Deutsche Gesetzliche Unfallversicherung
Spitzenverband

5/2017e

IFA Report

Hand-arm vibration: Exposure to isolated and repeated shock vibrations – Review of the International Expert Workshop 2015 in Beijing

Authors Part I: Paul Pitts
Health and Safety Executive (HSE), Buxton, United Kingdom
Uwe Kaulbars
Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung (IFA),
Sankt Augustin, Germany

Hans Lindell, Snævar Leó Grétarsson, Michael Machens
Swerea IVF, Mölndal, Sweden

Anthony J. Brammer
Department of Medicine, University of Connecticut Health, Farmington, Connecticut, USA, and
Envir-O-Health Solutions, Ottawa, Canada
Gongqiang Yu
Department of Medicine, University of Connecticut Health, Farmington, Connecticut, USA

Authors Part II: Thomas Schenk
KSZ Ingenieurbüro GmbH, Berlin, Germany

Uwe Kaulbars, Fabian Haas
Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung (IFA),
Sankt Augustin, Germany

Published by: Deutsche Gesetzliche Unfallversicherung e. V. (DGUV)
Glinkastr. 40
10117 Berlin
Germany
Phone: ++49 (0)30 288763800
Fax: ++49 (0)30 288763808
Internet: www.dguv.de
E-mail: info@dguv.de

– September 2017 –

Publication database: www.dguv.de/publikationen

ISBN (online): 978-3-86423-198-8
ISSN: 2190-7994

Abstract

Hand-arm vibration: Exposures to isolated and repeated shock vibrations – Review of the International Expert Workshop 2015 in Beijing

ISO 5349, developed by ISO Technical Committee ISO/TC 108, "Mechanical vibration and shock", is the generic standard for the measurement and assessment of human vibration exposure. Ever since it was originally published in 1986, this standard has been unclear in its assessment of repeated isolated shocks. The current version of ISO 5349-1:2001 states in its scope that the time dependency for human response to repeated shocks is not fully known. Caution is therefore advised in the application of this part of ISO 5349 to such vibration (isolated shocks).

In response to an initiative on the part of the ISO/TC 108 Technical Committee, a workshop was held at the 13th International Conference on Hand-Arm Vibration in Beijing in 2015 for the purpose of determining the current state of knowledge concerning exposure to repeated isolated shock vibration caused by machinery and tools and its pathophysiological and epidemiological assessment, and evaluating gaps in knowledge in the interests of future research activity.

This report contains the papers presented at the workshop. Part I provides an overview of the results of the workshop and of details of two papers. Part II contains a research report containing background information on two further papers presented at the workshop.

Kurzfassung

Hand-Arm-Vibration: Expositionen gegenüber wiederholt auftretenden Einzelstößen – Review des International Expert Workshop 2015 in Peking

Die vom Technischen Komitee ISO/TC 108 „Mechanical vibration and shock“ erarbeitete Norm ISO 5349 ist die Grundlagennorm zur Messung und Beurteilung der Schwingungseinwirkungen auf den Menschen. Seit ihrer Erstveröffentlichung im Jahr 1986 ist diese Norm in der Bewertung wiederholt auftretender Einzelstößen nicht eindeutig. Die aktuelle Version der Norm ISO 5349-1:2001 stellt im Anwendungsbereich fest, dass die Abhängigkeit zwischen der zeitlichen Einwirkung von wiederholt auftretenden Stößen und ihren Auswirkungen beim Menschen nicht vollständig bekannt ist. Die Anwendung dieses Teils von ISO 5349 sollte für solche Vibrationen (Einzelstöße) daher mit Vorsicht erfolgen.

Auf Initiative des Technischen Komitees ISO/TC 108 fand anlässlich der 13. Internationalen Konferenz über Hand-Arm-Vibration in Peking 2015 ein Workshop statt mit dem Ziel, den aktuellen Kenntnisstand zur Exposition gegen wiederholt auftretenden Einzelstößen durch Maschinen sowie Werkzeuge und deren Beurteilung hinsichtlich Pathophysiologie und Epidemiologie festzustellen sowie Lücken für künftige Forschungsarbeiten zu beurteilen.

Dieser Report enthält die im Workshop präsentierten Vorträge. Teil I gibt eine Übersicht über die Ergebnisse des Workshops sowie über die Einzelheiten zu zwei Vorträgen. Teil II enthält einen Forschungsbericht mit Hintergrundinformationen zu zwei weiteren im Workshop gehaltenen Vorträgen.

Résumé

Vibrations main-bras : exposition à des chocs et vibrations isolés et répétés – Rapport sur l'atelier international d'experts en 2015 à Pékin

Élaborée par le Comité technique ISO/TC 108 « Vibrations et chocs mécaniques », la norme ISO 5349 est la norme de base pour le mesurage et l'évaluation des effets des vibrations sur les êtres humains. Depuis sa première publication en 1986, cette norme ne prend pas clairement position quant à l'évaluation de chocs individuels répétés. La version actuelle de la norme ISO 5349-1:2001 constate, dans le domaine d'application, que la relation entre l'action dans le temps de chocs répétés et leur effet sur l'être humain n'est pas totalement connue. Il convient donc de faire preuve de prudence lors de l'utilisation de cette partie de la norme ISO 5349 quand il s'agit de telles vibrations (chocs individuels).

Sur l'initiative du Comité technique ISO/TC 108, un atelier s'est déroulé à Pékin, en 2015, dans le cadre de la 13e Conférence internationale sur les vibrations main-bras. Il avait pour but de faire le point sur les connaissances actuelles concernant l'exposition à des chocs individuels répétés causés par des machines et des outils et sur son évaluation en termes de patho-physiologie et d'épidémiologie, et de déterminer les lacunes susceptibles de faire l'objet de futurs travaux de recherche.

Ce rapport contient les exposés présentés durant l'atelier. La partie I donne un aperçu des résultats de l'atelier et des détails de deux exposés. La partie II contient un rapport de recherche, avec des informations de base sur deux autres exposés tenus pendant l'atelier.

Resumen

Vibración transmitida al sistema mano-brazo: exposiciones a impulsos individuales y reiterados. Revisión del taller de expertos internacionales en Pekín, en 2015

La norma ISO 5349 redactada por el Comité Técnico ISO/TC 108 «Mechanical vibration and shock» es la norma de base para medir y evaluar el efecto de las vibraciones sobre las personas. Desde su primera publicación en el año 1986, esta norma no resulta un instrumento claro para la evaluación de dichos impulsos reiterados. La versión actual de la norma ISO 5349-1:2001 determina en el ámbito de aplicación que la dependencia entre el efecto en el tiempo de esos impulsos repetidos y sus repercusiones para la persona no se conoce en toda su magnitud. Por tanto, esta parte de la ISO 5349 debería aplicarse con cautela para este tipo de vibraciones (impulsos individuales).

Por iniciativa del Comité Técnico ISO/TC 108, con ocasión de la 13ª conferencia internacional sobre la vibración transmitida al sistema mano-brazo, celebrada en Pekín en 2015, se llevó a cabo un taller con el objetivo de determinar los conocimientos existentes actualmente sobre la exposición a las sacudidas reiteradas por el efecto de la maquinaria o las herramientas y su evaluación respecto a la fisiopatología y la epidemiología así como las lagunas existentes para poder dedicarles futuros trabajos de investigación.

Este informe contiene las ponencias presentadas en el taller. La parte I ofrece un resumen sobre los resultados del taller así como sobre los detalles de dos de las ponencias. La parte II contiene un informe de investigación con informaciones de fondo sobre otras dos ponencias también presentadas en el taller.

Table of contents

Part I

Presentations of the Workshop on Single Shocks during the Thirteenth International Conference on Hand-Arm Vibration, 12-16 October, 2015, Beijing, China

Hand-arm vibration: Exposures to isolated and repeated shock vibration – Review of the International Expert Workshop 2015

Paul Pitts,
Health and Safety Executive (HSE), Harpur Hill, Buxton, United Kingdom
Uwe Kaulbars,
Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung (IFA), Sankt Augustin, Germany

Abstract

Since its initial publication in 1986, the international Standard guide to the evaluation of hand-transmitted vibration (ISO 5349) has been cautious on the evaluation of risks from isolated and repeated shock vibration. The current version of this standard notes in the scope that: "*The time dependency for human response to repeated shocks is not fully known. Application of this part of ISO 5349 for such vibration is to be made with caution.*"

In October 2015, international experts in hand-arm vibration were invited to a workshop to discuss issues associated with shock hand-arm vibration, including: pathophysiology, epidemiology, machinery, evaluation of exposure. The aim of the workshop was to highlight shock hand-transmitted vibration as an issue for research and to consider which aspects of shock hand-arm vibration may be important. The expert attendees provided observations, grouped under the workshop's discussion areas, with a view to identifying possible directions for future work and collaborations.

This paper, by the workshop's joint organisers, reviews the background to the workshop, summarises the presentations made and reviews the observations of the expert attendees.

Introduction

Since its initial publication in 1986, ISO 5439 [1] has been unclear on the evaluation of isolated and repeated shock vibration. The current version of ISO 5349-1:2001 [2] notes in the scope: "*The time dependency for human response to repeated shocks is not fully known. Application of this part of ISO 5349 for such vibration is to be made with caution.*"

This paper is the first of a set of 5 papers produced as a result of an international experts workshop on isolated shock held in conjunction with the 13th International Conference on Hand-Arm Vibration, in Beijing 2015. The papers from the workshop are presented in two parts. This part, Part I, contains this paper and two other papers, one from *H. Lindell*, the other from *A. Brammer* and *G. Yu*, providing details of the presentations to the Isolated Shock Workshop. Part II contains a research report, which covers background information to workshop by *T. Schenk*, *U. Kaulbars* and *F. Haas*.

This first paper reviews some of the issues that created the current uncertainty about the approach to evaluation of isolated and repeated shock vibration. It discusses some of the implications for control of vibration risks and development of machinery with low risks from hand-transmitted vibration and provides an introduction to and review of the outcomes from the workshop.

International Workshop Beijing 2015

In October 2015 international experts in hand-arm vibration were invited to a workshop to discuss issues associated with shock vibration, including: pathophysiology, epidemiology, machinery, evaluation of exposure. The aim of the workshop was to highlight shock vibration as an issue for research and to assess which aspects of shock vibration are believed to be important.

The workshop included a set of informal presentations, each presentation aimed at introducing one of the discussion points (Table 1).

Table 1:
Workshop presentations and discussion points

Presenter	Presentation topic and discussion point
Paul Pitts	Overview of issues/tools/processes/emission declaration *Discussion*: Agree scope and objective of workshop
Hans Lindell	Impact machines with transient vibration *Discussion*: Is ISO 5349 good enough for assessment of shocks?
Thomas Schenk	Criteria for the Definition of Single Shocks *Discussion*: What do we believe we mean by single shock/impulse /... vibration?
Uwe Kaulbars	Measurement method, example sources and measured values *Discussion*: What should or could we be measuring?
Anthony J. Brammer	Health effects/epidemiology *Discussion*: Is there a pathophysiology that is substantively different to that of r.m.s. vibration exposure?

Background to the workshop

ISO 5349-1:2001 [2] is the basis for many standards and test codes for the declaration of vibration emissions. One objective of vibration emission declaration is to promote the development of lower risk machines, by enabling comparison of vibration data across machines of similar types. In Europe, EC Directive 2006/42/EC [3] requires that machine manufacturers or suppliers declare vibration emissions.

Machine manufacturers selling products into the European Union are required to make a statement of hand-arm vibration emission. Where possible these emission declarations should be obtained by testing according to a recognised ("harmonized") European Standard. Within the standardisation working groups responsible for the harmonized standards for single or low-rate impact machines, the question of whether the method of ISO 5349:2001 applies to these machines, and specifically:

- Is it technically valid to apply the ISO 5349-1 W_h filter to shock events occurring at rates lower than 5 Hz?
- Is it correct to classify impacts at low-repetition rates as "hand-arm vibration"?

To date, national experts have been unable to provide satisfactory and consistent answers to these questions, therefore the Standards working group proposed a workshop to discuss the issue of isolated shock and to assess those aspects of shock vibration that are believed to be important for future work.

Review of workshop presentations

Overview and agreed workshop scope (P. Pitts)

In his introduction to the workshop *P. Pitts* recognised the difficulties of establishing a relationship between a shock exposure metric and possible health outcomes. Shock vibration has many potential characteristics that might be measured and there are a number of possible health outcomes that affect the vascular, neurological and musculoskeletal systems of the hand and arm. The damage mechanisms for these health effects are uncertain and the mechanisms for continuous vibration exposures may be quite different to those for repeated or isolated shocks (see Figure 1).

Mr. *Pitts* also noted that there is a complex relationship between the definitions of hand-arm vibration syndrome (HAVS) and musculoskeletal disorders (MSDs) or Upper Limb Disorders (ULDs) (see Figure 2), which means that isolated shocks may, in some cases, be considered as a repetitive strain, and therefore a risk for upper limb disorders. The boundary between what is considered as vibration risk and what is considered as upper limb disorder risk may be dependent on health and safety compensation systems and so may be different from country to country.

In his presentation Mr. *Pitts* compared high-speed video of the hand while being exposed to vibration from rotary and impactive tools. The video highlighted the issue of possible different energy transfer mechanisms between the two vibration types. This was a theme taken up by Mr. *Lindell* in his presentation to the workshop.

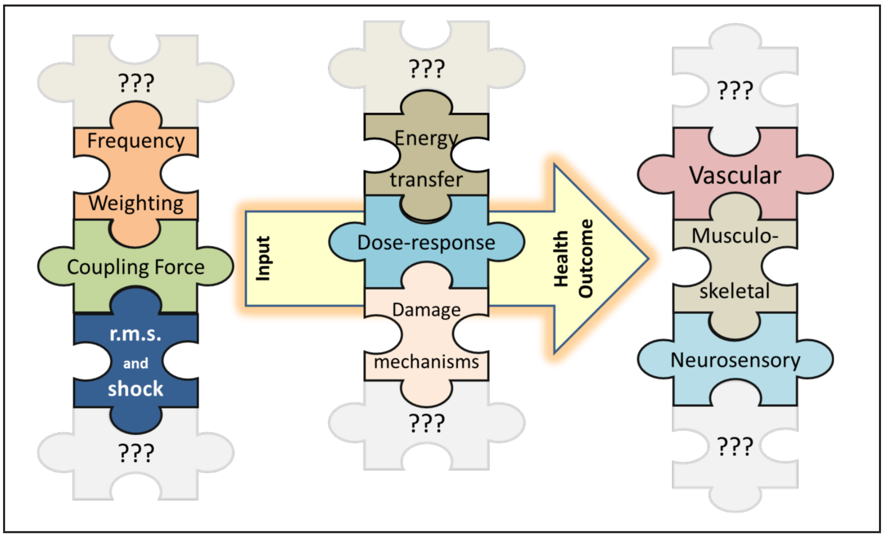


Figure 1:
Illustration of the relationships between shock and vibration characteristics, injury mechanisms and health outcomes

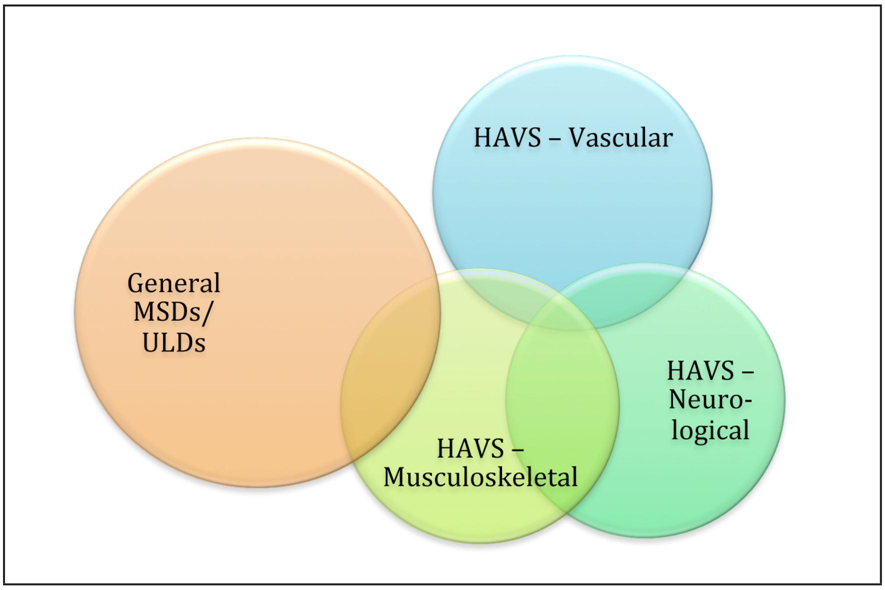


Figure 2:
Overlapping relationship between elements of HAVS and MSD/ULDs

Impact machines with transient vibration (H. Lindell [4])

High frequency vibration (above 1,250 Hz) is not covered by existing measurement standards [2] or legislation [3], however some studies suggest that exposure to vibration at high frequency can cause incidence of injury that is under-predicted by existing standards. For example, tools such as dental drills, with very high operating rotational speeds, where ISO 5349-1 would predict a vibration exposure of almost zero, appear to cause hand-arm vibration type injuries. Impactive tools that produce exceptionally high vibrations cause more injuries than predicted, perhaps because most of the vibration signal is filtered out by the current hand-arm vibration frequency weighting.

In presenting his work, Mr. *Lindell* explained some of the difficulties of reliably measuring high-frequency, high-amplitude vibration and illustrated modelling of the finger when exposed to shock. The model showed that pressure waves from high-frequency shock vibration can be transmitted into and within the fingers.

Mr. *Lindell*'s presentation highlighted the possible limitation of ISO 5349-1 for quantifying the risk of hand-arm vibration shock; noting that if high frequency and/or shock vibration is a particular type of vibration risk, then without a suitable definition for measurement it is impossible for machine manufacturers to assess and reduce the real vibration risks from their machines.

Criteria for the Definition of Single Shocks (T. Schenk [5])

The question of alternative metrics for hand-arm vibration evaluation was taken up by Mr. *Schenk* in his presentation to the workshop [5]. In his study Mr. *Schenk* had looked at how the sensitivity of subjects to vibration was affected by changes to a sequence of vibration stimuli.

Measurement method, example sources and measured values (U. Kaulbars [5])

Mr. *Kaulbars* [5] reviewed some of the alternative measurement metrics for shock vibrations that have been proposed [6] and tested [7]. However, there is a lack evidence of a relationship with injury or damage mechanisms. Alternatives to the W_h frequency weighting have also been proposed [8] and there is some evidence of improved relationship to incidence of vascular damage for impactive machines, but the alternative weightings are not designed for single or repetitive shocks.

Health effects/epidemiology (A. Brammer [9])

The lack of a recognised metric for shock vibration was also a theme of Dr. *Brammer*'s presentation [9]. While there is some evidence that shock increases the risk of some injuries, such as carpel tunnel syndrome (CTS), the evidence is limited, and could be attributed to the influence of high-frequency vibrations.

Hypothenar Hammer Syndrome (HHS) is an injury that is associated with manual hammering using the heel of the hand, but has become associated with HAVS from repetitive impactive tools. HHS may occur following repeated hypothenar trauma from vibrating tools. In such cases, the nature and magnitude of the individual impacts may be more important than the weighted acceleration level of vibration exposure.

Dr. *Brammer* differentiated between repeated shocks and isolated shocks, suggesting that there was some evidence of repeated shock being associated with an increased risk of developing CTS, but there was less evidence of (low repetition frequency) isolated shock being associated with vibration injuries.

Key workshop discussion points, comments and outcomes

Delegates to the Isolated Shock Workshop were provided with a response form and asked to provide a record of their thoughts and suggestions regarding each workshop session. The Annex provides a complete (anonymised) list of all the comments made by the workshop delegates. The comments have been sorted into categories and summarised.

Definition of shock

The greatest number of comments related to the definition of shock; many making the distinction between repetitive and isolated shock vibration. There were no strong suggestions on what characterised shock beyond duration (short), magnitude (high) and repetition rate, but some considered that factors such as high-frequency vibration or the maximum force generated may be important. One response questioned whether shock was an ergonomic, rather than a vibration, issue.

Workplace examples of shock were commonly given as nail guns and hand-as-hammer, however, some commented that some sports activities also present shock vibrations to the hand and arm.

Measurements

Many comments related to the question of how shock ought to be characterised. Current measurements based on acceleration at the vibrating surface were questioned. Suggestions were made of measurement issues to be considered, such as: frequency weighting, energy entering the body, measurement on the wrist (for hand-as-hammer process), force, time and use of high-speed imaging.

The importance of linking measurement to any health risk, physiological model or sensitivity data was expressed in several comments.

Damage mechanisms

The greatest variety of comments came under the category of damage mechanisms, perhaps reflecting it as the issue of greatest uncertainty. Comments were primarily regarding the need for an understanding of any damage mechanisms.

Many comments related to the propagation into, and possible damage at, the fingers. The frequency content of the driving signal was considered to be an important factor for some. The potential for damage due to the propagation of high-frequency vibration through blood vessels was highlighted and the potential of the finger to act as a wave-guide to these high frequencies (including ultrasound) was also questioned. It was also suggested that high-frequencies could cause damage to nerve endings, resulting in disruption to vasoregulation in the fingers.

Although, some delegates questioned whether low-frequency shocks present any risk of damage, it was also suggested that there were possible associations of low-frequency shock with musculoskeletal damage and with vasoconstriction and ischemia/reperfusion injury.

The possibility of shocks causing micro-trauma in the bones of the hand, possibly leading to increased risk of degenerative arthritis was proposed. Damage to the hand structures might also be considered from an engineering perspective, such as fatigue modelling.

Health effect research

Health research is possible, such as work with existing patient groups, looking at the prevalence of musculoskeletal disorders of groups exposed to shocks compared to non-exposed groups with similar workloads. Some work in this area is already available and a review of studies may help to identify types of damage.

One comment suggested that studies relating to the use of gloves (it is not clear whether the expert's intention was to refer to anti-vibration gloves here) may provide some insight into the health effects from shocks.

Some proposed shock/vibration perception testing, although the need for suitable equipment for generating repeatable shocks was also raised as an issue.

One comment suggested that indirect effects of damage may also be important. The adaptions by an individual made to compensate for joint injury or damage or the fatigue experienced might be investigated.

Epidemiology

The need for carefully targeted epidemiological studies was recognised, along with the need to test against different metrics. One comment noted that existing epidemiological data could not distinguish between r.m.s. (root mean square) and shock injury.

Evidence of health effects comments

A few comments were recorded regarding the evidence for ill health resulting from exposures to shock vibration. These comments were in part contradictory; two saying there is evidence, another saying that evidence is needed.

Damage prevention

Two comments related to prevention, either through improvements in tool design or the use of anti-vibration gloves to prevent bruising on hand-as-hammer operations.

Legislation

It was recognised that there may be a need to modify legislation, although the specific example of Canada was given, where there is (already) a duty to monitor for, and control, general workplace risks.

Ergonomics

The link to ergonomic risks was highlighted in many comments. One comment suggested the specific consideration of ergonomic factors (perhaps as a means to identify risks) and consequential improvements in workplace practices.

Discussion

Having an accepted definition of what is meant by hand-arm shock is essential to progress in determining whether there is a distinct set of injuries that should be associated with shock exposure. Currently, experts try to identify categories based on whether the shock events are "single", "isolated" or "repeated". The ISO 5349-1 frequency weighting is sometimes used as a guide, such that repetition rates greater than 5 Hz are regarded as continuous vibration.

