributions and variations in seat transmissibility over a seat surface.

- **Keywords:** apparent mass, cross-axis, biodynamic modelling, finite element model, vibration modes

Xiaolu Zhang, Yi Qiu & Michael J. Griffin. *Developing a simplified finite element model of a car seat with occupant for predicting vibration transmissibility in the vertical direction*. Pages 1220-1231.

The transmissibility of seat depends on the dynamics of both the seat and the human body, and shows how the amplification and attenuation of vibration varies with the frequency of vibration. A systematic methodology was developed for finite element (FE) modelling of the dynamic interaction between a seat and the human body and predicting the transmissibility of a seat. A seat model was developed to improve computational efficiency before models of the seat pan and backrest were calibrated separately using load–deflection and dynamic stiffness measurements, joined to form the complete seat model, and integrated with the model of a manikin for further calibration. The calibrated seat model was combined with a human body model to predict the transmissibility of the seat. By combining a calibrated seat model with a calibrated human body model, and defining appropriate contacts between the two models, the vibration transmissibility with a seat–occupant system can be predicted. **Practitioner Summary:** FE models are capable of reflecting complex dynamic characteristics of a seat–body system. A methodology for using FE methods to model a seat–body system to predict seat transmissibility has been demonstrated. The method can be developed to explore how seating dynamics interact with human biodynamics.

- **Keywords:** finite element model, seat transmissibility, dynamic stiffness, apparent mass

P. Paul F.M. Kuijer, Henk F. van der Molen, Astrid Schop, Fred Moeijes, Monique H.W. Frings-Dresen & Carel T.J. Hulshof. *Annual incidence of non-specific low back pain as an occupational disease attributed to whole-body vibration according to the National Dutch Register 2005–2012*. Pages 1232-1238.

Non-specific low back pain (nLBP) is the second most important reason for sick leave in the Netherlands, and more than 50% of the workers on sick leave attribute these complaints to their work. To stimulate recognition and prevention, an occupational disease (OD) registration-guideline was implemented for the assessment of the work-relatedness of nLBP in the Netherlands in 2005. The aim of this study is to present the annual incidence of nLBP as an OD and specifically for whole-body vibration (WBV) including patient characteristics such as age, sick leave and actions initiated by the occupational physician (OP). The data were retrieved from the National Dutch Register for 2005–2012. Each year about 118 OPs reported 509 cases (SD 139) of nLBP as an OD in a Dutch working population of 7.5 million workers (8% of all annual reported ODs). Less than 1% of these cases were attributed to WBV: 94% were men, 45% were between 51 and 60 years and 35% were on sick leave for more than 2 weeks. Most initiated actions were ergonomic interventions (35%). **Practitioner Summary:** The number of notified cases of nLPB as an occupational disease attributed to whole-body vibration is low with less than 1% of all cases in the Netherlands. An explanation is that other work-related risk factors for nLBP such as lifting are more frequently occurring, more visible and have a higher attributable risk than WBV. However, continuing attention for WBV remains warranted given a higher percentage of cases with sick leave of more than 2 weeks.

- **Keywords:** low back pain, whole-body vibration, occupational disease, incidence, prevention

Eckardt Johanning. *Whole-body vibration-related health disorders in occupational medicine : an international comparison*. Pages 1239-1252.

Workers with whole-body vibration (WBV) exposure are likely to report non-specific health complaints. Health and safety providers may not recognise such occupational injuries and may be unfamiliar with appropriate exposure assessment and prevention. This is a review of clinical studies, medical evidence, differential diagnostic evaluation protocols, surveillance programmes, national and international standards, and interventions recommendations utilising PubMed and other online resources. In summary, several studies show a clear trend: with increasing duration and intensity of occupational WBV exposure, primarily musculoskeletal or neurological disorders of the spine occur. Other organ damage has also been reported. In some European Union countries, spinal injury caused by WBV is recognised as an occupational disease and may be compensable. The WBV-related injury diagnosis includes a review of the work history, exposure assessment and differential diagnostic evaluation. WBV health surveillance should assess health status of WBV-exposed workers and address preventive measures. **Practitioner Summary**: Workers with whole-body vibration exposure report a variety of physical disorders. Health and safety providers may not recognise such injuries, or may be unfamiliar with exposure assessment and prevention. This review addresses health issues, exposure assessment and an international review of compensation criteria, trends and prevention efforts.

- **Keywords:** whole-body vibration, occupational health, musculoskeletal disorders, spine, causation, prevention