Expert discussion identified a number of features of a vibration signal that may be important for predicting health outcomes. Particular elements included very high frequency vibration, although the practicalities of reliable measurement of such signals were not discussed in any detail. Other parameters, such as impact force and energy entering the hand-arm system may also be influential. Use of high-speed video and measurement at the wrist were suggested as ways of assessing shock vibration transmission.

To be useful, any measurement or study methodology must be capable of reliable quantification of a parameter related to risk. It can be argued, for example, that vibration measurement on the vibrating surface does not assess the energy entering the hand and therefore the energy causing damage. However, measurement on the vibrating surface is significantly more reliable than measurement on the hand or arm, due to the complex and variable interaction between the hand and the vibrating surface, and the similarly complex and variable frequency-transmission characteristics to nerve endings, the vascular system, muscles, bones or joints.

Effective quantification of risk relies on a measurement metric targeted at a well-understood damage mechanism or injury type. Standard ISO/TS 15694:2004 [6] provides a number of potential metrics for single shocks, but there is no preferred metric, nor any indication of the relationship between each metric and a health outcome.

There is a general interest in carrying out health research, and some opportunities around existing patient groups and possible target worker groups. There is also potential for comparative perception studies, although such studies are somewhat dependent on an accepted shock measurement metric.

Currently, there is no strong evidence of a risk from hand-arm shock vibration that is clearly different to that from r.m.s. vibration. Epidemiological studies and the selection of measurement parameters both require some clarity on shock vibration risk. The possible link between workplace exposures to shock and similar exposures in sports activities may provide a route to information on damage mechanisms and health effects. Sports activities such as tennis, cricket and baseball may provide study populations where exposure to isolated shocks is common; with the advantage that such groups do not have an associated exposure to continuous vibration, which is usually the case with worker population groups.

The expert discussion highlighted the issue of the influence of high-frequency components of shock vibration, and the potential for damage from these high frequency components. High-frequency vibration is, however, problematic when considering the practicalities of measurement; particularly as the suggestion was of vibration frequencies well beyond the upper limit of either ISO 5349-1 or ISO/TS 15694, which are based on an upper frequency limit of 1,250 Hz. At high frequencies (i.e. above 1,250 Hz), the surface vibrations can be severely affected by local vibration modes, such that the measured magnitude would be highly dependent upon both the precise position of the transducer and the characteristics of the mounting method. From the point of view of control, the advantage of high-frequency vibration is that it is easily absorbed by resilient materials on tool handles, or by gloves.

Conclusions

The stated aim of the international expert workshop was to "highlight shock vibration as an issue for research and to assess those aspects of shock vibration which are believed to be important for future work". The workshop succeeded in this aim, and identified research areas where there are opportunities to investigate the human responses to shock vibration.

While there is currently no strong evidence to show that shock vibration is fundamentally different to r.m.s. vibration, i.e. that there is a difference between the injury mechanisms for the two types of exposure, there is some support for the idea that the two maybe different, or need to be considered differently.

There is no clear indication of what a definition of "shock" or "isolated shock" might be. There are parameters that experts consider to be important, such as acceleration, amplitude, duration, repetition rate, force, energy, etc., but none are currently regarded as a preferred option for a measurement metric.

There are hypotheses of damage mechanisms, which may be more applicable to shock than to r.m.s. vibration, due to factors such as amplitude and frequency content, and there may be some opportunities to study these mechanisms.

Unfortunately, the specifications for studies on shock vibration are dependent upon having an accepted definition of shock; and the definition of shock is dependent upon having the results of reliable studies. This circular dependence is inhibiting the development of the topic. Multi-parametric studies, perhaps based on the metrics in ISO/TS 15694:2004, are therefore essential to further the investigation in to shock hand-arm vibration.

This publication and the work it describes were supported by the Health and Safety Executive (HSE) and Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung (IFA). Its contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE or IFA policy.

References

[1] ISO 5349: Mechanical vibration – Guidelines for the measurement and the assessment of human exposure to hand-transmitted vibration. International Organization for Standardization (ISO), 1986

[2] ISO 5349-1: Mechanical Vibration and Shock – Evaluation of human exposure to hand-transmitted vibration – Part 1: General requirements. International Organization for Standardization (ISO), 2001

[3] Directive 2006/42/EC of the European Parliament and of the Council of 17 May 2006 on machinery, and amending Directive 95/16/EC (recast). OJ EC (2006) No. L 157, p. 24

[4] *Lindell, H.*: High frequency shock vibrations and implications of ISO 5349 – Measurement of vibration, simulating pressure propagation, risk Assessment and preventive measures (see page 19 in this report)

[5] *Schenk, T.; Kaulbars, U.; Haas, F.*: Studies for description and definition of shock events acting upon the human hand-arm system and of means of assessing these events (see page 39 in this report)

[6] ISO/TS 15694:2004 Mechanical vibration and shock — Measurement and evaluation of single shocks transmitted from hand-held and hand-guided machines to the hand-arm system. International Organization for Standardization (ISO), 2004

[7] *Heaton, R.; Hewitt, S.; Yeomans, L.*: Correlation between vibration emission and vibration during real use – Fastener driving tools (RR591). Health and Safety Executive (HSE), Buxton, United Kingdom 2007

[8] *Pitts, P.*: Evaluation of candidates for additional frequency weightings for hand-arm vibration measurement. In: 45th UK Conference on Human Response to Vibration, Institute of Naval Medicine, 6-8 September 2010

[9] *Brammer, A.; Yu, G.*: Health effects from exposure to the hand to mechanical shocks (see page 31 in this report)

Annex: Workshop delegates' comments and observations

This Annex provides a complete list of the written comments and observations made by the delegates to the International Workshop on isolated shock in Beijing 2015. These observations were transcribed from hand-written notes from the delegates and then separated into distinct comments. The 84 distinct comments listed in Table A.1, have been placed into 9 categories:

1. "Definition of shock": 26 comments
2. "Measurement": 17 comments
3. "Damage mechanism": 16 comments
4. "Health effect research: 12 comments
5. "Epidemiology": 5 comments
6. "Evidence of health effects: 3 comments
7. "Damage prevention": 2 comments
8. "Legislation": 2 comments
9. "Ergonomics": 1 comment

While every attempt has been made to record the delegate observations accurately, in some cases interpretation of the written notes was required to ensure that a clear point was recorded.

Table A.1:
Categorised delegate comments

Category	Delegate comment/observation
Definition of Shock	If the next shock arrives while the effect of the previous shock remains in the hand, then this is not a shock wave (it is vibration).
Definition of Shock	t = 1 m sec High amplitude
Definition of Shock	A very high magnitude or short time in one cycle
Definition of Shock	Need to define and characterise shock: magnitude, frequency, duration
Definition of Shock	Shock events mixed in with continuous vibration events/see high shock wave
Definition of Shock	If the complete system is settled out before the next impulse comes, it's a shock. Otherwise, evolve a standing wave in the hand-arm system and there is a vibration and not an isolated shock.
Definition of Shock	This is critical. We need an agreed upon definition: 1. repetition, 2. magnitude, 3. duration
Definition of Shock	Definition of shock (what does it mean)
Definition of Shock	What is shock
Definition of Shock	Duration
Definition of Shock	*Jim Potuin* (Canadian Biochemist) has done considerable work on impact load for hand-hammer and hard push p.n force (is this shock, is it more of an ergonomic issue? A Soccer injury – e.g. heading a football – is this shock?)
Definition of Shock	Maximum force
Definition of Shock	kHz not studied – needs to be

Category	Delegate comment/observation
Definition of Shock	Impact tools have both low Hz and kHz frequency power.
Definition of Shock	Cut-off Hz
Definition of Shock	Distinguish between hand-hammering and tools: different force -> different coupling -> different effects(?)
Definition of Shock	When hand is used as a tool single impact – repeated (shock?) Damage to hand/arm
Definition of Shock	Hand-as-hammer examples?
Definition of Shock	What is the definition of shock – is intensity important?
Definition of Shock	Magnitude
Definition of Shock	Tool shock only?
Definition of Shock	Hand hammer process (nail gun)
Definition of Shock	Shock – perception of single events – velocity.
Definition of Shock	What is a shock? What is a single shock?
Definition of Shock	Need definition single/repeated shocks.
Definition of Shock	Shock from impact in sport e.g. Soccer players heading a ball
Measurement	Are accelerometers a proper device to measure r.m.s. acceleration?
Measurement	Is acceleration the correct thing to measure?
Measurement	Acc. At wrist for hand-hammer process
Measurement	Shocks do not have deceleration that vibrations do.
Measurement	Can we measure the energy that goes into the body?
Measurement	Force/time magnitudes important, more important than r.m.s.
Measurement	How to consider the frequency weighting?
Measurement	Can we use FFT to estimate shock?
Measurement	How should we do calculations on the frequency?
Measurement	With measurements between surface acceleration (vibrations at the handle) and real masses (hand) should be distinguished accelerations. Acceleration sensors measure both. But the measured acceleration is not the acceleration of the hand or the handle.
Measurement	High speed camera acceleration + measurement
Measurement	We don't know what parameters we have to measure until we know what physiology and effects are of shock exposure.
Measurement	Matching between sensation model and physiological model of neural transmission of signals.
Measurement	I think we need some objective parameters to be complemented by the psychophysical data.
Measurement	Need also clear metric(s) to link with potential injury risk.
Measurement	What's the standard methods for shock measurement and how to quantify it
Measurement	What should we measure?
Damage mechanism	Does it damage if the shock is isolated to the fingers/hands?
Damage mechanism	Does the shock damage if low-frequency?
Damage mechanism	There may be some more effects due to the propagation through vessels of high-frequencies. Where do these high frequencies arrive?
Damage mechanism	Does filter removing high kHz frequency cause injury.
Damage mechanism	Need research to determine whether low Hz is causing vasoconstriction and blood-vessel damage, ischemia reperfusion injury, high Hz causing nerve ending damage but not blood vessel constriction so less innervation (vasoconstriction and vasodilation regulators), so physiological disruption of vasoregulation.
Damage mechanism	Think about science from material engineering – what causes fatigue?
Damage mechanism	Pathophysiology of shock needs to be known.
Damage mechanism	What is the potential injury mechanism
Damage mechanism	Can single shocks give micro-trauma to bone (carpel bone/wrist) which increase degenerative arthritis in hand.
Damage mechanism	Emphasis on musculoskeletal disorders which seems to be more intimately linked to use of percussive tools (in this respect how can transient vibration & finger models i.e. *Lindell* presentation relate to MSDs?)

Category	Delegate comment/observation
Damage mechanism	The frequency spectrum width of shocks is inversely proportional to its time width. So containing the same frequencies of continuous vibration why should we have different effects?
Damage mechanism	No damping: propagation through vessels and the only damping is the expansion and contraction of the vessel wall.
Damage mechanism	Shockwave propagation into finger m/s^2.
Damage mechanism	Wavelength, waveguide properties of finger.
Damage mechanism	Low Hz – vasoconstriction/reperfusion injury.
Damage mechanism	The research on ultrasound wave propagation would be interesting
Health effect research	Gloves
Health effect research	We have patient groups who are exposed to shocks so we are interested in what and how to do it. This is so we can try to couple exposure to health outcome
Health effect research	Joint injury/damage: fatigue processing & adaption
Health effect research	We need health research
Health effect research	See if single shocks increase the prevalence of musculoskeletal disorders compared to work with similar workload and vibration exposure.
Health effect research	Test the physiology response (neurological) during people exposed to shock.
Health effect research	Compare only shock feel damage to only r.m.s. feel physiological damage
Health effect research	Currently observed effects are intertwined; need to separate.
Health effect research	To investigate shocks, you need a stimulator, which can produce shocks. Shakers do not have enough energy. New test setup would be needed.
Health effect research	Shocks with a magnitude of a nail gun must be reproducible and consistent to investigate this. The nail gun is unsuitable for this purpose because of their scattering. We need a pulse stimulating machine.
Health effect research	What is the tissue damage? Carry out a review of current research on shocks, i.e. Riley‘s work and others to show nerve damage – blood cell damage?
Health effect research	Test the physiology response (FST) during people exposed to shock.
Epidemiology	The development of HAVS within workers exposed with normal vibration at the same r.m.s. rate.
Epidemiology	Study on workers using tools with (high freq. high mag input) and impaired.
Epidemiology	Need more epidemiological studies to relate effects to measured vibration using different metrics.
Epidemiology	Is there evidence that shock results in injury. With regard to MSD, is it shock or is it vibration (existing epidemiology evidence won‘t let you make a distinction between injury from r.m.s. and injury from shock).
Epidemiology	Identify workplace/worker injuries
Evidence of health effects	Evidence of health effects
Evidence of health effects	Any evidence? Yes.
Evidence of health effects	Most/all have both high Hz shock and low freq. Combined has documented damage
Damage prevention	MBD reliability design
Damage prevention	What about manufacturing – use the hand as a hammer – impact gloves have been used to help prevent bruising.
Legislation	In Canada there is general duty clause in the OHs -› so there is still a need for increase in awareness to enable development and implementation of controls.
Legislation	Challenge is also the legislation
Ergonomics	Ergonomic factors/work practices

High frequency shock vibrations and implications of ISO 5349 – Measurement of vibration, simulating pressure propagation, risk assessment and preventive measures

Hans Lindell, Snævar Leó Grétarsson, Michael Machems, Swerea IVF, Mölndal, Sweden

Summary

This report covers the material presented at the Workshop on Single Shocks at 13th International Conference on Hand-Arm Vibration, Oct. 16, 2015, Bejing, China. Parts of the content have been updated with recent finding from research at Swerea when applicable.

High frequency shock vibrations above 1,250 Hz are likely to cause a significant amount of vibration injuries [1 to 6] but there is inadequate understanding of the injury mechanisms. There is also no standard assessing the risk associated with these vibrations. The current standard, ISO 5349, that all regulations and legislation are based upon such as the EU Vibration Directive covers only vibrations up to 1,250 Hz. Frequencies above this are not considered at all. This results in that several occupational groups are exposed to potential harmful vibrations that are not regulated by any workers protection directives. Examples of major occupational groups exposed to high frequency vibrations are users of impact wrenches for assembly and repair of vehicles and personnel in the dental sector.

The objectives with this study are; **first**, to measure and compare vibrations from impact tools with tools with a continuous vibration and study how the weighting filter in ISO 5349 affects the acceleration; **second**, study how high frequency impact vibration is transmitted into the finger tissue via the skin in a finite element (FE) model; **third**, a brief review of literature on how high frequency vibrations affect red blood cells and hand arm vibration syndrome (HAVS) prevalence and; **fourth**, shown that the high frequency vibrations can be significantly reduced by measures in common machines.

The conclusions are:

- Acceleration can be measured accurately up 50 kHz with newly developed ultra light Micro Electrical Mechanical Systems (MEMS) accelerometers.
- Impact machines generate high amplitude high frequency transient accelerations.
- High frequency accelerations from impact machines are nearly eliminated by the weighting filter in ISO 5349 and thereby disclosed from risk evaluation.
- Transient vibrations from machines generate a shock wave that propagates into the finger tissue.
- The epidermis layer of the finger has a relatively small attenuation.
- There are several studies that show that ISO 5349 underestimates the risk for HAVS from transient vibrations.
- Transient vibrations can be substantially reduced by redesign of machines.
- ISO 5349 cannot be used for estimation of injuries from high frequency vibration (HFV) and was never intended to which is clearly stated in the scope.
- There is a need for an amendment to ISO 5349 covering HFV to create an incentive for tool manufacturers and users to reduce the vibration levels.

The intent is that with an increased understanding on how high frequency vibrations from machines are interacting with biological tissue will emphasize the need to regulate these and establish a standard for these vibrations and thereby create an incentive for machine producers and users to reduce the high frequency vibrations.

1 Introduction

High frequency vibration of 1,250 Hz is likely to cause a significant part of vibration injuries [1 to 6] but there is a lack of understanding of the injury mechanisms as well of a functioning standard for measurement of high frequency vibrations. Today‘s standard, ISO 5349, that all regulations and legislation is based on only covers vibrations up to 1,250 Hz. Frequencies above this are not considered at all. This means that major occupational groups are exposed to harmful vibrations that are neither measured nor regulated by either the EU Directives or the Work Environment Authority. Examples of major occupational groups exposed to high frequency vibrations are users of impact wrenches at assembly and repair of vehicles and personnel in dental industry.

For vehicle repairer workers the impact wrenches is one of their most used tools which emits high impact vibrations. An impact wrench has typically an impact blow rate of 20 Hz which is well within the ISO 5349 range, but each stroke creates a pulse of high frequency vibrations with very high acceleration levels of several thousands of m/s^2. Since the pulse of high frequency vibration is short these vibrations are often called for transient. Several medical studies [1; 2] have since long pointed out that ISO 5349 greatly underestimates the risk of HAVS at workers subjected to transient vibrations.

Dentists, dental technicians and dental hygienists work with tools that expose them to high frequency vibrations. A dental drill typically rotates about 400,000 rpm i.e. vibrate with a frequency of about 7,000 Hz. In a recent article [6] it was revealed that the high frequency vibrations from the dental drills often cause vibration injuries to the dentists who have worked with repair of teeth in spite of that the ISO 5349 vibration being almost zero.

There have also been studies on how transient vibrations affect red blood cells [4; 5] and rat tails [3]. The results have shown that there is a very large negative impact.

The authors of ISO 5349-1:2001 have clearly been aware of the problem with high frequency transient vibrations which is reflected in the scope where it says that it only covers vibrations within the frequency range of the octave bands from 8 to 1,000 Hz. It also states in the Scope: "*Provisionally, this part of ISO 5349 is also applicable to repeated shock type excitation (impact)*" and further "*The time dependence for human response to repeated shocks is not fully known. Application of this part of ISO 5349 for such vibration is to be made with caution*". There is no doubt that the effects from high frequency transient vibrations are not fully covered by ISO 5349 but it still forms the basis for risk evaluation on these machine categories.

The objective for this study was to describe how the vibrating surface of hand-held tools affects the finger tissue with respect to pressure wave propagation. This was done by developing a FEM LS-DYNA model. The acceleration input parameter was taken from measurement on a hand held impact wrench.

2 Study of "transient" and "normal" acceleration above 1,250 Hz

2.1 Measuring high frequency and high amplitude acceleration

Recent development of accelerometer technology with Micro Electrical Mechanical Systems (MEMS) has opened new possibilities to study high frequency vibrations from hand-held machines. The advantage is that the weight of the sensor can be greatly reduced which ease the mounting and allows measurement on polymer handles.

In this study the accelerations were measured with a piezoresistive bridge shock MEMS accelerometer, model 3501A2060KG, from PCB (Figure 1).

Figure 1:
MEMS accelerometer

It weighs 0.15 gram and has a 2 dB frequency range at 50 kHz and an amplitude range of 600,000 m/s^2. The resonance frequency of the accelerometer is 150 kHz. The acceleration signal was anti-alias filtered with an analog 4th order low pass Bessel filter at 200 kHz and then sampled in the AD converter at 1 MHz. The signal was then digitally low pass filtered at 30 kHz with a 6th order Bessel low pass filter. The filter frequency of 30 kHz was chosen both to prevent amplification from the accelerometer resonance at 150 kHz and ensure that the fixation method of the accelerometer would be rigid below that frequency. Bessel filters were chosen since they have a linear phase shift and thereby create minimum distortion of the time signal.

In order to investigate the influence of the fixation method of the accelerometer to the machine surface a test rig (Figure 2) was developed that gives a high peak acceleration similar to that from an impact wrench with high repeatability. The accelerometer was attached to the surface in three ways, plastic melt glue, accelerometer wax and tack-it from UHU Patafix. Also different temperatures from 10 °C to 40 °C were tested.

It was found that up to 30 kHz the difference between the methods were small, approx. below 10%. Due to its simplicity tack-it was used in this study.

Note: Recent development of the measurement technique shows that accurate measurements can be made up 50 kHz but the results in this study are filtered at 30 kHz.

Figure 2:
Test rig for accelerometer mounting evaluation

2.2 Comparison of acceleration between an impact machine and a grinder and the influence of ISO 5349 filtering

In order to study the difference between a machine with impact vibrations and a machine with continuous vibrations measurements were performed at the handles on a CP734 impact wrench and a IR88V85 straight grinder (Figure 3). Both machines are pneumatic with metal handles.

The accelerations are presented below both before and after ISO 5349 filtering (Figure 4).

What can be seen is that the impact wrench has very high acceleration peaks around 10,000 m/s^2 and that the ISO 5349 weighting almost eliminates these peaks. The grinder has peak vibration at about 500 m/s^2 (Figure 5) which is 1/20 of the impact wrench. Note that the grinder vibration is closed to the noise level of the measurement system which is about 100 m/s$^2_{peak}$. Both machines have an ISO 5349 weighted acceleration of about 5 m/s^2 measured in three axes and thereby they should have the same associated risk for HAVS (Figure 6).

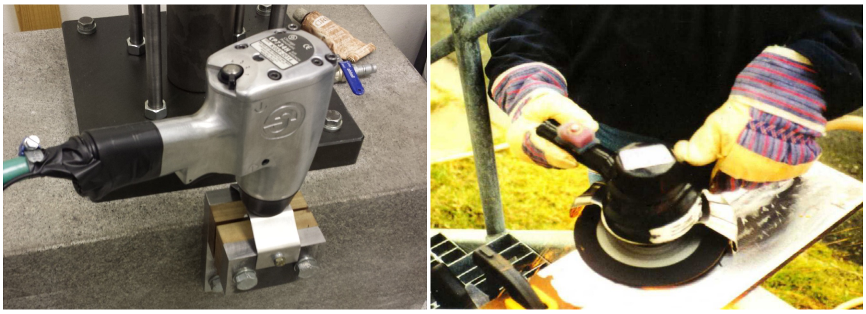


Figure 3:
Impact wrench CP734 and Ingersoll Rand 88V85 grinder

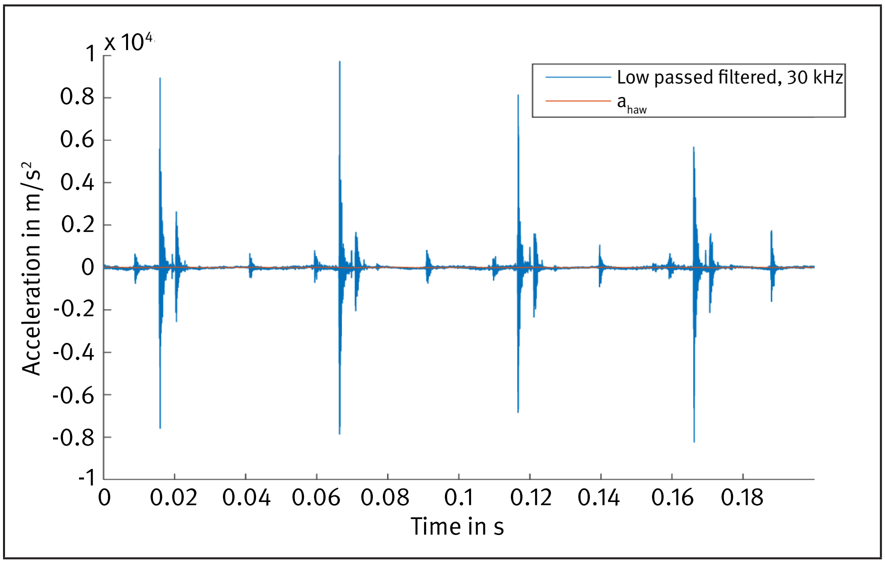


Figure 4:
Impact wrench vibration before and after ISO 5349 filtering

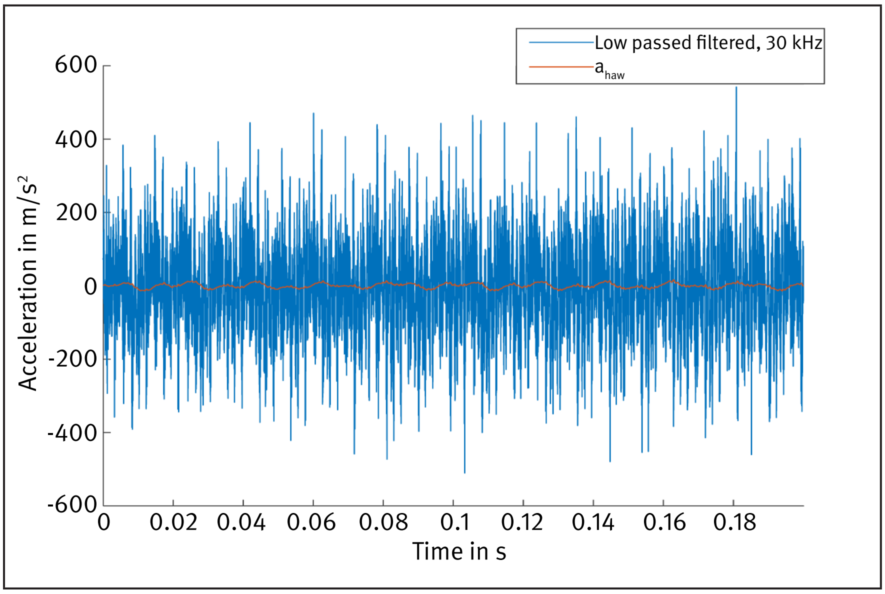


Figure 5:
Grinder vibration filtered at 30 kHz and with ISO 5349 filtering

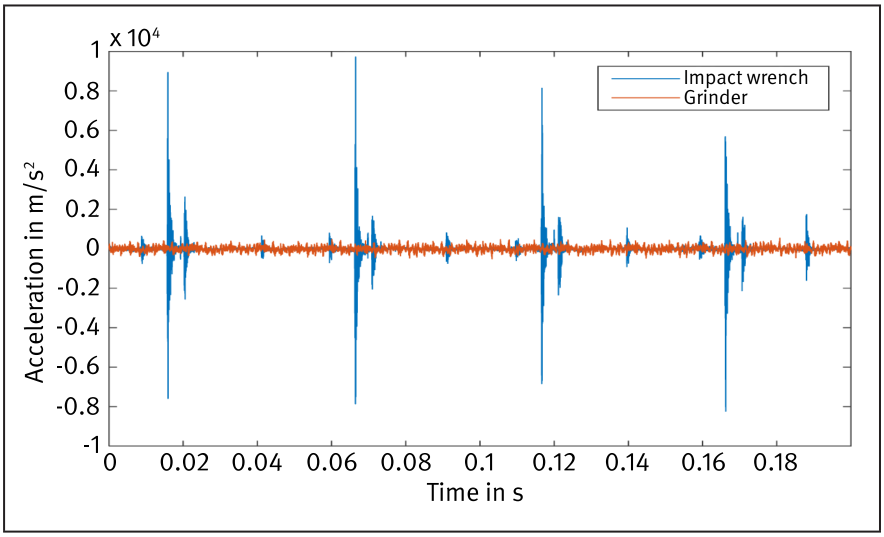


Figure 6:
Grinder and impact wrench vibrations filtered at 30 kHz

3 Simulation of pressure propagation into finger tissue

In order to study how transient vibrations affect the finger tissue a finite element (FE) model is built up. The objective with the model is to be able to simulate how the vibrating surface of the machine interacts with the skin layers in the finger and study how the created pressure wave propagates into the soft tissue of the finger.

The prediction of wave propagation in viscous tissue material is modeled with a 2D plane strain finite element simulation model. It is solved by the multiphysics simulation program LS-DYNA, whereby the central difference method is adopted. The numerical simulation model consists of a finger model, discretized with 2D plane strain continuum elements.

Initial simulations with a full 3D simulation model with relatively coarse discretization of the finger revealed that a 2D plane strain approach is valid at a distance of at least 25 mm from the tip of the finger in order to reach 2D plane strain conditions within the finger under the short period of the applied acceleration pulse.

The numerical simulation model of the finger includes the components of the human skin e.g. stratum corneum, living epidermis, dermis and subcutaneous tissue. The geometric properties of the different skin layers and the overall dimensions of the finger are derived from findings published [7; 8]. Special attention is paid to the contour of the fingerprint where load introduction appears. The structure of the fingerprint of skin is an important factor since it acts as a vibration isolator. Therefore an epoxy casting of the index finger fingerprint pushing on a plane plate with a force of 5 N was made. The casting was analyzed in a confocal microscope which built a 3D model of the finger print. The finger depth profile was then parameterized and described by five parameters representing the finger print profile. The exact dimensions are integrated into the simulation model (Figure 7).

Literature data about mechanical properties of the skin layers stratum corneum, epidermis, dermis and subcutaneous tissue reveal differences in the order of magnitude, depending on test set-up, loading conditions, gender, age, location and environmental conditions [8; 9]. However, the elastic material properties for dermis and subcutaneous tissue are taken from publications in [7] and the properties for bone material are taken over from [10]. In [11] a compression bulk wave speed of about 1,500 m/s is listed for human skin from various investigations. Bulk modulus, density, the corresponding speed of sound and the shear modulus are listed in Table 1.

The material response of the skin layers is time and history dependent and is therefore described by a viscoelastic constitutive model, based on exponential stress relaxation functions with shear relaxation behavior described in [12]. The viscoelastic material used in LS-DYNA utilizes the Zener model which is a configuration of a spring and spring-damper element in parallel.

$$G(t) = G_\infty + (G_0 - G_\infty)e^{-\beta t}$$

The viscoelastic behavior is described by the long term asymptotic shear modulus G_∞, the short term shear modulus G_0 and the stress relaxation time 1/ß. The stress relaxation time and long term shear modulus for subcutaneous tissue is taken from [13]. The long term shear modulus for the other tissue layers is adapted proportionally.

The material data for the skin layers stratum corneum and epidermis stated in [7] is further refined by an experimental investigation of the finger and fingerprint distortion under compressive forces. The experimentally evaluated fingerprint geometry in both uncompressed and compressed state is used to validate the finite element simulation model in an inverse optimization approach. With this approach the shear modulus of the skin layers in the numerical simulation model are verified (Figure 8).

Figure 7:
Numerical simulation model with experimentally validated geometry of the fingerprint

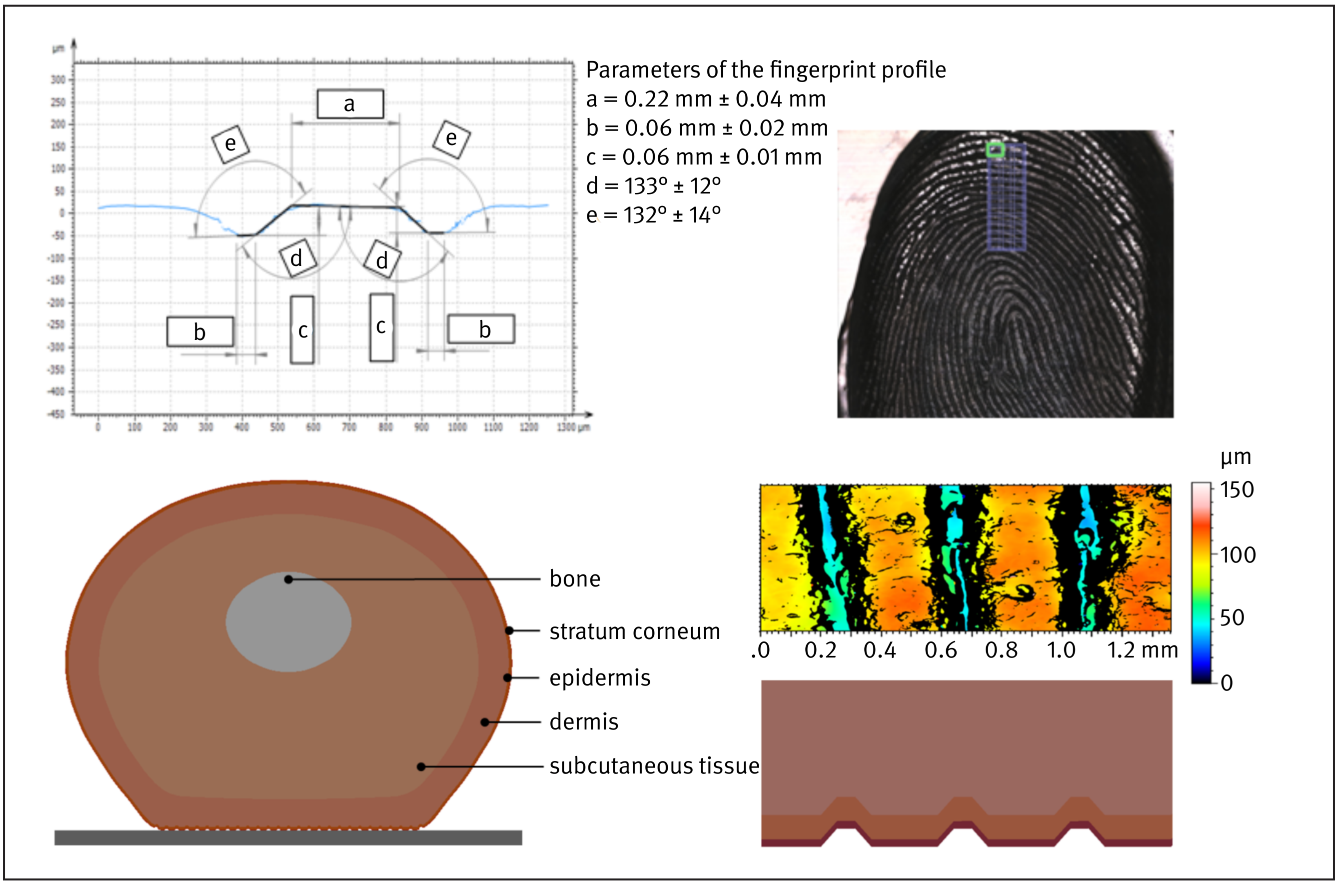
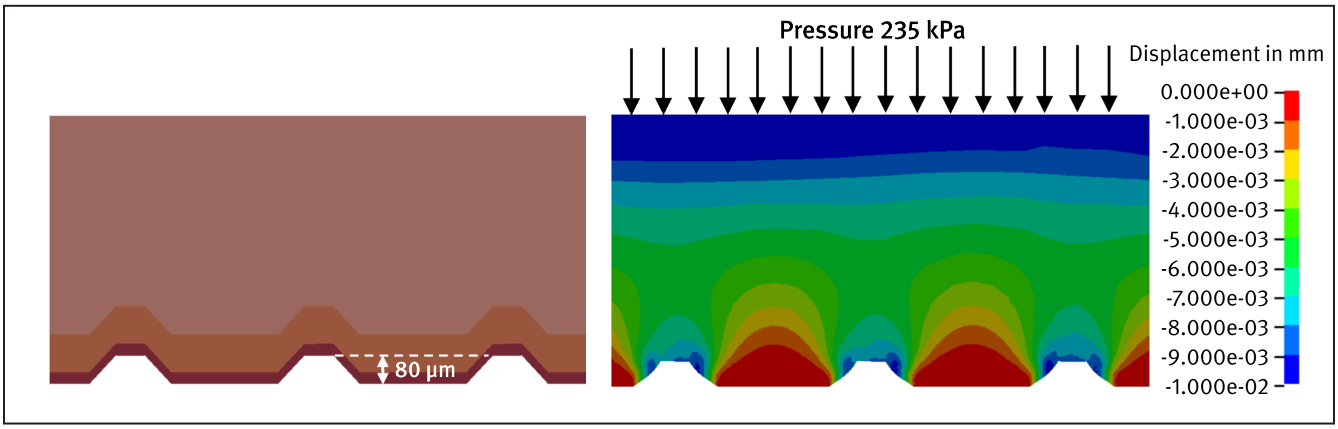


Table 1:
Material properties of the skin layers

Component	Density in g/cm³	Bulk-Modulus in MPa	Shear-Modulus in MPa	Soundspeed in m/s
Stratum Corneum	1.04	2,259.0	3.100	1,500.0
Epidermis	1.04	2,259.0	0.210	1,500.0
Dermis	1.04	2,259.0	0.080	1,500.0
Subcutaneous Tissue	1.00	2,161.0	0.034	1,470.0
Bone	1.96	20,070.0	7,719.0	3,200.0

Figure 8:
Unloaded geometry of the fingerprint (left) and numerical validation of the fingerprint distortion under constant pressure loading (right)



The volume or bulk viscosity of tissue material is hardly investigated in literature for frequencies below 1 MHz. The most comprehensive overview is published in [14] where the sound attenuation coefficient of human skin is defined to 0.35 dB/cm MHz and at least decreasing linearly towards lower frequencies. With this in mind and because of the short time period investigated the sound attenuation coefficient is disregarded in the present study and left as a topic for future research.

The metal plate acting on the fingerprint is accelerated by a single sinusoidal acceleration pulse characteristic for hand held tool vibrations with:

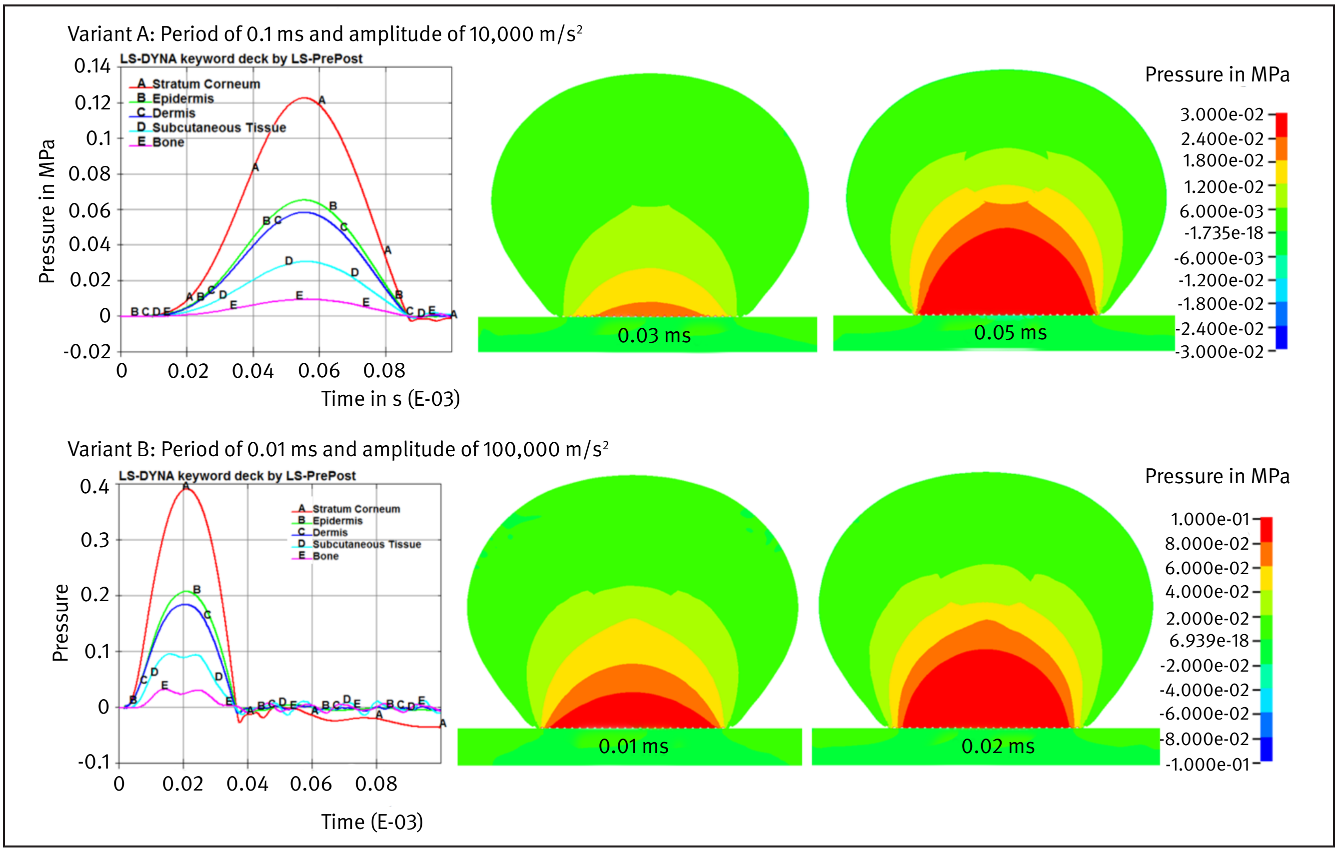
A: Period of 0.1 ms and amplitude of 10,000 m/s^2
B: Period of 0.01 ms and amplitude of 100,000 m/s^2

The pressure is evaluated in centered position throughout the height of the different skin tissue layers to capture the transient propagation and subsequent reflection of the pressure waves (Figure 9).

The numerical simulation model unveils a significant pressure level in the finger under the transient acceleration pulse. For Variant A a pressure of at least 0.6 bar is reached in the 3 outer tissue layers and for Variant B the pressure level is increased to more than 2 bar in the outer three tissue layers. However, there is still further experimental research necessary to experimentally verify the viscoelastic material response of the different skin layers as publications over viscoelastic tissue material properties are differing considerably.

Investigations in [15; 16] on strain rate behavior of skin material revealed that elastic properties can increase significantly for strain rates in the same range as seen in the current simulation. Furthermore in literature studies [17] a strong dependence of water content on elastic skin properties is found.

Figure 9:
Pressure distribution after load initiation and corresponding pressure propagation in the different finger sections for Variants A and B



4 Transient vibrations and effect on biological material

In order to investigate if transient vibrations have any effect on biological material there have been studies on exposing red blood cells *in vitro* and also rat tail *in vivo* to transient vibrations. Results from three studies are presented in this chapter as examples on findings where transient vibrations have shown to cause severe damages to biological material. It has not the intention to be a comprehensive review and there are substantially more publication available in this field.

4.1 Study 1: Transient vibration from impact wrenches: Vibration negative effect on blood cells and standards for measurement

The first study [4] was published in 1998 where cow blood was placed in containers on the handles of an impact wrench and on a straight grinder (Figure 10). There was also a container on the socket of the impact wrench.

What was found (Table 2) was that there was a four times higher degree of damaged red blood cells on the impact wrench handle than on the grinder handle in despite of that the ISO 5349 vibration on the impact wrench handle was three times lower. And even more, since ISO 5349 estimates the risk by taking the weighted acceleration in square the associated risk should have been 9 times higher on the grinder handle then on the impact wrench handle.

On the impact wrench socket there was a complete destruction of red blood cells.

These results clearly indicate that ISO 5349 weighted acceleration do not correlate to the amount of damaged red blood cells. Instead is the peak acceleration a much better indicator of the damages.

Figure 10:
Blood container on impact wrench socket, handle and grinder handle

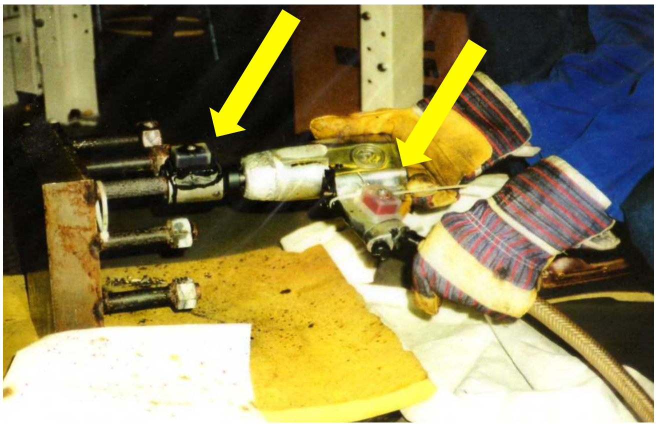


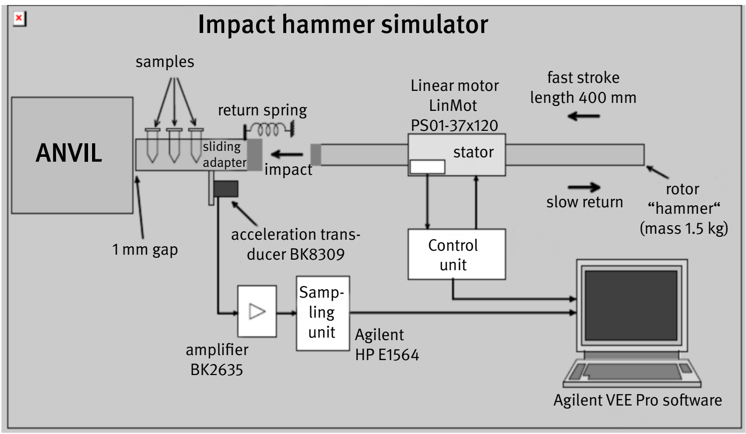
Table 2:
Results of damaged red blood cells after 15 min exposure

Test case	Peak vibration amplitude in m/s²	Measured ISO 5349 vibration in m/s²	Lysis (%) after 15 min exposure
Impact wrench handle	15,000	2.2	0,4
Impact wrench socket	›30,000	10	100
Grinder handle while grinding	1,000	7.1	0.1

4.2 Study 2: Effect of impulsive vibration on red blood cells in vitro

The second study [5] was published in 2005 where red blood cells were subjected to transient vibrations in a test rig (Figure 11). The result was similar to the first study and it was shown that red blood cells were damaged by the transient vibrations and that the degree was depending on the acceleration level and exposure time (Figure 12).

Figure 11:
Test setup for red blood cells



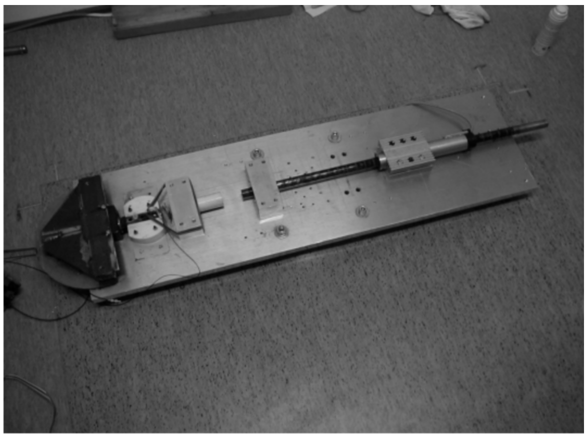
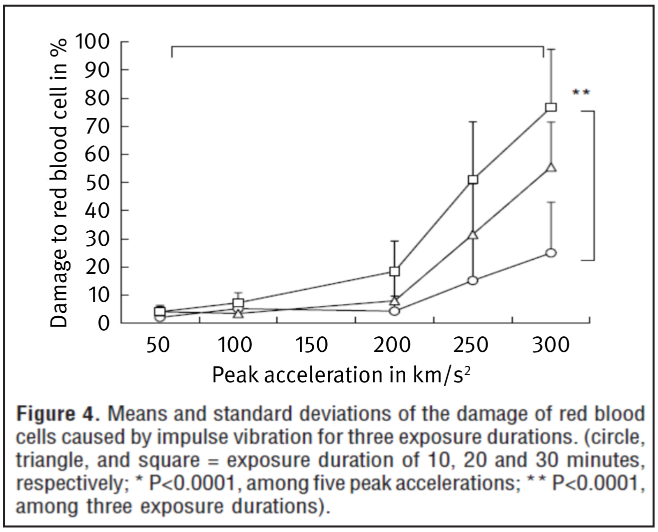


Figure 12:
Degree of damaged red blood cells from vibration



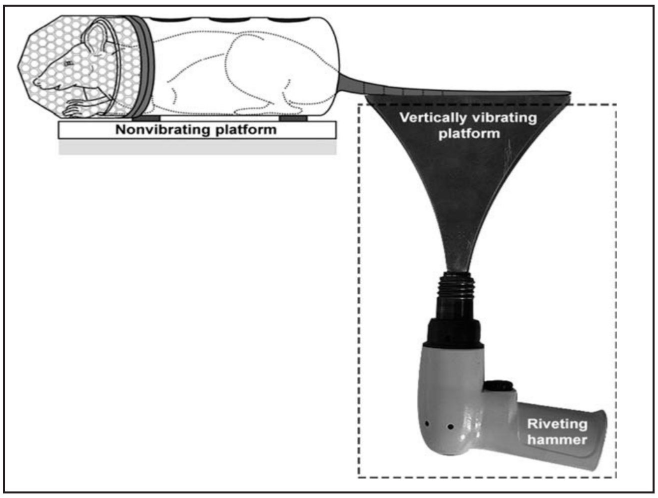
4.3 Study 3: Vibration from a riveting hammer causes severe nerve damage in the rat tail model

This study [3] is made on a rat tail model *in vivo* were the rat tail was exposed to transient vibration from a dedicated test rig with the intention to have the same vibration level as a bucking bar (Figure 13). Recent measurements made on the test rig after publishing the article gave that the ISO 5349 vibration was 9 m/s^2 and the peak acceleration is in the region of 100,000 m/s^2 measured up to 50 kHz. This is a vibration that is similar to what is found on bucking bars, impact wrench sockets and chisels.

The tails were exposed to vibration for 12 minutes per day during 4 days and produced immediate damage to nerve endings in the skin, mast cell degranulation and hypersensitivity to thermal stimulation.

The result from the study is summarized in: "*Shock-wave vibration causes severe nerve damage. Frequency weighting seriously underestimates the risk of nerve injury with impact tools.*"

Figure 13:
Test rig for rat tail



5 Transient vibrations and HAVS prevalence

There are several studies emphasizing the increased risk for HAVS from machines with transient vibrations. Here will two of them be closer examined.

5.1 Vibration from riveting tools in the frequency range 6 Hz to 10 MHz and Raynaud's phenomenon

The first study [2] from 1986 is a study of the prevalence of Raynaud's phenomenon, which is finger blanching and part of HAVS, among worker in the aircraft industry in Sweden. In this industry the main tools used were riveting hammers and bucking bars (Figure 14) for assembling the aircraft structures. Fastening a rivet takes only a second, thus the daily exposure time becomes low but measuring the acceleration on these machines reveals very high acceleration peaks in the region of 100,000 m/s^2.

The cohort was 288 riveters with more than 10 year of work exposure. The average exposure time was 1 minute/day and the ISO 5349 vibration level were 10 m/s^2 for the rivet hammer and 11 m/s^2 for the bucking bar.

According to the ISO 5349 risk estimation there would be very little risk for HAVS but the result was that there was a 50% prevalence of Raynaud's phenomenon.

The conclusion is that ISO 5349 cannot accurately estimate the risk related to these machines.

5.2 Hand-arm vibration syndrome in Swedish car mechanics

The second study [1] on HAVS prevalence was made in 2003 on car mechanics in Sweden. The main tool used were impact wrenches with an ISO 5349 weighted acceleration of 3,5 m/s^2 but with high transient vibrations. The average exposure time were only 10 minutes but the prevalence of neurological symptoms according to the Stockholm Workshop scale varied from 8 to 55% depending on years of work exposure which is by far more than what ISO 5349 would predict (Figure 15).

The conclusion is that ISO 5349 underestimate the risk from tools with transient vibrations.

Figure 14:
Riveting hammer (left) and bucking bar (right) and corresponding accelerations

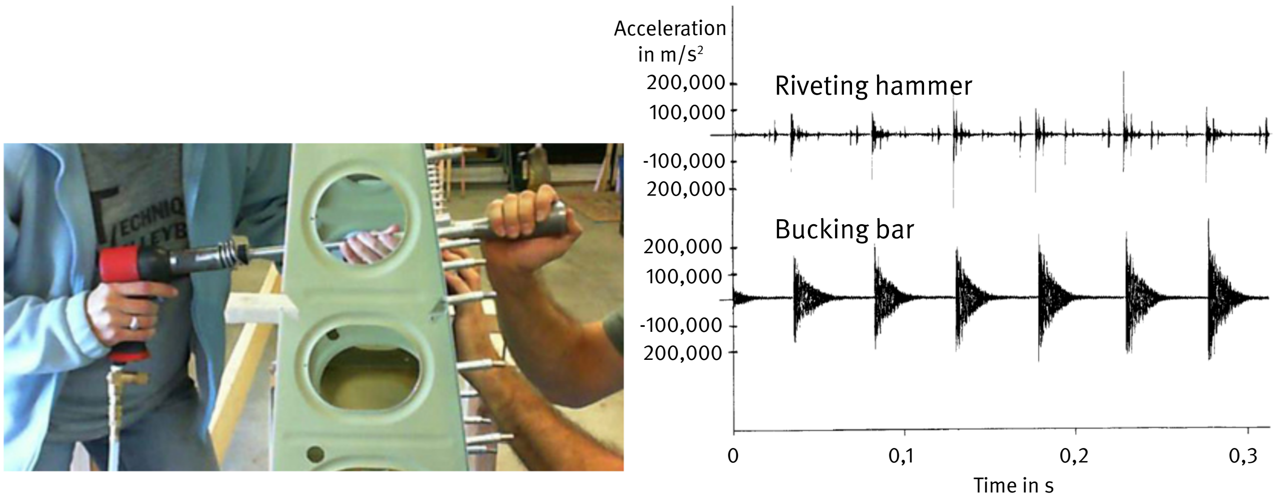


Figure 15:
Prevalence on neurological symptoms

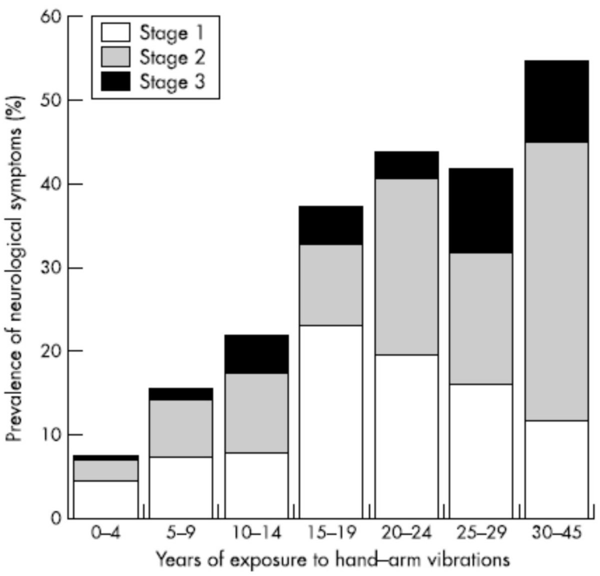


Figure 5 Prevalence of neurological symptoms in different stages according to the Stockholm Workshop scale,[7] in 801 car mechanics, as function of exposure time (in years, information lacking in five mechanics) to hand-arm vibrations. The total number of workers with symptoms and/or signs at the clinical examination was 184, including 20 workers with other conditions that could have contributed to the symptoms (see "Results").

6 Preventive measures to reduce transient vibration

If it can be considered to be an increased risk for vibration injuries when humans are subjected to transient vibrations is it then a possibility to reduce these vibrations? The answer to this question is absolutely yes. The technical possibility to reduce high frequency vibrations is very good especially if this is done at the design stage of the machine.

Below are two examples on preventive measures described closer where large reductions on peak accelerations have been accomplished.

6.1 Modified anvil used in an assembly line

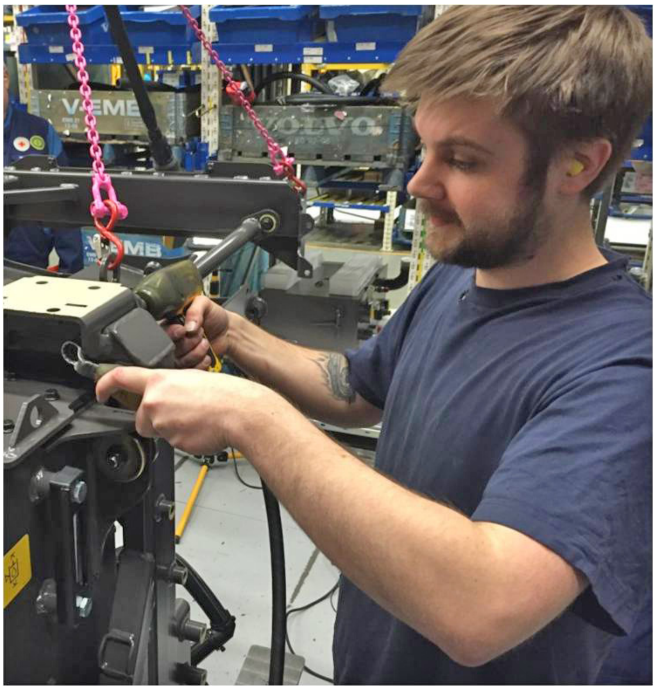
In the assembly line for heavy vehicles, impact wrenches are frequently found where they are used to tighten screw joints (Figure 16) and there is 33% prevalence of HAVS according to internal health reports.

The nuts used are often purposely deformed to avoid loosening when subjected to vibrations. This means that there is a fairly high torque needed to tighten the joint. The tightening of the joint is made by an impact wrench and an anvil holding the nut. The anvil used was an ordinary wrench.

The measured vibrations on the original anvil showed an ISO 5349 vibration of 13 m/s^2 and peak accelerations up to 8,000 m/s^2 (Figure 17).

By designing an anvil with an internal vibration isolation layer (Figure 18) the ISO 5349 vibration was reduced to 6 m/s^2 and the peak acceleration to 150 m/s^2.

Figure 16:
Tightening of screw joints with impact wrench and anvil



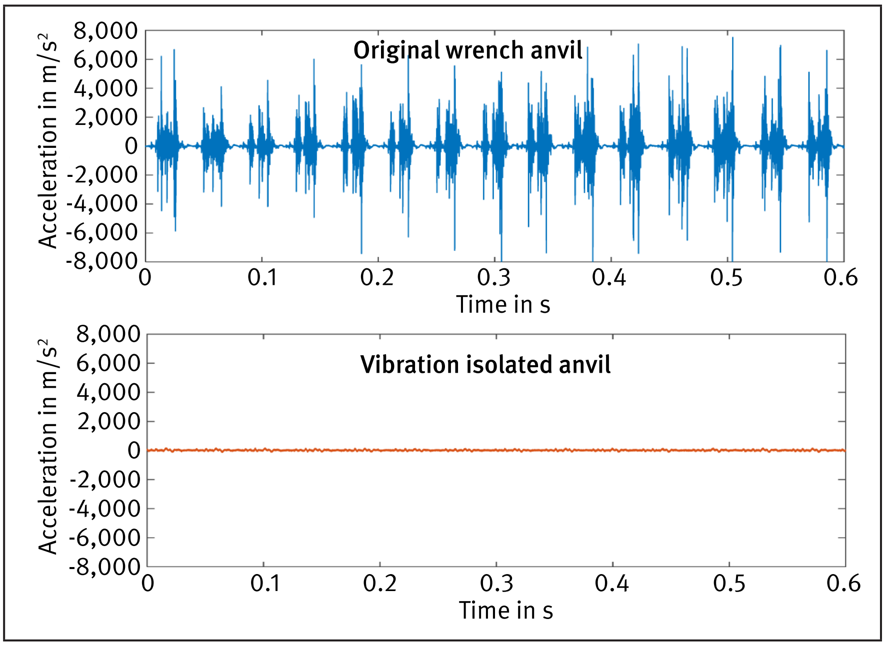


Figure 17:
Vibration on original wrench anvil (top) and vibration isolated (below)

Figure 18:
Vibration isolated anvil

6.2 Modified impact wrench for repair

Impact wrenches are frequently found in car repair shops and is the main vibrating tool used among mechanics. The exposure time is short since it takes typically less than a second to tighten or loosen a nut. The ISO 5349 vibrations are in the region of 5 m/s^2 but they all show very high transient vibrations.

The modified machine (Figure 19) has a redesigned main bearing. It has been equipped with a vibration isolated layer which prevents both the impacts between the socket and the screw and the internal flywheel and clutch to directly be transmitted to the casing of the machine.

By this limited modification the peak acceleration could be reduced from 7,000 m/s² to 800 m/s² (Figure 20) and still maintaining the same efficiency. The ISO 5349 vibrations did not alter and remained at 4,5 m/s². All vibrations were directly on the aluminum handle.

Figure 19:
Vibration reduced impact wrench

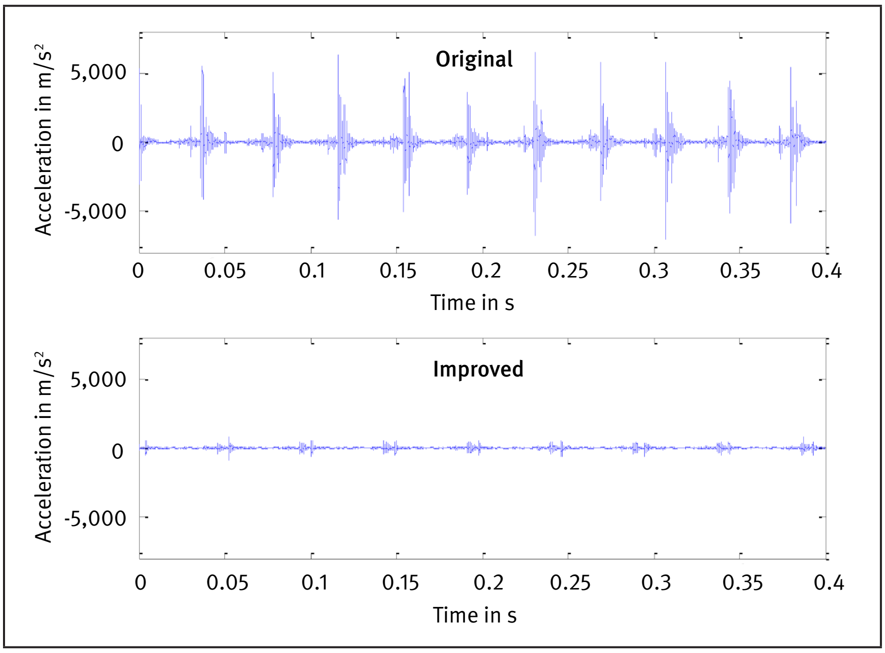


Figure 20:
Vibration on original impact wrench and improved

7 Conclusion and discussion

The work in this study can be concluded in the following:

- Acceleration can be measured accurately up 50 kHz with newly developed ultra light MEMS accelerometers.
- Impact machines generate high amplitude high frequency transient accelerations.
- High frequency accelerations from impact machines are nearly eliminated by the weighting filter in ISO 5349 and thereby disclosed from risk evaluation.
- Transient vibrations from machines generate a shock wave that propagates into the finger tissue.
- The epidermis layer of the finger has a relatively small attenuation.
- There are several studies that show that ISO 5349 underestimates the risk for HAVS from transient vibrations.
- Transient vibrations can be substantially reduced by redesign of machines.
- ISO 5349 cannot be used for estimation of injuries from HFV and was never intended to which is clearly stated in the scope.
- There is a need for an amendment to ISO 5349 covering HFV to create an incentive for tool manufacturers and users to reduce the vibration levels.

An opportunity to better address the associated risk from transient vibrations is to study and learn from how neighboring disciplines handle transient, impulse stimulus. There are considerable similarities with regulation for areas such as, impulse noise, head impacts, fragile goods, material fatigue etc. What all these areas have in common is that they mainly study the effect of the stimuli in the time domain and not in the frequency domain as is the case for ISO 5349.

References

[1] *Barregård, L.; Ehrenström, L.; Marcus, K.*: Hand-am vibration syndrome in Swedish car mechanics. Occup. Environ. Med. 60 (2003), p. 287-294

[2] *Dandanell, R.; Engström, K.*: Vibration from riveting tools in the frequency range 6 Hz – 10 MHz and Raynaud's phenomenon. Scand. J. Work Environ. Health 12 (1986), p. 338-342

[3] *Govinda Raju, S.* et al.: Vibration from a riveting hammer causes severe nerve damage in the rat tail model. Muscle&Nerve 44 (2011) No. 5, p. 795-804

[4] *Lindell, H.; Lönnroth, I.; Ottertun, H.*: Transient vibration from impact wrenches: Vibration negative effect on blood cells and standards for measurement. Eighth International Conference on Hand-Arm Vibration, Umeå, Sweden 1998, June 9-12, p. 113-117

[5] *Ando, H.; Nieminen, K.; Toppila, E.; Starck, J.; Ishitake, T.*: Effect of impulsive vibration on red blood cells *in vitro*. Scand. J. Work Environ. Health 31 (2005) No. 4, p. 286-290

[6] *Rytkönen, E. A.; Sorainen, E.; Leino-Arjas, P.; Solovieva, S.*: Hand-arm vibration exposure of dentists. Int. Arch. Occup. Environ. Health 79 (2006) No. 6, p. 521-527

[7] *Vodlac, T.; Vidrih, Z.; Sustaric, P.; Rodic, T.; Wessberg, J.; Peric, D.*: Computational assessment of spiking activity during surface exploration: From finite element analysis to firing-rate. In: *Bello, F.; Kajimoto, H.; Visell, Y.* (eds).: Haptics: Perception, Devices,Control and Applications. 10th International Conference, EuroHaptics 2016, Lundon, United Kingdom, July 4-7, 2016, Proceedings Part II. Springer, 2016, p. 406-415

[8] *Geerlings, M.*: In vitro mechanical characterization of human skin layers: stratum corneum, epidermis and hypodermis, Technical University Eindhoven, The Netherlands 2006

[9] *Leyva-Mendivil, F.; Page, A.; Bressloff, N.*: A mechanistic insight into the mechanical role of the stratum corneum during stretching and compression of the skin. J. Mechan. Behav. Biomed. Mater. (2015), p. 197-219

[10] *Pal, S.*: Design of artificial human joints and organs. New York: Springer 2014

[11] *Goss, S. A.; Johnston, R. L.; Dunn, F.*: Comprehensive compilation of empirical ultrasonic properties of mammalian tissues. Bioacoustics Research Laboratory, University of Illinois, 1978

[12] *Herrman, L.; Peterson, F.*: A numerical procedure for viscoelastic stress analysis. In: Proceedings of ICRPG Mechanical behavior working group, Orlando, 1968

[13] *Krave, U.*: Modelling of diffuse brain injuries: Combining methods to study possible links between transient intracranial pressure and injury. Gothenburg: Chalmers University of Technology, 2010

[14] *Mast, T. D.*: Empirical relationships between acoustic parameters in human soft tissues. Acoust. Res. Lett. Online 1 (2000) No. 2, p. 37-42

[15] *Shergold, O.; Fleck, N.; Radford, D.*: The uniaxial stress versus strain response of pig skin and silicone rubber at low and high strain rates. Int. J. Impact Eng. 32 (2006), p. 1384-1402

[16] *Lim, J.; Hong, J.; Chen, W.; Weerasooriya, T.*: Mechanical response of pig skin under dynamic tensile loading. University of Nebraska, 2011

[17] *Geerlings, M.*: A literature review of the mechanical behavior of the stratum corneum, the living epidermis and the subcutaneous fat tissue. Philips Research Europe, The Netherlands, 2006

Health effects from exposure of the hand to mechanical shocks

Anthony J. Brammer,
Department of Medicine, University of Connecticut Health, Farmington, CT, USA, Envir-O-Health Solutions, Ottawa, ON, Canada
Gongqiang Yu,
Department of Medicine, University of Connecticut Health, Farmington, CT, USA

Abstract

While the vibration frequency spectra of power tools have been the subject of many investigations, their time histories have been less studied. Many tools produce shock waveforms that are separated in time – so called isolated mechanical shocks. The large, but transient, peak accelerations produce large dynamic stresses in tissues and may result in health effects in addition to the hand-arm vibration syndrome (HAVS) in persons exposed to mechanical shocks but the evidence is not conclusive. The onset of the vascular component of HAVS (finger blanching) seems to be adequately predicted by the method described in ISO/TR 18570:2016, with no additional allowance for exposure to mechanical shocks. The onset of suspected carpal tunnel syndrome from exposure to mechanical shocks appears to be greater than might be expected on the basis of the acceleration spectrum, but the evidence is only from one study. There is evidence of an association between work involving operation of percussive power tools and an excess prevalence of premature elbow and wrist osteoarthrosis. While there are animal data suggesting high frequencies may be involved in structural changes to nerve fibers and nerve endings, there is no evidence to support this hypothesis from either finger biopsies of workers suffering from vibration-induced white finger who have operated impact or non-impact power tools, or acute exposures to shock-like vibration. There is also no evidence that impact power tools operating with extremely low repetition rates (e.g., ~ 3/s) cause additional health effects that could be attributed to vibration exposure.

Introduction

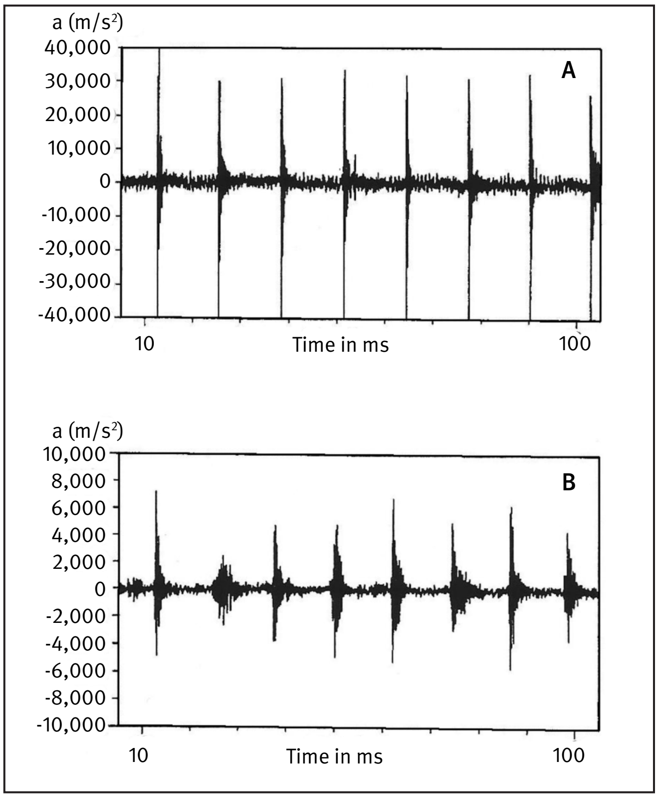
It has long been questioned whether the health effects resulting from exposure to mechanical shocks are the same as those resulting from exposure to continuous or intermittent vibration. Despite laboratory and field studies conducted for almost half a century, attempts to provide answers to this question have provided information on acute health effects but little convincing evidence of chronic health effects caused solely by shock exposure. The purpose of this contribution to the Workshop is to characterize isolated mechanical shocks, as illustrated by time histories and frequency spectra of common impact power tools, and provide a discussion of the health effects associated with exposure to repeated shocks. While it is evident that both impact and non-impact hand-held or hand-guided tools may cause common signs and symptoms of the hand-arm vibration syndrome (HAVS), distinguishing the role of vibration from that of the musculoskeletal consequences of heavy manual work remains largely unresolved.

Mechanical Shocks

A mechanical shock is a non-periodic motion of a mechanical system characterized by suddenness and severity, with the maximum forces and displacements being reached typically in milliseconds and a total duration of less than 100 ms. An isolated mechanical shock is one with a time history such that its motion decays to zero before another shock occurs. Shocks are commonly created in power tools by rapidly expanding gases, such as compressed air in a pneumatic tool or combustion gases in an internal-combustion engine powered tool, or by electro-dynamic forces. The forces accelerate objects, commonly pistons, to impact on work pieces, which excite modes of vibration of the coupled system in addition to the initial shock that may propagate as a wave within the structure. Impacts are also produced when a rotating part collides with another object or the work piece. Holding or guiding such a power tool by the hand is likely to exposure it to large amplitude accelerations. In most occupations the wearing of gloves will attenuate the highest frequencies, though there are occupations, such as those involving performing fine work, in which it may not always be possible to wear gloves (e.g., stone carving).

The vibrations of the chisel and barrel of a pneumatic hammer when used by stone workers to carve granite are shown in Figure 1 [1].

Figure 1:
Acceleration-time history of the vibration in the direction of the percussion axis of the chisel (A) and barrel (B) of a pneumatic hammer used by stone carvers, repetition rate 83/s (from [1])



The time histories were obtained using miniature piezoelectric accelerometers and mechanical filters to reduce the risk of overloading the measurement system or introducing nonlinearities (e.g., "DC shifts"). The waveforms were recorded with a bandwidth extending from 2 Hz to 10 kHz, and show that the motions of the chisel and barrel consist of isolated mechanical shocks. The repetition rate of the shocks is 83/s. The motion of the chisel consists of large amplitude shocks (with peak accelerations of ~30,000 $m \cdot s^{-2}$), each of duration approximately 1 to 2 ms (panel A). The motion of the barrel consists of shocks almost one-tenth the amplitude of those of the chisel and of longer duration (panel B), suggesting that the reaction forces are exciting motions in various structures that together form the body of the hammer. Examples of the handle vibration of three generations of chain saws, obtained using the same apparatus, are shown in Figure 2 [1].

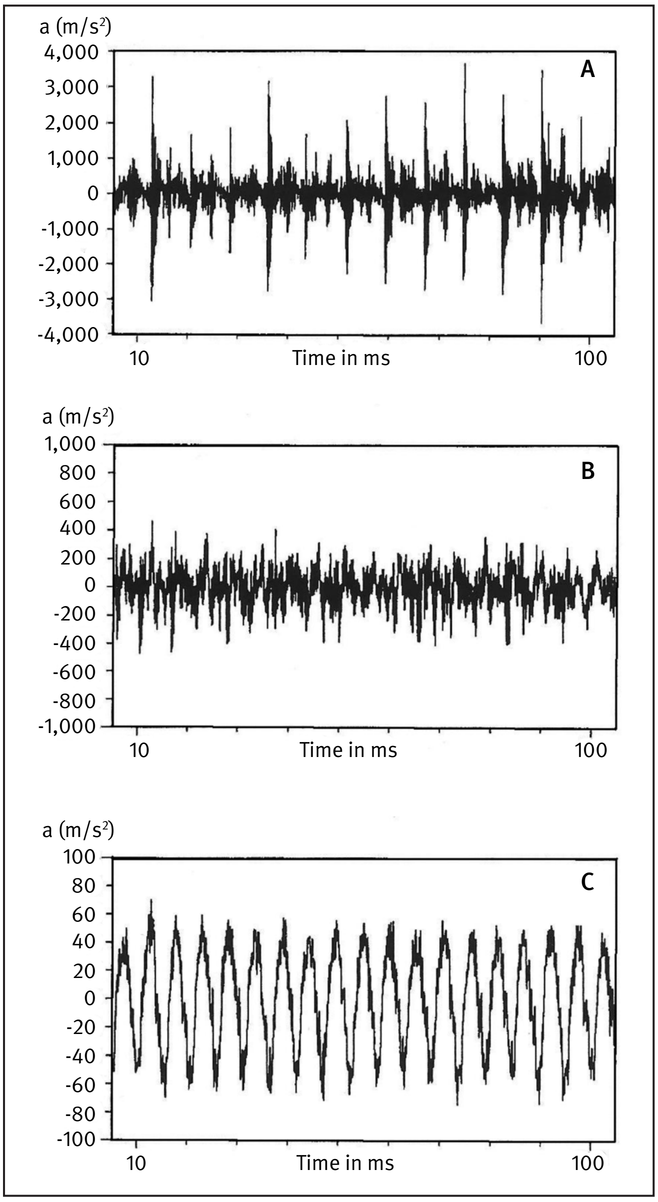


Figure 2:
Acceleration-time history of the front handle vibration of three generations of chain saws in the direction of the 3rd metacarpal. A: saw with rigidly attached handles, repetition rate 77/s ; B: saw with first generation handle vibration isolation, repetition rate 150/s; C: saw with second generation handle vibration isolation, repetition rate 160/s (from [1]

The measurements were performed when the saws were cross-cutting logs mounted horizontally. The handles of the oldest saw were rigidly attached to the body of the saw that contained the two-stroke internal-combustion engine (panel A). The waveform appears to consist of at least two, and perhaps three, motions – large amplitude, short-duration shocks of varying magnitudes, and a comparatively low magnitude near-continuous vibration (i.e., <500 $m \cdot s^{-2}$ peak accelerations) on which is superimposed almost regular amplitude modulations. The mechanical shocks at the handle are now not separated in time but part of a continuing motion.

The more recent generations of chain saws, both of which possess some form of vibration-isolation for one or both handles (Figure 2, panels B and C, respectively), display little or no shock behavior (panel C). In the latter case, the handle vibration waveform is almost sinusoidal, suggesting the combustion forces are being almost totally absorbed by the isolation system, providing an example of the potential effectiveness of tool redesign.

The vibration frequency spectra recorded at the handles of impact and non-impact power tools are markedly different. Examples are shown in Figure 3 for the one-third octave-band component accelerations recorded at the handle of a typical pneumatic rock drill in the direction of impacts (i.e., along the percussion axis) when drilling into granite (circles), and at the handle of a chain saw with vibration-isolated handles when cross-cutting wood (triangles) [2].

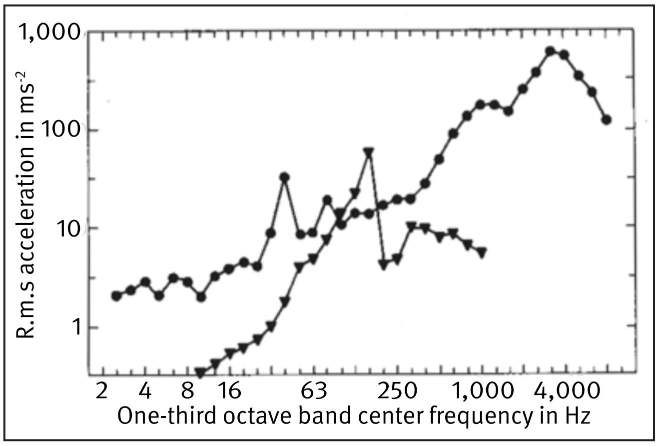


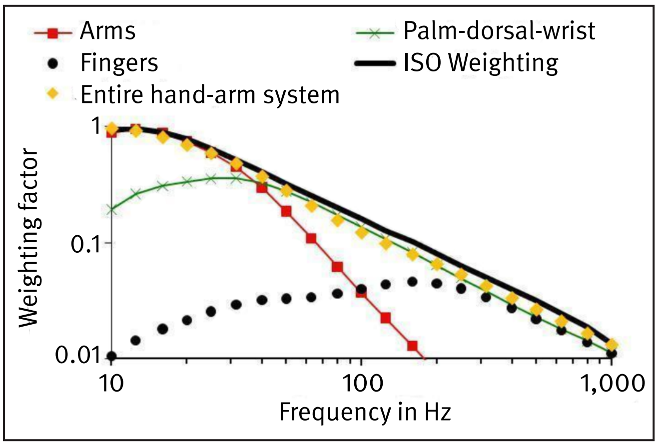
Figure 3:
Mean, one-third octave-band handle accelerations of a rock drill in the direction of the percussion axis (circles) and chain saw in a direction specified in ISO 7505:1986 (triangles) (from [2])

The spectrum of the non-impact power tool (chain saw) displays a large peak in the band with center frequency of 160 Hz, which corresponds to the engine firing frequency, and is typical of saws with vibration-isolated handles. The waveform of such saws is shown in Figure 2C. The spectrum of the impact power tool (rock drill) displays a peak at the repetition frequency (38 Hz) and, in contrast to the non-impact power tool, increasing acceleration with frequency up to the maximum measured (10 kHz). The waveform consists of isolated shocks similar to those shown in Figure 1B but more consistent in magnitude, with duration of ~5 ms [2].

Hand-Arm Vibration Syndrome

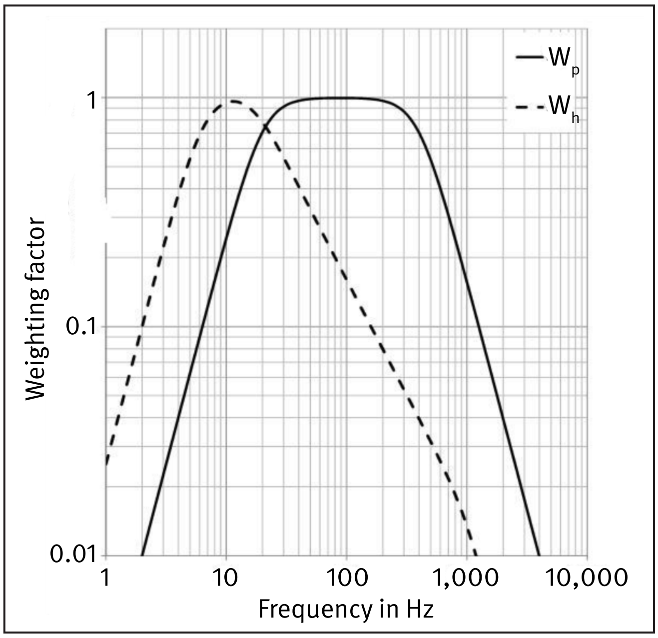
The hazard of developing symptoms of the HAVS involves assessing the contribution of vibration at different frequencies. The distribution of injuries to be expected from exposure to vibration at different frequencies is informed by the predictions of a lumped parameter model of the hand-arm system [3]. The relative frequency weightings to be applied to the major substructures of the model were predicted from the magnitude and frequency of vibratory power absorbed in the hand-arm system. Consistent with measurements of transmissibility, vibration at frequencies below about 40 Hz is transmitted to, and absorbed within, the arms and upper torso, while much of the vibration at higher frequencies is absorbed in the hand and wrist (Figure 4). Vibration at frequencies throughout the range shown in Figure 4 is predicted to be absorbed within the fingers, with the majority of energy being absorbed at frequencies between about 25 and 500 Hz. It should be noted that while the model‘s identification of substructures in which energy is absorbed is informative, it does not identify the precise sites or nature of biological effects.

Figure 4:
Relative frequency weightings for major substructures of the lumped parameter model of the hand-arm system. Also shown is the frequency weighting in ISO 5349-1:2001 (from [3])



Procedures for measuring and evaluating vibration transmitted to the hands from a power tool or surface in contact with the hands are described in two international standards, ISO 5349-1:2001 and ISO 5349-2:2001 [4; 5]. In addition to recommending measurement procedures applicable in the field, the standard describes the common neurological, vascular and musculoskeletal signs and symptoms of HAVS, e.g., finger numbness and blanching, tingling and pain in the hands, muscular weakness, and reduced hand grip (for a more complete description of signs and symptoms, see [6]). A primary consideration is to specify vibration magnitudes at different frequencies that are believed to possess equal hazard of causing one or more symptoms of HAVS. The ISO standard addresses this issue by adjusting the relative magnitudes of vibration at different frequencies prior to their assessment by means of a frequency weighting that is assumed to represent the risk of causing injury to the hand. The weighting factors are shown by the dashed line in Figure 5 (W_h), and are taken to apply to all magnitudes and directions of vibration entering the hands. Reference to Figure 4 reveals that a frequency weighting derived from a model of the total vibratory power absorbed in the hand-arm system, shown by the black line (labeled „ISO Weighting“), is predicted to be compatible with W_h at frequencies above 10 Hz.

Figure 5:
Frequency weighting in ISO 5349-1:2001 (W_h: dashed line), and alternate frequency weighting for assessing the risk of vascular injury in ISO/TR 15870:2016 (W_p: solid line) (from [7])



ISO 5349-1:2001 [4] also provides a method for predicting the occurrence of a common health effect – the prevalence of episodic finger blanching. Several studies conducted since publication of the original version of the standard in 1986 have reported discrepancies between the predicted occurrence of finger blanching and the observed occurrence in population groups occupationally exposed to vibration (see, for example, [8]). While it is unrealistic to expect the simplistic ISO procedure for estimating the occurrence of finger blanching in a vibration-exposed population to provide accurate predictions for all exposure conditions, several studies have suggested that an improvement may result from revising the frequency weighting currently employed by ISO 5349-1:2001 [9 to 13].

An alternative method for estimating the onset of episodic finger blanching, which employs a different frequency weighting, has recently been proposed in an ISO technical report [7]). The weighting factors are shown by the solid line in Figure 5 (W_p), and, again, are taken to apply to all magnitudes and directions of vibration entering the hands.

By comparing the weighting factors for W_h and W_p, it is evident that W_p affords much greater weight to frequencies above 20 Hz. The relative importance of the hazard to the hands of frequencies between 20 and 400 Hz has been documented in working populations using non-impact and impact power tools [10; 13], and is predicted from vibratory energy entering the hand-arm system [3]. The technical report adopts a cautious approach to predicting the occurrence of white fingers, merely suggesting a daily exposure limit above which episodic finger blanching may be expected to occur. The limit is described by a range of daily exposures in which lower values are believed applicable to dominant single-axis accelerations (such as those shown for the rock drill and chain saw in Figure 3), and values closer to the upper limit of the range are believed applicable to daily exposures constructed from the vector sum of component accelerations entering the hand.

Examples of the application of the method in the technical report to the prediction of the hazard of developing white fingers in power tools producing shocks are given in the Table.

The Table lists the shock type and repetition rate, and whether episodic finger blanching was reported in the study cited as well as whether it is predicted to occur from the daily vibration exposure estimated according to ISO/TR 18570:2016 [7]. For these data, the threshold for the occurrence of finger blanching is that for the dominant component acceleration entering the hands (1,150 m · $s^{-1.5}$), such as along the percussion axis for the rock drill (see Figure 3).

Table:
Occurrence of episodic finger blanching in some power tools producing shocks

Study	Shock type	Repetition rate in s^{-1}	Finger blanching observed?	Prediction of occurence of finger blanching (ISO/TR 18570:2016)	
				Exposure in m · $s^{-1.5}$)	White fingers predicted?
Chain saw (Taylor et al. [14])	Shock and continuous	~110	Yes	20,000[1]	Yes
Rock drill (Pelmear et al. [15; 16] and Keith and Bramme [2])	Isolated shocks	35 to 40	Yes	7,000[1]	Yes
Rivet gun/Bucking bar[2] (Engstrom et al. [17] and Dandanell et al. [18])	Isolated shocks	20 to 25	Yes	1,350[1]	Yes
Pavement Breaker (Walker et al. [19]and Tasker [20])	Isolated shocks	~20	Yes	2,300[1]	Yes
Nail/Staple Gun[3] (Louda et al. [21])	Isolated shocks	≤3	No	250 to 1,260[1]	Possibly

1 Suggested threshold for onset of finger blanching (single axis acceleration) - 1,150 m · $s^{-1.5}$
2 Other power tools used by riveters not included in exposure estimate
3 Workers also used a non-powered hand tool (hammer) not included in exposure estimate

All tools in the table, with the exception of the chain saw, are pneumatically powered. They are listed by repetition rate, with the highest rate being for chain saws with handles rigidly attached to the body of the saw [14]. The time history of the accelerations at the handles of the chain saws used in this study will be similar in form to that in Figure 2A, and may be described as shocks in near-continuous vibration. All the other power tools listed in the Table are believed to produce isolated shocks, as illustrated by the examples in Figure 1. With the exception of the nail/staple gun, all the tools are observed and predicted to lead to episodic finger blanching based on the estimated daily exposure.

The nail/staple gun possesses the lowest repetition rate of the tools. It is controlled by the operator and therefore job specific, and is usually less than 3 shocks per second [21]. There were no cases of finger blanching reported in the study by *Louda* et al. [21], but more than 20% of the workers were diagnosed with carpal tunnel syndrome (CTS), and there was one case of the neurological component of HAVS (4%). The authors provided two measures of the time the workers used the power tool: the first was constructed from the number of nails or staples inserted per work shift, which was estimated to be 60 to 90 s, and the second was the time the workers held the power tool during a work shift, which was estimated to be about 30 minutes. These two values have been used to construct the exposure range for the nail/staple gun in Table 1. It is evident that the lower extreme of the range predicts that the vascular component of HAVS will not occur, while the upper extreme of the range predicts that episodic finger blanching will be reported. It should be noted that the work also involved the use of a second, non-powered impact hand tool (hammer). Hammers can produce large amplitude shocks [22], which have not been included in the exposure estimate as no acceleration or exposure data were included in the original study. Thus, while the daily exposures estimated from the study by *Louda* et al. [21] straddle the boundary of 1,150 m· $s^{-1.5}$ for the onset of finger blanching, they probably underestimate the total exposure. It should be noted that the vascular component of HAVS has been reported in individual users of nail guns referred to a laboratory for confirmation of the diagnosis [23]. In summary, as the method described in ISO/TR 18570:2016 [7] is believed applicable to exposures not containing shocks, it would appear from the results in the Table that no additional allowance for exposure to mechanical shocks is needed for estimating the hazard of developing finger blanching.

In an informative series of papers, Bovenzi and co-workers have compared the development of signs and symptoms of HAVS in a longitudinal study of two population groups [9; 24 to 27]. The workers in one group operated power tools producing continuous vibration (chain saws and brush saws), and in the other operated power tools producing vibration containing mechanical shocks (stone hammers and grinders). It is instructive to compare the onset of signs and symptoms in the two groups, even though the group exposed to shocks also used a power tool that may have produced continuous vibration (grinders). The ratio of the median daily exposures of the two groups (impact group/non-impact group) ranged from approximately 2 to 4, depending on whether it was calculated according to ISO 5349-1:2001 [4] or ISO/TR 18570:2016 [7], with the workers operating stone hammers and grinders experiencing more daily exposure. The cumulative incidence of finger blanching during the three years of the study was 14.3% for the group using the impact tools when diagnosed by medical history, and 20% when diagnosed in addition by an objective vascular test, and 4.3% for the group using non-impact tools [24], which is consistent with the rate of development of finger blanching to be expected from the difference in the exposure rate. However, the cumulative incidence of tingling and musculoskeletal disorders of the neck, shoulder and elbow did not differ significantly between the two groups, suggesting that these symptoms may be more associated with the nature of the manual work rather than vibration exposure [26; 27]. A similar conclusion may be reached for hand grip strength, which also did not differ between the two groups.

The cumulative incidence of numbness was elevated in the group using impact tools compared to that of the group using non-impact tools by almost 40% but the difference did not reach statistical significance [26]. In contrast, a psychophysical test of sensory perception revealed that the workers using impact tools possessed much less sensitive touch than the workers using non-impact tools. Similarly, the cumulative incidence of suspected CTS was significantly greater in the workers using impact tools (22.6%) compared to those using non-impact tools (2.6%). In addition, an increased cumulative incidence of musculoskeletal symptoms in the wrist and hand was also found in the group using impact tools compared to the group using non-impact tools [27].

Health Effects from Exposure to Mechanical Shocks

Mechanical shocks differ from continuous vibration both in the time domain (e.g., Figure 1 versus Figure 2C) and frequency domain (e.g., Figure 3). The major difference between the time histories will be the magnitudes of the peak accelerations, which will generate instantaneous stresses within tissues that may exceed those produced by continuous vibration by several orders of magnitude. Peak accelerations measured at the handles of impact power tools can exceed 10,000 $m \cdot s^{-2}$, while those at the handles of non-impact tools may be no more than 100 $m \cdot s^{-2}$. While it may be anticipated that large dynamic displacements and stresses will produce tissue and joint responses that will differ from those produced by non-impact tools, there is at present no direct method for predicting the differences in health effects.

There is little direct epidemiological evidence linking the large dynamic stresses to health effects in addition to those already described. It has been suggested that vibration exposure can lead to hypothenar hammer syndrome (HHS), which is a vascular condition caused by occlusion of one or more arteries in the hand usually attributed to using the palm of the hand as a "hammer" [28; 29]. In most reports the workers are described simply as exposed to hand-transmitted vibration. However, in a case study of three workers occupationally exposed to vibration who were suffering from HHS, two operated impact power tools while the third used his hand as a hammer [30]. While the evidence is far from conclusive, there may be reason to suspect HHS in addition to HAVS in persons exposed to mechanical shocks.

If the phase relationships between the frequency components of the waveforms are ignored, the shocks can be evaluated from the magnitudes of accelerations in the frequency domain. The major differences between the profiles of impact and non-impact power tools' acceleration spectra occur at "low" and "high" frequencies. This can be seen from the examples in Figure 3, where the "low" frequencies are taken to be below approximately 80 Hz, and the "high" frequencies are taken to be above approximately 250 Hz. Reference to Figure 4 suggests that vibratory power will be absorbed effectively in the palm and wrist at frequencies from about 10 to 80 Hz, and in the arms at frequencies below about 40 Hz.

An ideal power tool that produces repetitive shocks at a rate determined by the engine (as opposed to the operator) will generate impacts at a constant rate when under constant load. Under these conditions the lowest component in the frequency spectrum will be at the repetition rate. Inspection of the rock drill handle spectrum in Figure 3 shows that this is indeed the case, with the lowest acceleration peak occurring in the one-third octave band centered at 40 Hz[1]. In such circumstances there will not be significant shock energy transmitted to the hands at frequencies below the repetition rate of the tool. Thus, the repetition rate of the shocks becomes the determinant of the lowest frequency coupled into the hand-arm system. In the case of the rock drill this include the "low" frequencies as defined above, which suggests substantial amounts of energy will be transmitted into the wrist and up the arms. Tools involving processes that result in varying repetition rates will contain frequencies that extend to the minimum repetition rate. Tools that operate at rates determined by the operator (e.g., nail guns) are not subject to this frequency cutoff and so may contain substantial spectral components at very low frequencies (e.g., 3 Hz).

It is tempting to attribute the increased cumulative incidence of musculoskeletal symptoms in the hand and wrist and suspected CTS found by *Bovenzi* and co-workers in the group operating impact power tools compared to the group operating non-impact tools to the accelerations observed. The maximum component one-third octave-band accelerations recorded at the handle of the stone hammer exceeded that of the chain saw at frequencies between 10 and 80 Hz by a factor of close to 5 (bands at 63 and 80 Hz of Figures 2 and 3 in [9]. CTS has been confirmed in workers using rock drills with acceleration spectra similar to that in Figure 3 in [31], which can also be seen to possess large components at frequencies between 10 and 80 Hz. However, it has proved difficult to differentiate clinically between CTS, which arises from medial nerve compression at the wrist, and a neuropathy occurring more distally in the fingers, which is considered the

1 N.B. Any fluctuations in the repetition rate in this case are within the frequency range of the 40 Hz one-third octave band.

more common site for a vibration-induced neuropathology [32]. There have been many studies of associations between CTS and vibration, hand force, task repetition, and wrist posture without discriminating whether the exposure involved impact or non-impact power tools. The most recent meta-analysis suggests that of the factors commonly considered to cause cumulative trauma disorders and listed above [6], exposure to vibration was associated with the greatest increase in the risk of developing CTS (odds ratio 2.26, 95% confidence interval 1.73-2.94) [33]. Thus, while it appears that vibration exposure is associated with increased risk of developing CTS, there is only one study that differentiates between the risk posed by impact versus non-impact tools and finds the risk is substantially greater for power tools that produce mechanical shocks.

As already noted, vibratory energy at frequencies less than about 40 Hz may be transmitted to, and absorbed within, the arm and upper torso. There is evidence of an association between work involving operation of percussive hand-held pneumatic tools and an excess prevalence of premature elbow and wrist osteoarthrosis [34]. The excess risk is also related to the joint loading accompanying manipulating the power tool (i.e., heavy manual work) and repetitive movements of the hands and arms. Both loading the joint surfaces in extreme or awkward postures as well as exposure to mechanical shocks are believed necessary to precipitate the bone and joint symptoms observed.

Bovenzi and co-workers‘ comparative longitudinal study of population groups operating either a non-impact power tool or (mostly) an impact power tool also considered the effects of exposure to high frequencies (here taken to be frequencies above about 250 Hz). They employed statistical models to derive relationships between the development of selected signs or symptoms of HAVS and different measures of vibration exposure. The assessment of tool acceleration involved different frequency weightings: W_h (see Figure 5), two weightings similar to W_p in Figure 5, or W_{h-bl}, an unweighted acceleration with “flat” frequency response and bandwidth from 6.3 Hz to 1.25 kHz [25]. The influence of high frequencies on the onset of a selected sign or symptom can be deduced from the relative performance of the models employing different frequency weightings. When modeling the incidence of finger blanching, there was a small preference for constructing exposures using W_{h-bl}, that is, including all high frequencies with a flat response up to 1.25 kHz, followed by the two frequency weightings that approximated W_p. This conclusion was not confirmed in a subsequent analysis that found W_p to be a better predictor for the onset of finger blanching [10]. The results in the Table would appear to support using W_p and, as already remarked, no additional allowance for exposure to mechanical shocks, such as increasing the contributions to exposure from frequencies above 400 Hz, is believed necessary to estimate the hazard of developing finger blanching.

Bovenzi and co-workers analyses of the two population groups revealed significant relationships between the four measures of vibration exposure and the development of neurosensory disorders [26], but the data unfortunately did not permit selection of one frequency weighting over another, leaving unresolved the question of the role of different frequencies, and in the present context high frequencies, in the development of this component of HAVS.

The potential role of high frequencies in the pathogenesis of peripheral neurosensory disorders has been suggested by the results of an animal model. *Raju* and co-workers exposed the restrained tails of awake, caged rats to the impact vibration of a riveting hammer, which produced shocks at a repetition rate of 33/s [35]. A single 12 minute exposure was found to cause structural changes in the nerves, consisting of fragmentation of terminal nerve fibers immediately after the exposure and disruption of the myelin sheath several days later. There is little doubt that the riveting hammer contained substantial vibration at frequencies extending to well above 10 kHz [18], though the role of different frequencies in the pathology is unclear. Similar disruption involving demyelination and loss of nerve fibers has been observed in finger biopsies of workers using chain saws or pneumatic hammers who suffered from vibration-induced white finger [36], and in rock drillers, riveters, and operators of road breakers [37]. However, no distinction was made between the pathological changes observed in users of the different tools in either study, again leaving unanswered the role of high frequencies in the pathogenesis of the neurosensory disorders.

The potential hazard of high frequencies in the pathogenesis of peripheral neurosensory disorders has been studied in humans using acute responses to shock vibration. In an intriguing experiment, *Lundström* explored the change in vibrotactile perception threshold (VPT) in response to repeated impacts, which were generated in the laboratory to possess a bandwidth extending up to 2, or 12.5 kHz [38]. The shock repetition rate was 30/s. Data were obtained from nine male and nine female subjects, none of whom had been exposed occupationally to hand-transmitted vibration and were in good health, with no history of vascular or neurological disease, or of trauma to the hand. Before the shock exposures all subjects possessed normal VPTs at the fingertips. The mean change in threshold induced by the exposures were 36 dB for exposure to the shocks with bandwidth extending to 2 kHz, and 38 dB for exposure to the shocks with bandwidth extending to 12.5 kHz. However, there was no statistically significant difference between these results. In addition, the recovery of VPTs after the exposures to the pre-exposure thresholds showed no difference for the two shock bandwidths. Thus, there is no evidence from the results of this experiment that the acceleration components of shocks at frequencies above those specified in ISO 5349-1:2001 [4] produce an acute health effect, suggesting that there is no additional response of the sensory nerves in the fingertips to vibration exposure at frequencies above 2 kHz.

An attempt has also been made to establish whether impact power tools operating with extremely low repetition rates, such as nail guns, result in additional health effects to those described. For this reason, a literature search was performed using Medline, Google and BAIDU.com (a Chinese database). While occupational injuries and the consequences of undertaking manual work in poor postures are reported in the literature (e.g., puncture wounds from shooting nails into the body, pain in the spine, arms and hands), and musculoskeletal effects associated with cumulative trauma disorders can be anticipated, no further health effects were found that could be attributed to vibration exposure.

Discussion and Conclusions

While the vibration frequency spectra of power tools have been the subject of many investigations, their time histories have been less studied. It is therefore perhaps surprising to find so many tools produce shock waveforms that are separated in time – so called isolated mechanical shocks. The large, but transient, peak accelerations produce large dynamic stresses in tissues and there is reason to suspect may result in health effects, such as HHS, in addition to HAVS in persons exposed to mechanical shocks.

The onset of the vascular component of HAVS (finger blanching) seems to be adequately predicted by the method described in ISO/TR 18570:2016 [7], with no additional allowance for exposure to mechanical shocks. However, estimating exposure durations may need further consideration for tools that operate for only a few seconds to complete as task (e.g., riveting hammer, nail gun). In the case of the nail gun (and hammer) exposure considered, calculating the duration of exposure from the number of nails or staples inserted per work shift leads to an extremely low estimate of the vibration exposure. It seems probable that the biological response to the trauma caused by a single impact will persist in tissues after the termination of the mechanical shock. Thus, estimates for the biologically relevant duration for the trauma resulting from isolated shocks may exceed the physical duration of the shock and so increase the effective duration of the exposure.

The onset of suspected CTS associated with exposure to mechanical shocks appears to be greater than might be expected on the basis of the acceleration components at frequencies between 10 and 80 Hz, but the evidence is only from one study. There is evidence of an association between work involving operation of percussive power tools and an excess prevalence of premature elbow and wrist osteoarthrosis. While there are animal data suggesting high vibration frequencies may be involved in structural changes to nerve fibers and nerve endings, there is no evidence to support this hypothesis from either finger biopsies of workers suffering from vibration-induced white finger who have operated impact or non-impact power tools, or acute exposures to shock-like vibration. There is also no evidence at present that impact power tools operating with extremely low repetition rates result in additional health effects that could be attributed to vibration exposure.

References

[1] *Starck, J.*: High impulse acceleration levels in hand-held vibratory tools. Scand. J. Work Environ. Health 10 (1984), p. 171-178

[2] *Keith, S. E.; Brammer, A. J.*: Rock drill handle vibration: Measurement and hazard estimation. J. Sound Vib. 174 (1994), p. 475-491

[3] *Dong, R. G.; Welcome, D. E.; McDowell, T. W.; Xu, X. S.; Krajnak, K.; Wu, J. Z.*: A proposed theory on biodynamic frequency weighting for hand-transmitted vibration exposure. Industr. Health 50 (2012) No. 5, p. 412-424

[4] ISO 5349-1: Mechanical vibration – Measurement and evaluation of human exposure to hand-transmitted vibration – Part I: General requirements. International Organization for Standardization (ISO), Geneva, Switzerland 2002

[5] ISO 5349-2: Mechanical vibration – Measurement and evaluation of human exposure to hand-transmitted vibration – Part 2: Practical guidance for measurement at the workplace. International Organization for Standardization (ISO), Geneva, Switzerland 2002

[6] *Pelmear, P. L.; Wasserman, D. E.*:. Hand-arm vibration – A comprehensive guide for occupational health professionals. 2nd ed. OEM Press, Beverly Farms, MA, 1998

[7] ISO/TR 18570: Mechanical vibration – Measurement and evaluation of human exposure to hand-transmitted vibration – Supplementary method for assessing vascular injury. International Organization for Standardization (ISO), Geneva, Switzerland 2016

[8] *Bovenzi, M.*: Epidemiological evidence for new frequency weightings of hand-transmitted vibration. Industr. Health 50 (2012), p. 377-387

[9] *Bovenzi, M.; Pinto, I.; Piccioli, F.; Mauro, M.; Ronchese, F.*: Frequency weightings of hand-transmitted vibration for predicting vibration-induced white finger. Scand. J. Work Environ. Health 37 (2011), p. 244-252

[10] *Brammer, A. J.; Pitts, P. M.*: Frequency weighting for vibration-induced white finger compatible with exposure-response models. Industr. Health 50 (2012), p. 397-411

[11] *Griffin, M. J.; Bovenzi, M.; Nelsen, C. M.*: Dose-response patterns for vibration-induced white finger. Occup. Environ. Med. 60 (2003), p. 16-26

[12] *Pitts, P. M.; Mason, H. J.; Poole, K. A.; Young, C. E.*: Relative performance of frequency weighting Wh and candidates for alternative frequency weightings for predicting the occurrence of hand-transmitted vibration injuries. Industr. Health 50 (2012), p. 388-396

[13] *Tominaga, Y.*: New frequency weightings of hand-arm vibration. Industr. Health 43 (2005), p. 509-515

[14] *Taylor, W.; Pearson, J. C. G.; Keighley, G. D.*: A longitudinal study of Raynaud‘s phenomenon in chain saw operators. Proc. Int. Occup. Hand-Arm Vibration Conference, (DHEW (NIOSH) Pub. 77-170) 1977, p. 69-76

[15] *Pelmear, P. L.; Leong, D.; Taraschuk, I.; Wong, L.*: Hand-arm vibration syndrome in foundrymen and hard rock miners. J. Low Freq. Noise Vib. 5 (1986), p. 26-43

[16] *Pelmear, P. L.; Roos, J.; Leong, D.; Wong, L.*: Cold provocation test results from a 1985 survey of hard-rock miners in Ontario. Scand. J. Work Environ. Health 13 (1987), p. 343-347

[17] *Engström, K.; Dandanell, R.*: Exposure conditions and Raynaud‘s phenomenon among riveters in the aircraft industry. Scand. J. Work Environ. Health 12 (1986), p. 293-295.

[18] *Dandanell, R.; Engström, K.*: Vibration from riveting tools in the frequency range 6 Hz - 10 MHz and Raynaud‘s phenomenon. Scand. J. Work Environ. Health 12 (1986), p. 338-342

[19] *Walker, D. D.; Jones, B.; Ogden, S.; Tasker, E. G.; Robinson, A. J.*: A study of white finger in the gas industry. Br. J. Ind. Med. 42 (1985), p. 672-677

[20] *Tasker, E. G.*: Assessment of vibration levels associated with hand-held road breakers. Scand. J. Work Environ. Health 12 (1986), p. 407-412

[21] *Louda, L.; Rousková, H.; Svoboda, L.; Muff, V.*: Disease and disorders resulting from hand-arm shocks. Proceedings 6th International Conference Hand-Arm Vibration, Bonn 1992 (HVBG, Sankt Augustin, Germany), pp. 271-277

[22] *Suggs, C. W.*: Vibration of manual tool handles. In: *Brammer, A. J.; Taylor, W.* (eds.): Vibration effects on the hand and arm in industry. John Wiley & Sons, New York 1982, p. 253-257

[23] *Poole, K.; Mason, H.*: Data mining in a HAVS referral population. Health & Safety Executive Research Report RR666, London, United Kingdom 2008. pp. 1-81

[24] *Bovenzi, M.*: A longitudinal study of vibration white finger, cold response of digital arteries, and measures of daily vibration exposure. Int. Arch. Occup. Environ. Health 83 (2010), p. 259-272

[25] *Bovenzi, M.*: A prospective cohort study of exposure-response relationship for vibration-induced white finger. Occup. Environ. Med. 67 (2010), p. 38-46

[26] *Bovenzi, M.; Prodi, A.; Mauro, M.*: Relationships of neurosensory disorders and reduced work ability to alternate frequency weightings of hand-transmitted vibration. Scand. J. Work Environ. Health 41 (2015), p. 247-258

[27] *Bovenzi, M.; Prodi, A.; Mauro, M.*: A longitudinal study of neck and upper limb musculoskeletal disorders and alternative measures of vibration exposure. Int. Arch. Occup. Environ. Health 89 (2016), p. 923-933

[28] *Cooke, R. A.*: Hypothenar hammer syndrome: A discrete syndrome to be distinguished from hand-arm vibration syndrome. Occup. Med. 53 (2003), p. 320-324

[29] *Turcot, A.; Fortier, M.; Dumitrescu, D.*: Hypothenar hammer syndrome: An underdiagnosed cause in workers exposed to hand-arm vibration. Can. Acoustics 39 (2011) No. 2, p. 22-23

[30] *Thompson, A.; House, R.*: Hand-arm vibration syndrome with concomitant arterial thrombosis in the hands. Occup. Med. 56 (2006) No. 5, p. 317-321

[31] *Chatterjee, D. S.; Barwick, D. D.; Petrie, A.*: Exploratory electromyography in the study of vibration-induced white finger in rock drillers. Brit. J. Industr. Med. 39 (1982), p. 89-97

[32] *Dahlin, L. B.; Sandén, H.; Dahlin, E.; Zimmerman, M.; Thomsen, N.; Björkman, A.*: Low mylineated nerve-fibre density may lead to symptoms associated with nerve entrapment in vibration-induced neuropathy. J. Occup. Med. Toxicol. 9 (2014), p. 7

[33] *Barcenilla, A.; March, L. M.; Chen, J. S.; Sambrook, P. N.*: Carpal tunnel syndrome and its relationship to occupation: A meta analysis. Rheumatology 51 (2012), p. 250-261

[34] *Gemne, G.; Saraste, H.*: Bone and joint pathology in workers using hand-held vibrating tools. Scand. J. Work Environ. Health 13 (1987), p. 290-300

[35] *Raju, S. G.; Rogness, O.; Persson, M.; Bain, J.; Riley, D.*: Vibration from a riveting hammer causes severe nerve damage in the rat tail model. Muscle Nerve 44 (2011), p. 795-804

[36] *Takeuchi, T.; Futatsuka, M.; Imanishi, H.; Yamada, S.*: Pathological changes observed in the finger biopsy of patients with vibration-induced white finger. Scand. J. Work Environ. Health 12 (1986), p. 280-283

[37] *Goldsmith, P. C.; Molina, F. A.; Bunker, C. B.; Terenghi, G.; Leslie, T. A.; Fowler, C. J.; Polak, J. M.; Dowd, P. M.*: Cutaneous nerve fibre depletion in vibration white finger. J. R. Soc. Med. 87 (1994), p. 377-381

[38] *Lundström, R.*: Acute effects on tactile sensitivity caused by shock-type vibration exposure of the hand. Proceedings 6th International Conference Hand-Arm Vibration, Bonn. Hauptverband der gewerblichen Berufsgenossenschaften (HVBG), Sankt Augustin, Germany 1992. p. 301-309

Part II

Studies for description and definition of shock events acting upon the human hand-arm system and of means of assessing these events

Abstract

Studies for description and definition of shock events acting upon the human hand-arm system and of means of assessing these events

Isolated shocks are a particular type of hand-arm vibration arising during work with mechanized (e.g. nailers, bolt guns) or non-mechanized (axes, hammers) tools.

No verified information on their subjective and biological or health effects has been available before now. Numerous different terms describing the form of vibration under investigation are in use (isolated shocks, repetitive shocks, impulse vibration), and it is uncertain whether different researchers mean the same thing when using the same term.

This report concerns studies into the principles for measurement of the conditions of exposure to single shocks and laboratory studies of subjective distinction between isolated shocks, continuous series of shocks, and other forms of mechanical vibration affecting the human hand-arm system during work.

The results show that state-of-the-art measurement technology can be used to record several measurement parameters describing the shock exposure with the required accuracy. Many of these parameters are correlated to each other. The choice of one or more of these parameters for judgment of the potential risk or the relevance to human health must be investigated in future studies of medical and biological cause-effect relationships.

The results further reveal three regions of subjective perception to be distinguished with regard to shock exposure:

- Repeated isolated shocks
- Continuous series of shocks
- Stochastic vibration

Repeated isolated shocks and continuous series of shocks are separated by threshold A at around 15 s^{-1}, whereas continuous series of shocks and stochastic vibration are separated by threshold B at around 25 s^{-1}.

Even relatively low magnitudes of acceleration cause a shock sensation. Significant interdependency exists between the magnitude and the pulse duration, with a slope of 10 dB/decade in double logarithmic scaling. This relationship would appear to be due to the principle of energy equivalence.

1 Problem

1.1 Introduction

At many workplaces in industry, the trades, agriculture and forestry, mechanical vibration is generated that is transmitted to the operators of machinery and tools through the hand-arm system, and that as a result may under certain conditions cause a number of different health disorders. In most cases, vibration is transmitted to the hand-arm system through handles or controls on the tool or machine, and in some cases also through the workpiece when it must be held in the hand. The form of vibration exposure varies according to the specific underlying conditions at the workplace. By virtue of the differences in their frequency and amplitude distribution, and also in the time structure and other influencing factors such as pushing and gripping forces, the technologies and tools used for work are a particular cause of wide variation in the associated hand-transmitted vibration exposure. This variation may in turn also lead to differences in the health disorders to which the vibration gives rise. The exposure to stationary vibration, more high-frequency in nature, arising during work with grinding machines is for example more likely to lead to circulatory disturbances, whereas the more low-frequency vibration containing pulses generated by paving breakers is more likely to damage the bones and joints.

In recent decades, considerable research activity has been undertaken in order to set out the engineering principles for methods by which the exposure to hand-transmitted vibration can be measured and described (including description of the instrumentation). At the same time, extensive biological and medical research has been conducted into the adverse health impact arising, and suitable methods have been developed for diagnosis of this impact. The result of this research includes the development of criteria for risk assessment and for preventive measures for the safeguarding of health (low-vibration machinery, workplace design, organizational measures, occupational medical examinations).

Wherever possible, these activities have also been incorporated into the relevant statutes and regulations for the protection of health, and into national and international standards.

Despite the significant technical and scientific progress made, gaps still remain in the understanding of hand-transmitted vibration. One problem that is still largely unanswered concerns exposure to discrete (isolated) mechanical shocks that may occur during work with tools, both mechanized and non-mechanized. Isolated shocks are a particular form of exposure of the hand-arm system to mechanical vibration. Characteristic for this form of exposure is that in contrast to the usual stationary continuous vibration, the hand-arm system is exposed only very briefly to mechanical energy.

The particular physical characteristics of shock exposure give rise to numerous problems regarding measurement (primarily but not exclusively concerning the instrumentation) of the exposure conditions, biological and medical study of the possible effects, and also the laboratory and field methods for study of the cause-and-effect relationships. For a long time, these problems were an obstacle to purposeful and systematic study of exposure to shock. In addition, owing to the comparatively low number of individuals exposed to shock, no urgency was generally seen for intensive study.

For some years now, studies have reported that the health impact of recoil generated by tools such as nail drivers or powder-actuated nail guns was underestimated in the past [1; 2]. This concerns not only the familiar, specific effects of vibration, which have been comparatively well studied (harm to the musculoskeletal system, peripheral circulatory disorders), but also forms of harm with cause-and-effect relationships that as yet are less well known (impairment of the peripheral nervous system, hypothenar hammer syndrome, carpal tunnel syndrome). At present however, no internationally generally accepted method is known for assessment of the risks presented by isolated shocks.

The scientific reasoning for recognition of the “de-facto” occupational disease of hypothenar hammer syndrome was published in 2012 by the German Federal Ministry of Labour and Social Affairs (BMAS) together with the recommendation by the medical advisory council that this disorder be included in the list of formally recognized occupational diseases under the German ordinance on occupational diseases (BKV).

Within the statutory occupational accident insurance institutions, an evaluation exists of 62 formally recognized cases of occupational disease No. BK 2114 (hypothenar hammer syndrome) from between 1991 and 2012. Vibration exposure is a factor in at least 16 of these 62 cases. Isolated shocks involving tools are also a factor in 9 cases.

A further disorder worthy of mention is formally recognized occupational disease No. BK 2113 (carpal tunnel syndrome), which may also be caused by vibration or exposure to shocks (see also [1].

Bovenzi [3] reports high prevalences of osteoarthritis of the wrist and arthritis and osteophytosis of the elbow among workers in coal mining, road construction and the metal industry who are exposed to shocks and low-frequency, high-amplitude vibration caused by pneumatically powered percussive tools.

Whether manufacturers of fastener-driving tools must state vibration emission values in accordance with the Machinery Directive owing to the isolated shocks that these tools generate is the subject of heated debate on international standards committees. As yet, the available national and international standards and bodies of regulations governing the effect of mechanical vibration upon the human hand-arm system contain no scientifically validated method for assessing the onerosity and threat to health of exposure to isolated shocks. The existing standards permit provisional application to periodic impulsive vibration, such as that occurring during work with pneumatic hammers. The scope of EN ISO 5349-1:2001 [4] draws attention to the provisional nature of the standard's applicability to "repeated shock type excitation (impact)". Note 1 states that the time dependency for human response to repeated isolated shocks is not fully known.

Experts doubt whether isolated shocks, i.e. shocks repeated at greater intervals, can be correctly recorded and assessed by means of these methods. In some studies, discrepancies have been observed between the incidence of harm calculated from the measured values for acceleration and exposure duration and the number of workers actually harmed by exposure to hand-transmitted vibration containing pulses [5; 6]. This can be interpreted as indicating that the current standard assessment and evaluation methods for vibration containing pulses are not applicable here.

In the course of work on safety standards for hand-held and hand-guided machines (Machinery Directive), ISO/TC 118/SC 3 "Pneumatic tools and machines", ruled in 2011 that shocks are not to be regarded as vibration and do not therefore need to be considered as a safety aspect in the sense of the Machinery Directive (see Resolution 83, WG 3 Milan 9 [7]).

At its 2011 meeting, ISO/TC 108/SC 4, "Human exposure to mechanical vibration and shock" adopted Resolution 2/2011, in which the position of ISO/TC 118/SC 3 was criticized. SC 4 saw no justification for the isolated shocks generated by machines with a strike/trigger rate of ‹5 Hz not to be treated as a vibration issue [8].

The above discussion shows that far-reaching deficits remain in findings concerning subjective adverse impact and the possible relevance to health of isolated shocks upon the hand-arm system. Not only do deficits exist in application or practical implementation of known methods and procedures concerning exposure to hand-transmitted vibration, fundamental gaps in knowledge also exist in the sphere of research into "shock". At the same time, the current discussion in the context of the likelihood and severity of occupational disease and during international standardization activity has generated a certain pressure for action.

A comprehensive solution to the existing problems will be found only if numerous individual studies are conducted with cross-discipline cooperation between technical and medical disciplines. Before further studies are performed however, it would appear absolutely essential for a uniform definition of "shocks" to be formulated, the technical and methodological principles for the measurement of shock exposure to be set out, and a comprehensive overview to be procured of shock exposure as it occurs in practice in the world of work.

1.2 Current state of knowledge

1.2.1 Measurement of the exposure conditions

The first studies into the measurement of shock exposure were performed in the 1980s, and were based upon experience gained with measurement of vibration exposure on percussive machinery such as pneumatic hammers and percussive drilling machines [9]. The focus of these studies lay upon error-free and reproducible measurement of shocks acting upon the human hand-arm system during work involving mechanized and non-mechanized tools, and the selection of suitable physical variables and measurement parameters for description of the shock exposure. An obstacle to these studies was the measurement technology of the time, which was still largely analogue, and the limited means available at the time for recording and analyzing of transient signals. Typical workplaces involving shock exposure were nevertheless described in accordance with the state of the art of measurement instrumentation at the time [10; 11].

With the advent in recent years of digitalized measurement technology, the storage, recording and flexible analysis of measurement signals has been simplified considerably. The measurement of shock exposure can also benefit from this development. Fundamental measurement problems still exist however, for example regarding the selection and coupling of sensors. A harmonized method for comprehensive measurement is still unavailable. Initial progress has been made in this area by the ISO/TS 15694 pre-standard/technical specification [12].

1.2.2 Cause-effect relationships

No validated knowledge exists in occupational medical practice of whether isolated shocks can have a harmful effect upon the organism, or whether they differ in their effect from impulsive vibration, such as that from pneumatic hammers. The German and international literature contains relatively little in the way of published study results in this area, and the available results are highly inconsistent. These inconsistencies can probably be attributed to authors and researchers reporting on studies of "shock exposure", but differing in their understanding and opinions of what actually constitutes a "shock". Some publications on the subject of shock provide little information on the tasks studied or the exposure, as a result of which it is not clear whether they concern isolated shocks, series of shocks, or vibration with shock content.

The few papers dealing with medical studies of what is clearly shock exposure show that the mechanisms of action at play probably differ between stationary hand-transmitted vibration and periodically repeated series of shocks [13; 14]. For example, studies of 313 smiths and 51 workers performing straightening work were reported; these studied involved capillaroscopy, pallesthesiometry and skin temperature measurements [13]. For these two occupational groups, circulatory disturbances and rises in sensation thresholds were observed as a function of the number of years in the occupation. This was more conspicuous among the workers performing straightening work compared to the smiths.

Starck et al. and other authors suspect that impulsiveness of hand-transmitted vibration in general, i.e. including vibration with a shock component such as that generated by pneumatic hammers, give rise to a higher health hazard [15 to 18]. The results of studies by *Zuravljov* et al. [19; 20] also indicate that shock exposure involves other mechanisms of action upon the organism. The effect of the higher frequency components, in particular, appears to have been underestimated before now [21; 22].

By contrast, a series of publications by *Dupuis* et al. [23 to 25] concluded that vibration with a shock component should essentially be assessed against the same criteria as stationary random vibration. *Ying* et al. [26] arrive at similar conclusions.

The effect of vibration consisting of a series of shocks (impulsive vibration) is very often presented as being particularly harmful to health [27 to 29]; it is however measured, recorded epidemiologically, and assessed for occupational medical purposes against the same criteria as harmonic/wideband stationary hand-transmitted vibration. It is however doubtful whether the same measurement and assessment methods can be used when the periods between the isolated shocks are greater, as is the case during work with powder-actuated nail guns, nail drivers or similar mechanized or non-mechanized tools.

1.3 Deficit analysis

From the findings made to date, it can be concluded that evaluation of the relevance to health of workplaces involving impulsive exposure has not yet been possible for the following reasons:

1. The performance of studies involving measurements of mechanical shocks is difficult, and requires modern and complex technology and sufficient experience of measurement. Considerable progress has been made in this area in the past 20 years or so with the introduction of digital technology, particularly with regard to the storage and analysis of shock signals. Certain fundamental problems associated with the sensor (selection and coupling of the sensor, mechanical filter, linearity in the frequency range of interest, etc.) and with the measurement technology (frequency range, phase response, reliable prevention of overdriving, baseline jumps) still remain, however.

   A comprehensive overview of measured shock exposure occurring in practice still does not exist.

2. Likewise, no definition of isolated shocks exists that is relevant for OSH (OSH: occupational safety and health) purposes. Accordingly, there is also no clear distinction between isolated shocks and stationary vibration or similar forms of exposure (vibration containing pulses, vibration with a shock component, series of shocks, etc.). It is doubtful whether researchers responsible for the studies conducted to date into shock exposure are in agreement regarding what is understood by a “shock”.

3. Whether isolated shocks can have a harmful effect upon the organism, or whether they differ in their effect from vibration with a shock component, such as that produced by pneumatic hammers, is not known. Accordingly, no validated findings exist regarding the possible harm arising and its medical diagnosis.

   Studies of hypothenar hammer syndrome (HHS) in which a relationship has been determined between arterial circulatory disturbances in the hand and manual impacts (shocks) performed with the hand permit the assumption that health may also be harmed during work with mechanized or non-mechanized tools generating shocks.

4. No findings exist concerning which physical variables (e.g. acceleration, velocity, force) and which signal parameters (root mean square and/or root mean quad, positive peak value, negative peak value, peak to peak, crest factor, shock duration, rise time, etc.) are biologically relevant. What spectral information (amplitude spectrum, root mean square spectrum, power density, energy density, etc.) is relevant? Can the frequency weighting functions used up to now (e.g. to EN ISO 5349-1) be applied; are new (yet unknown) weighting functions required?

   At this point in time, it cannot simply be assumed that the quantities standardized to date are also suitable for all types of shock. It may be necessary for completely new assessment quantities to be defined. The possible need for guideline or limit values for exposure is also an issue in this context.

International research into the subject of shock is made difficult by major inconsistencies in the terminology. A number of terms are used in relation to shock exposure, such as: single shocks, isolated shocks, repetitive shocks, transients, transient vibration, impulsive vibration, shock-type vibration.

The terminology in related areas (engineering mechanics, vibration technology) is based upon the physical definition of shock, according to which the duration of the shock must be very short compared to the natural period [30 to 32] contains several definitions of “shock”. None of these definitions are however practicable or adequate for the specific case of exposure of the hand-arm system to shock.

In the absence of a uniform definition for isolated shocks, studies in the past that have addressed the effect of vibration with a shock component or series of shocks (for example on pneumatic hammers) have often been classified under the heading of “shock”. At the same time, many studies may have failed to distinguish clearly between exposure to isolated shocks and other forms of hand-transmitted vibration [33], as a result of which the differences in effect between isolated shocks and series of shocks are not evident.

Some experts [5; 34] take the frequency of a series of shocks at the lower frequency limit of the hand-arm frequency weighting curve of EN ISO 5349-1 (5.6 Hz) as the criterion for distinguishing isolated shocks from series of shocks. ISO/TS 15694 [12] specifies down a strike rate of 5 Hz as definitive for the scope of the standard. This criterion is not scientifically validated, however. It should be noted here that all frequency weighting curves used in the past were developed for the effects of stationary vibration, in order for the biological effect of different frequency components to be described better. They were not developed in order to characterize the structure of the vibration incidence over time. Focusing upon a corner frequency from a de-facto continuous filter curve (accurate to one decimal place) therefore appears highly arbitrary.

2 Research objective

The essential objective of the research described here was firstly, to set out methodical principles for uniform measurement of shocks (Part A), and secondly, to determine criteria for distinguishing shocks from other forms of vibration exposure of the hand-arm system (Part B).

2.1 Part A (performed by the Institute for Occupational Safety and Health, IFA)

The measurement and assessment of shocks acting upon the human hand-arm system during work involving hand tools and manually operated machines continues to present problems and unanswered questions. Shocks must be measured under particularly close observation of the principles known from the measurement of mechanical vibrations on percussive tools. Answers are to be found to questions concerning the use of mechanical filters and the coupling of the vibration sensors to rigid handles and to handles with an elastic coating.

Since at this stage, hardly anything is known of the biologically relevant physical variables and measurement parameters, the waveform of the shocks must be stored with a range of measurement parameters to enable them to be analyzed at a later stage. In order to ensure that the peak values obtained in different measurements are comparable, an upper frequency limit must be set. A suitable threshold frequency must be determined for this purpose.

Within the project reported here, these observations and this experience are to be brought into line with the current state of measurement technology, and standardized methods for measurement and analyses are to be developed in consideration of the existing national and international standards and the results of Sub-task A. These methods are to be trialed in the laboratory by means of available stored shock signals and also at real-case workplaces involving exposure to shock. The following specific studies are planned:

1. Creation of an overview of measurements of shock exposure occurring in practice (the IFA‘s and KSZ‘s own measurements, literature and other sources, for example the WTZ scientific and technical centre for occupational safety and health)

2. Development and trialing in practice of a harmonized method for the measurement of shocks, with reference to examples of typical tools and work equipment involving isolated shocks (sensors, measurement technology, frequency ranges, storage, measurement parameters, analysis, etc.)

2.2 Part B (performed by KSZ Ingenieurbüro GmbH)

Where reference is made in the context of hand-transmitted vibration to a single shock, the term “single shock” does not mean that only one single shock occurs in the entire working life of the worker, or only one shock for example per working shift. Exposure to single shocks (discrete shocks or rather isolated shocks) in the sense used in this document indicates that the duration before the incidence of the next shock is very long compared to the duration of energy exposure (duration of the shock), and that it can generally be determined by the worker themselves. Work involving powder-actuated nail guns is a typical example of such shock exposure.

The objective of Sub-task B is to be determined under these terms of reference by means of a theoretical example. The upper part of Figure 1 shows a number of individual events (shocks), all of which exhibit the same intensity and a duration of 10 ms. At a pulse interval of 200 ms, 5 shocks per second occur (strike rate 5 s^{-1}/strike frequency 5 Hz). In the lower part of the Figure, 10 shocks with the same pulse duration and the same intensity occur (pulse interval 100 ms, corresponding to a strike rate of 10 s^{-1}).

With the exception of the pulse interval, the two graphs are very similar. Some experts [5; 34]) take the view however that unlike exposure as shown in the lower graph in Figure 1, exposure as shown in the upper graph in Figure 1 can no longer be addressed by the methods in the current standards (e.g. EN ISO 5349-1).

EN ISO 5349-1:2001 applies “to periodic and to random or non-periodic vibration” [4]. Application to “repeated shock type excitation (impact)” is permitted “provisionally”. In the absence of further scientific validation, [5] proposes a strike rate of 5 s^{-1} for demarcation of the scope of EN ISO 5349-1 in the case of repeated shocks (series of shocks). In view of the – very similar – characteristics in the upper and lower graphs of Figure 1 (with the exception of the interval between the discrete events), this demarcation appears highly arbitrary.

The problem to be addressed by the studies is as follows:

Problem 1:
How great must the interval between two successive shocks be in order for them still to be considered isolated shocks, or conversely how quickly must the shocks follow each other in order to be considered a series of shocks rather than isolated shocks?

Further details must be considered with regard to the distinction between shocks and other forms of hand-transmitted vibration. If the duration of the five discrete events in the upper graph in Figure 1 is extended from 10 to 200 ms (lower graph in Figure 2), five events with the same intensity still occur. However, there is then no vibration-free period between these events. The characteristic is then more a saw-tooth vibration waveform than five individual events. The intensity does not change suddenly; rather, the signal tends to increase and decay slowly. Under these circumstances, it does not appear justified to speak of shocks. Between the upper and lower graphs, the change in rate of rise must have been accompanied by a gradual transition from shocks to non-shocks.

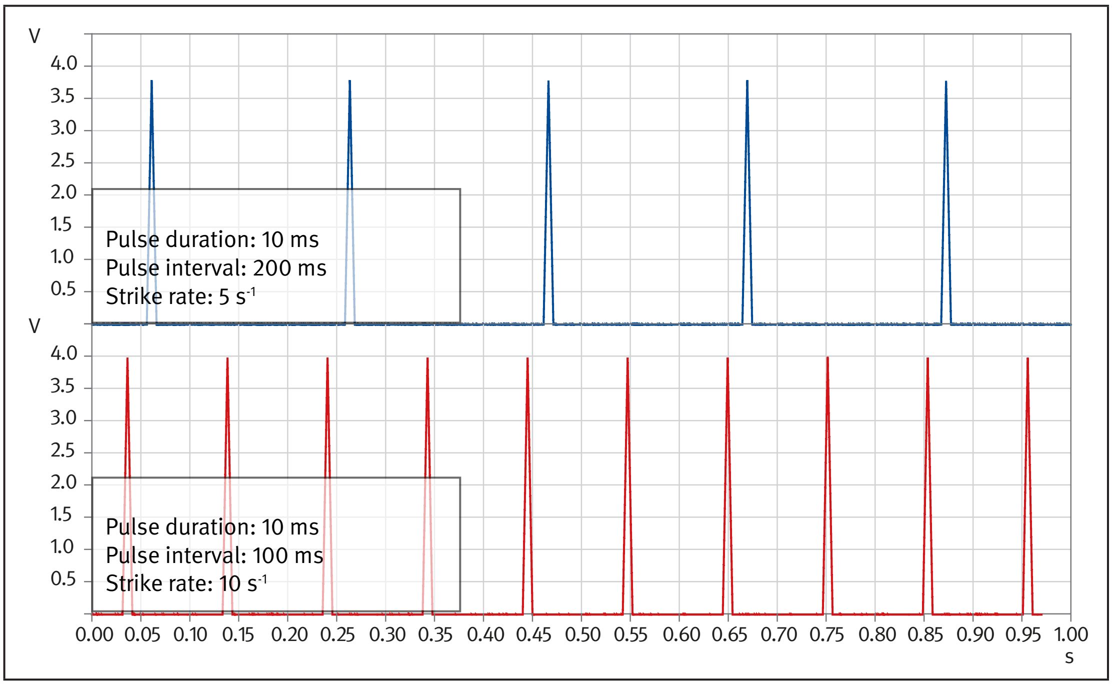


Figure 1: Theoretical example of successive isolated pulses

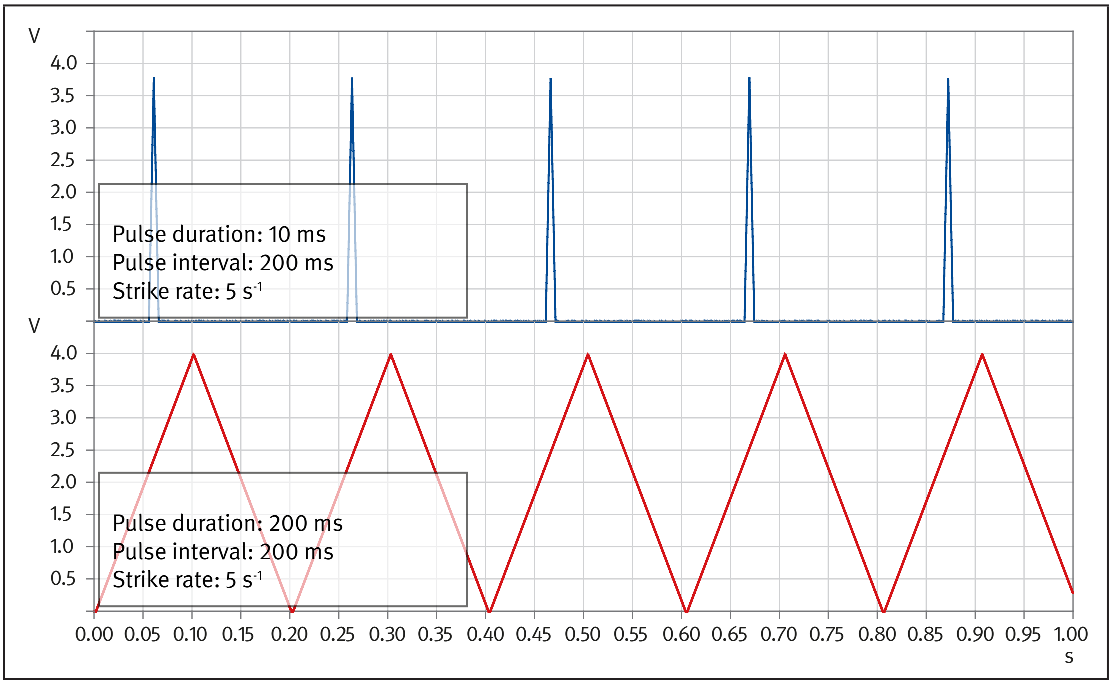


Figure 2: Sequence of pulses from Figure 1, with different rise times

The studies must therefore also answer the following questions in relation to the differences in rise time:

Problem 2:
Does a lower intensity limit exist for shocks?
Does a lower and/or upper limit exist for the duration of an event in order for it to be described as a shock?
Do the intensity and duration of a shock have an interdependency to each other?

Two essential objectives therefore exist for study of the distinction of shock exposure from other forms of hand-transmitted vibration exposure:

1. Distinction in terms of the strike frequency of the individual events (pulses)

2. Distinction in terms of intensity and duration (rate of rise)

The studies are to determine only the test subjects' subjective perception of the events (movements, pulses) sensed on the hand or fingers. The test subjects decide which events (movements, pulses) they consider to be shocks or series of shocks, and which they do not. No studies were performed of biological effects or effects upon health. This also enabled the studies to be performed with intensities lying only marginally above the sensory threshold. The accelerations acting in the tests at the point of load transfer to the hand-arm system (50 to 100 m/s^2 peak) lie several orders of magnitude below the peak values occurring during practical work tasks (peak values of several 1,000 m/s^2).

3 Part A: Studies for the measurements of shocks at realistic workplaces

3.1 Current standards and regulations

EN ISO 5349-1 is the definitive standard for measurement, evaluation and assessment of the vibration impact upon the hand-arm system (vibration exposure) [4]. The emissions measurement standards and the measurement standards for assessment of the health hazard at the workplace are based in particular upon the frequency weightings and averaging methods stated in EN ISO 5349-1. Part 2 of EN ISO 5349 [35] contains more precise provisions for the performance of workplace measurements.

Technical Specification ISO/TS 15694 [12] specifies further variables for better description of the excitation of the hand-arm system by repeated shocks at below 5 Hz. Further requirements for the measurement apparatus are also specified in accordance with EN ISO 8041 [36]. It thus constitutes a basis for measurements and evaluations of the emissions of isolated shocks from hand-held and hand-guided machines, but without additional assessment methods.

An additional frequency weighting for better assessment of the health risk of vibration-induced circulatory disorders in the hands is currently being developed. This publication, planned in the form of a Technical Specification, currently has the designation ISO/PWI 18570 [37].

The requirements placed upon the instrumentation for measurement of the vibration impact upon human beings are set out in EN ISO 8041 [36] in the form of the specific performance characteristics and their traceable verification. The revised edition of 2006, with further changes in the amendment of 2015 [38], also contains the requirements concerning the phase response necessary for the measurement of shocks.

3.2 Methods

3.2.1 Analysis methods and parameters

Both frequency weighting and time weighting of the measured acceleration are performed for analyzing of the results of hand-transmitted vibration measurements. The basis for the frequency weighting is that vibration at different frequencies differs in the potential hazard it presents to the human hand-arm system. In order for this issue to be covered, the measured accelerations are weighted over their frequency range with a frequency-dependent weighting factor of between 0 and 1. The characteristic of such weighting factors is presented in frequency weighting curves. This study employs three different frequency weighting filters. The $flat_h$ weighting corresponds to band limiting between 6.3 and 1,250 Hz.

Band limiting is first performed for all measurements with the $flat_h$ weighting filter. This essentially constitutes band limiting between 6.3 and 1,250 Hz (see Annex A, Figure A.1). Within this frequency band, the acceleration is weighted with a factor of 1.

Following band limiting, the measured signal is weighted by means of the hand-arm weighting filters W_h and W_p. EN ISO 5349 specifies the W_h hand-arm weighting filter (Annex A, Figure A.2) [4]. This frequency weighting is based upon curves of identical perception and has been applied to date to periodic, random and non-periodic vibrations. EN ISO 5349 further specifies that until updated parts of the standard for addressing isolated shocks become available, the W_h frequency weighting filter can also be used for the weighting of individual shocks (“impact”).

The W_p hand-arm weighting filter is defined in ISO/PWI 18570 (see Annex A, Figure A.3) [37]. This filter is intended for the evaluation of vascular disorders of the hand and arm.

In addition to the frequency weighting, a time weighting of the measured acceleration is applicable for the value of the variable. The timeframe for analyzing of the acceleration must be selected such that comparison between different isolated shock events is possible. The time intervals of 1 to 3 s proposed in ISO/TS 15694 are used. These enable the shock event to be recorded within the measurement duration (Figure 3) [12].

The values determined for this project correspond to those laid down in the ISO/TS 15694 Technical Specification. The rise times and pulse durations of the shocks are also recorded. Finally, the measurement results are presented both unweighted and with the W_h and W_p frequency weightings.

All measurements were analyzed by means of the MEDA software application (refer to Annex B for a description of the measurement system and the software). Measurement data for the firearm, the captive bolt gun and the powder-actuated nail gun were already available from field measurements performed by the IFA. These measurements were imported into MEDA in ASCII format for further analysis. A fresh series of measurements was conducted for the locksmith‘s hammer. These data were recorded and analyzed directly by means of MEDA.

With the exception of the jerk and the root-mean-quad value, all values were generated by means of MEDA. The exceptions stated were computed by means of MatLab.

Definitions of the parameters are shown below in detail with the essential properties for the example of the $flat_h$ weighting. The values for the frequency weightings W_h and W_p were formed using the same methods.

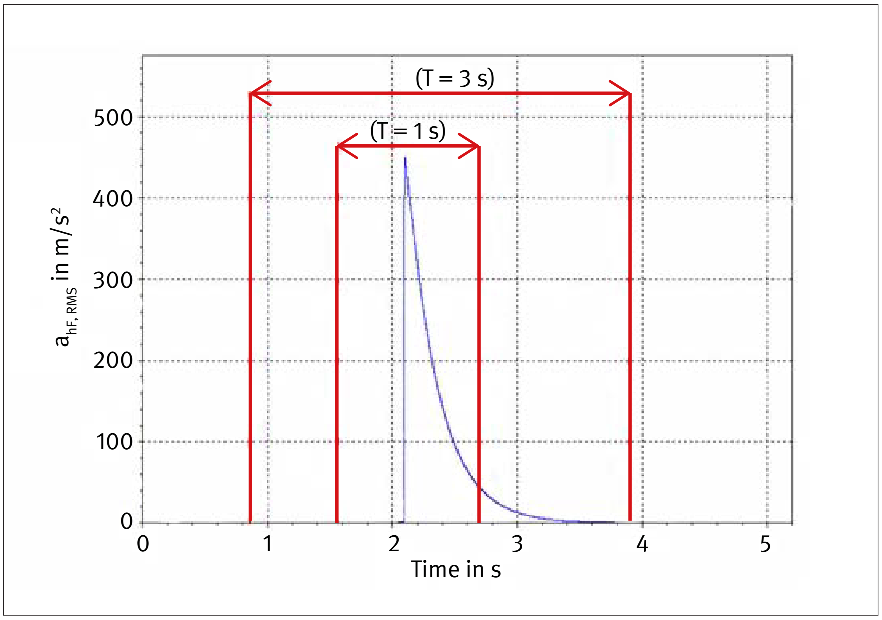


Figure 3:
Example characteristic of the $flat_h$-weighted running root-mean-square value (time constant τ = 0.125 s) during use of a hammer, with corresponding time weighting of 1 s and 3 s

Root-mean-square value of the acceleration over a specified time interval:

The root-mean-square value of the acceleration a_{hF} over the specified time interval T, $a_{hF,\,RMS,\,T}$ is given by:

$$a_{hF,\,RMS,\,T} = \sqrt{\frac{1}{T}\int_0^T a_{hF}^2(t)\,dt} \qquad (1)$$

where
a_{hF} = acceleration
t = time of observation
T = time interval

A fixed averaging time permits comparison between isolated shock events of differing measurement duration. Time frames of 1 and 3 s around the pulse were specified for the purposes of analysis. Figure 3 shows by way of example the characteristic of the $flat_h$ band-limited running root-mean-square value during use of the hammer and the corresponding time intervals in which the signal was analyzed.

Running root-mean-square value:

The running root-mean-square value of an acceleration a_{hF} at the time of observation t is:

$$a_{hF,\,RMS,\,\tau}(t) = \sqrt{\frac{1}{\tau}\int_0^t a_{hF}^2(\xi)e^{-\frac{t-\xi}{\tau}}\,d\xi} \qquad (2)$$

where
a_{hF} = acceleration
t = time of observation
ξ = integration variable
τ = time constant

The time constant τ = 0.125 s was selected for all analyses.

Root-mean-quad value:

The root-mean-quad value of an acceleration a_{hF} with a time interval T is stated as:

$$a_{hF,\,RMQ,\,T} = \sqrt[4]{\frac{1}{T}\int_0^T a_{hF}^4(t)\,dt} \qquad (3)$$

where
a_{hF} = acceleration
t = time of observation
T = time constant

The fourth power in the calculation gives particular weighting to outliers and maximums in the acceleration characteristic.

Maximum transient vibration value:

The maximum transient vibration value is the maximum of the running root-mean-square value in the time interval T.

$$a_{hF,MTVV,\tau} = \max_{0\le t\le \tau}\{a_{hF,\,RMS,\tau}(t)\} \qquad (4)$$

where
$a_{hF,\,RMS,\,\tau}$ = running root-mean-square value
t = time of observation

Peak value of the acceleration:

The peak value of the acceleration is the maximum absolute instantaneous acceleration value.

$$a_{hF,\,PV} = \max_{0\le t\le T}\{|a_{hF}(t)|\} \qquad (5)$$

where
a_{hF} = acceleration
t = time of observation

Crest factor of the acceleration:

The crest factor is the quotient of the peak value of an acceleration and the root-mean-square value measured over the same time interval T.

$$CF_h = \frac{a_{hF,PV}}{a_{hF,RMS,T}} \qquad (6)$$

where

$a_{hF,\,PV}$ = peak value of the acceleration

$a_{hF,\,RMS,\,T}$ = root-mean-square value of the acceleration in the time interval

Shock content quotient of the acceleration:

The shock content quotient is formed by division of the root-mean-quad value by the root-mean-square value measured over the same time interval T.

$$SC_h = \frac{a_{hF,RMQ,T}}{a_{hF,RMS,T}} \qquad (7)$$

where

$a_{hF,\,RMQ,\,T}$ = root-mean-quad value

$a_{hF,\,RMS,\,T}$ = root-mean-square value of the acceleration in the time interval

Jerk:[1]

The jerk j(t) is defined by derivation from the acceleration a(t).

$$\vec{j}(t) = \dot{\vec{a}}(t) = \ddot{\vec{v}}(t) = \dim\,[m/s^3] \qquad (8)$$

where

v = velocity

a = acceleration

The root-mean-square values in the time interval (T = 1 s, T = 3 s) and the peak-to-peak value are also considered for the jerk. In the past, the jerk has primarily been considered in the context of vehicle dynamics and is not yet used in ISO/TS 15694.

Rise times of the acceleration:

The rise time (t_a) of an acceleration is the duration from the beginning of the shock event to attainment of the peak value. Figure 4 shows determining of the rise time with reference to the example of a locksmith‘s hammer.

Pulse duration of the isolated shock event:

The pulse duration t_i is the duration from the beginning of a shock event to its decay to 10% of the attained peak value and sustained dwell below it. Figure 5 shows the pulse duration with reference to the example of an impact involving a locksmith‘s hammer.

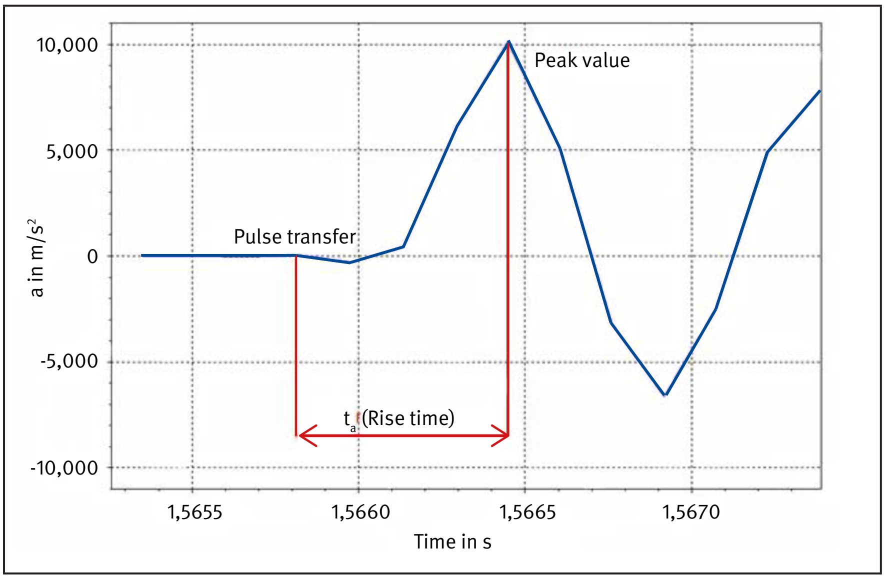


Figure 4:
Rise time with reference to the example of an impact with a locksmith‘s hammer

[1] jerk, is the rate of change of acceleration; that is, the derivative of acceleration with respect to time, and as such the second derivative of velocity, or the third derivative of position

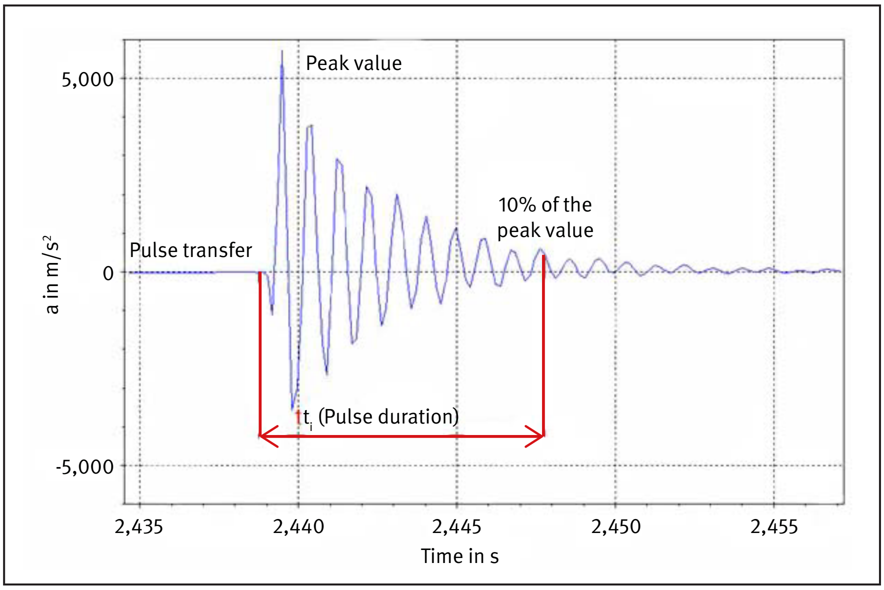


Figure 5:
Pulse duration with reference to the example of an impact with a locksmith's hammer

3.2.2 Selection of typical tools and performance of the tests

The tools selected for testing comprise typical mechanized and non-mechanized tools the use of which gives rise to characteristic isolated shocks. The tools were selected with a view to producing a spectrum of different areas of application and modes of use. The areas of application of the tools tested comprise areas in the trades and the metalworking sector (locksmith's hammers), material testing (firearms), construction (powder-actuated nail guns) and the meat industry (captive bolt guns).

In addition, tools were intentionally selected with a range of forms of drive. Both manually operated tools (locksmith's hammers) and tools operated by the ignition of a charge (powder-actuated nail gun) were tested.

In addition to the tools already stated, a partial test was performed with a pneumatic nail gun. The objective of this partial test was to detect and eliminate interference variables resulting from the inherent movement of the user (see Section 3.2.3).

The individual tools are described briefly below together with the performance of testing.

Locksmith's hammer

For the purposes of this project, the measurements were performed with a typical locksmith's hammer (weight of the hammer head: 0.5 kg) [39]. These hammers have a very wide range of application with relevant uses in the metal industry and the trades. Work typically involves impact with locksmith's hammers directly on metal. Very heavy impacts may be required in order to form metal, for example during straightening work.

The individual test subject can be expected to have a major influence upon the measurement result during hammering. The measurement result may be influenced substantially not only by the force and velocity of the hammer blow, but also by the angle between the hammer head and the workpiece at the point of impact. The defined work task also has a decisive influence upon the measurement result. The values measured may differ significantly depending for example upon whether the hammer is used to drive nails into wood or to deform metal plastically. Since the influence of the user and the work task may differ enormously, importance was attached in the test arrangement to a high level of reproducibility. For this purpose, an S235JR steel plate (400 · 300 · 20 mm³) firmly screwed in place was hammered (see Figure 6). The test subjects practiced hammering evenly at a perceived „medium intensity" to accustom them to the task.

The option was first considered of making the hammer blows comparable by having them performed from a defined „impact height". This option was rejected however, as it was shown that the „impact height" on its own is not sufficient as a criterion for the blow intensity; very fast, firm blows can be executed from a low height, and blows can also be executed comparatively slowly and gently from a greater height.

Figure 6 shows the location of the sensors on the locksmith's hammer and the axes of vibration measured at each measurement point. The sensors for measurement points 1 and 2 were attached to the handle of the hammer. Measurement point 1 is located between the user's thumb and index finger; measurement point 2 within a handle adapter in the test subject's hand. All three spatial directions were measured on measurement point 2, whereas only the z axis was recorded for the other measurement points.

The sensor at measurement point 3 (see Figure 7) is located on the metal plate being worked, and serves in this test arrangement as a reference measurement point (see Section 3.2.3). The aim here was to determine the precise point in time of the hammer impact on the metal plate.

As shown in Figure 8, the sensor at measurement point 4 is secured in the anatomical snuffbox on the wrist. Additional measurement points such as this may provide information on the strain when the same tool is handled in different ways.

Figure 6:
Location of the sensors (MP) and directions of measurement on the locksmith's hammer

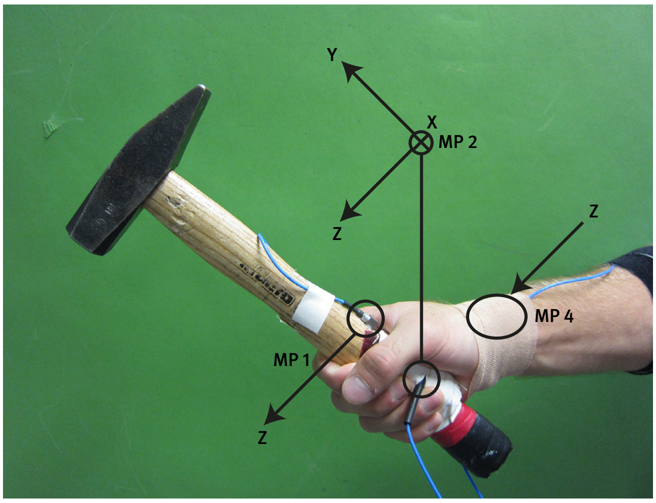
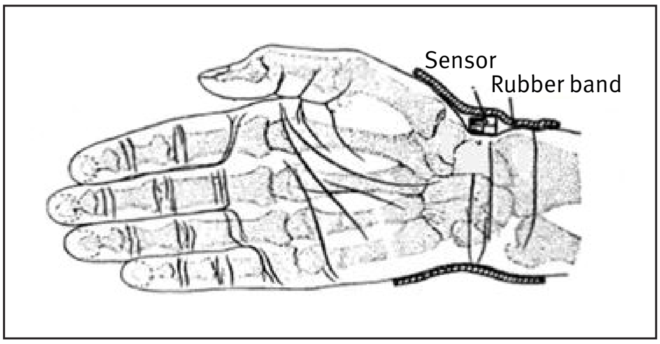


Figure 7:
Test arrangement for the locksmith's hammer, showing measurement point 3

Figure 8:
Location of the accelerometer in the anatomical snuffbox on the wrist (based upon *Schäfer* [40])



Figures 9 and 10 show by way of example the acceleration signal during hammering (measurement 0328 14.2). The time signal of the $flat_h$-weighted acceleration (Figure 9) and the time signal of the W_h-weighted running root-mean-square (Figure 10) for measurement 2 are shown. Figure 11 shows the time signal (expanded scale) of the $flat_h$-weighted acceleration for the same measurement. The acceleration time signal (expanded scale) reveals no drawing-back movement by the user in preparation for execution of the strike; the time signal shows only the decaying isolated shock caused by impact of the hammer head upon the workpiece. Accordingly, it was not necessary during performance of measurements with the locksmith's hammer in this test arrangement to filter out the component of the vibration exposure caused by the user's drawing-back movement, which would have been included in calculation of the values.

Figure 9:
Time signal of the $flat_h$-weighted acceleration at measurement point 2 during use of the locksmith's hammer (measurement No 0328 14.2)

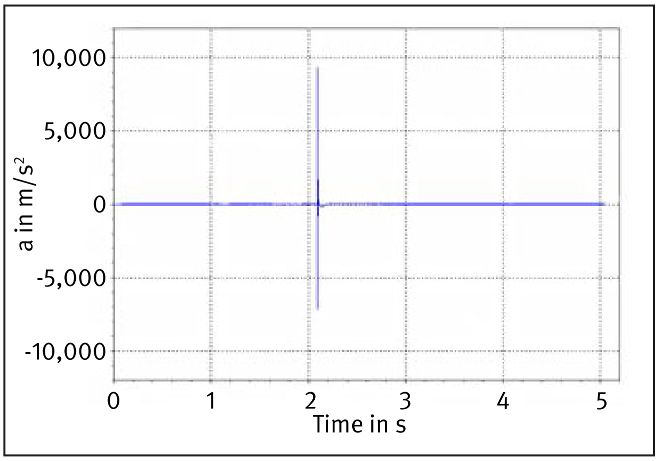


Figure 10:
Time signal of the W_h-weighted running root-mean-square value at measurement point 2 during use of the locksmith's hammer (measurement No 0328 14.2)

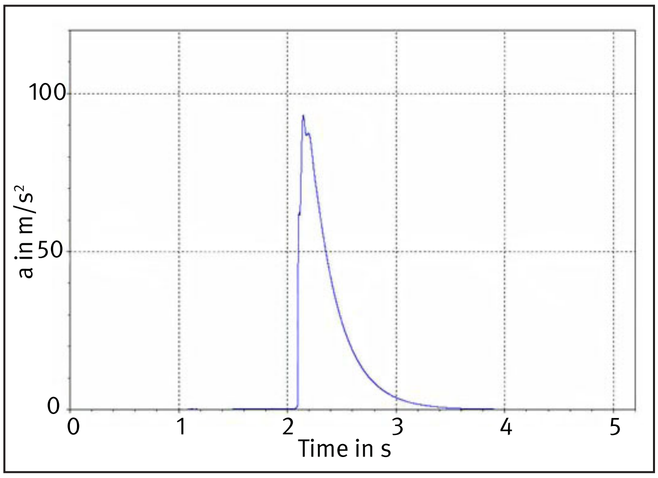
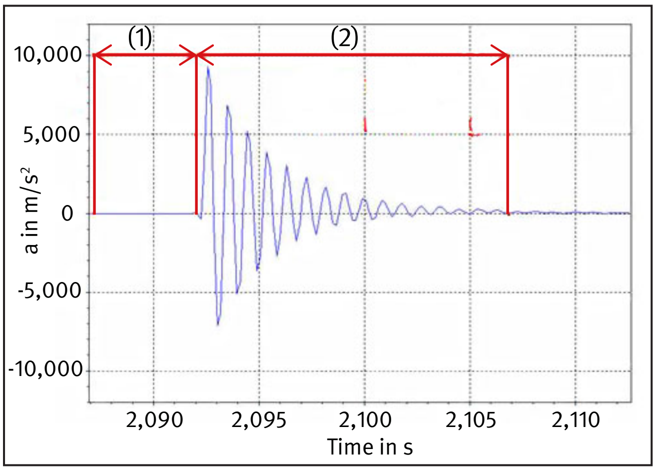


Figure 11:
Time signal (expanded scale) of the flat$_h$-weighted acceleration at measurement point 2 during use of the locksmith's hammer (measurement No 0328 14.2); (1) no drawing-back motion evident on the part of the user, (2) decaying hammer strike



Firearm

A pistol was used in this measurement, which was performed at an official firing range. Single shots with 9 mm ammunition were performed for material testing in this test. Weapons testing requires up to 20,000 shots to be fired manually. This gives rise to stress levels that may cause occupational disease.

All measurement points were measured in the direction of shooting (z axis; see Figure 12). Measurement point 1 is located on the trigger guard, measurement point 2 in the anatomical snuffbox on the wrist (see also Figure 7), measurement point 3 on the inside of the heel of the hand between the magazine and the grip, and measurement point 4 on the grip adapter. Figure 13 shows the position of the hand-arm system during testing with the pistol.

Figures 14 and 15 show the time signals of the flat$_h$-weighted acceleration and the time signal of the W$_h$-weighted running root-mean-square value at measurement point 1.

Figure 12:
Location of the sensors and directions of measurement on the firearm

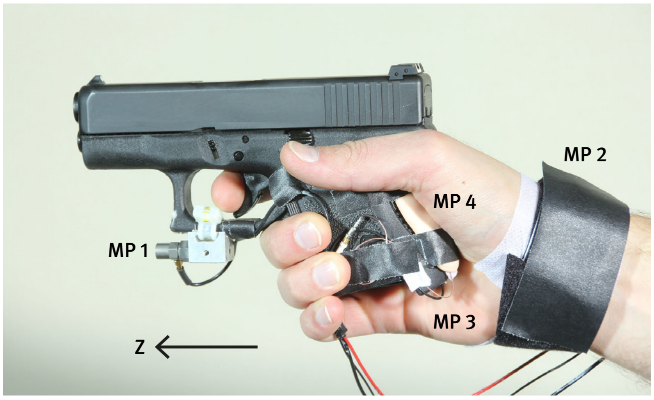


Figure 13:
Performance of the test and position of the hand-arm system involving the pistol

Figure 14:
Time signal of the flat$_h$-weighted acceleration at measurement point 1 on the pistol (measurement No 0254 5.3)

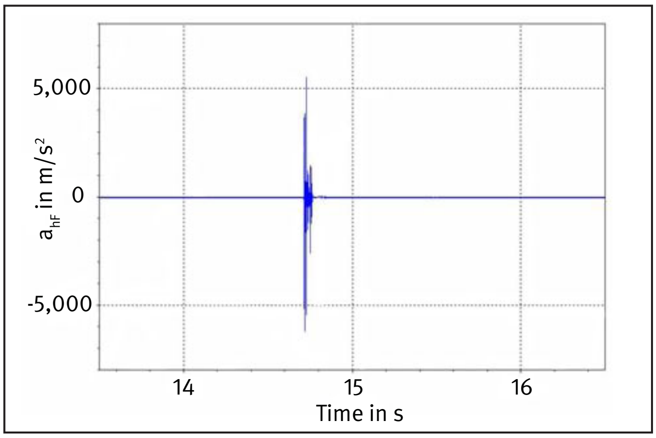
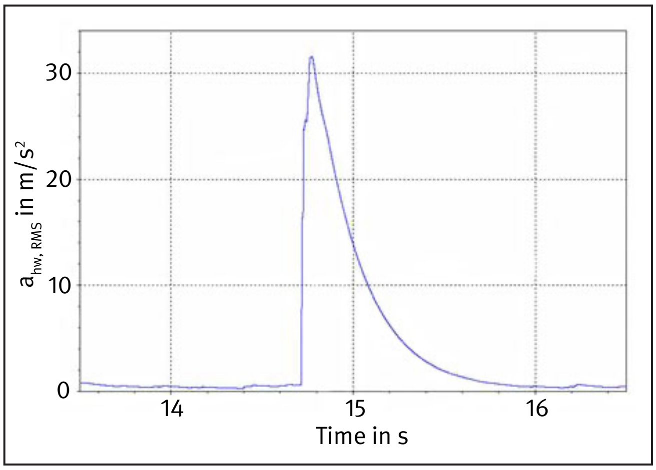


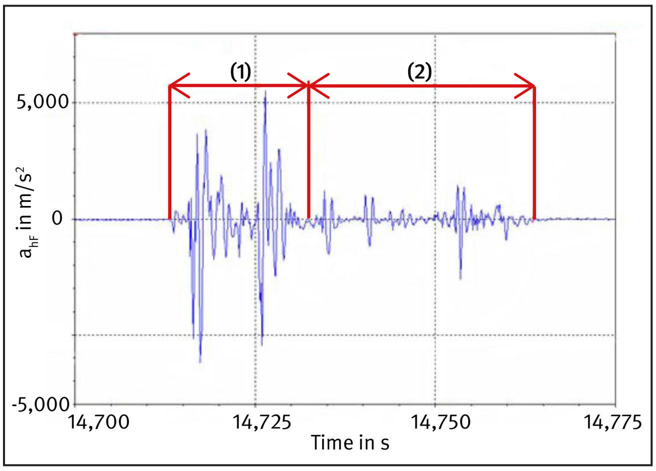
Figure 15:
Time signal of the W$_h$-weighted running root-mean-square value at measurement point 1 on the pistol (measurement No 0254 5.3)



The firearm used exhibited a characteristic pattern in the acceleration characteristic, composed of ignition of the explosive charge and recoil of the firing pin (see Figure 16). The user is exposed to both of these processes. Accordingly, both processes were considered in formation of the values.

For consideration of the pulse durations and rise times, only the ignition process of the explosive charge was analyzed.

Figure 16:
Time signal (expanded scale) of the $flat_h$-weighted acceleration at measurement point 1 on the pistol (measurement No 0254 5.3); (1): ignition of the explosive charge, (2): recoil of the firing pin



Captive bolt gun

Captive bolt guns, which are used in the meat industry, are a further example of tools with a high pulse component. In this case, the isolated shock is generated by ignition of an explosive charge, which drives the pin into the test arrangement (or the skull of the animal). The measurements for the captive bolt gun were performed at only a single measurement point, in the direction of shooting (z axis; Figure 17).

For this measurement, a substitute working process was employed in which an animal skull was simulated by a layered wood and polyurethane structure (Figure 18). To improve absorption of the shock, this arrangement was located in a sand pit. Following each shot process, a new explosive charge was loaded into the captive bolt gun. It was therefore necessary to perform each shot process as a measurement in its own right.

Figures 19 and 20 show the time signals of the $flat_h$-acceleration and of the W_h-weighted running root-mean-square value on the captive bolt gun.

Figure 21 shows the time signal (expanded scale) of the measured $flat_h$-weighted acceleration on the captive bolt gun. Since no drawing-back movement takes place during operation of the tool, it is not necessary to filter out the artefacts caused by the user‘s own movement.

Figure 17:
Location of the sensors and directions of measurement on the captive bolt gun

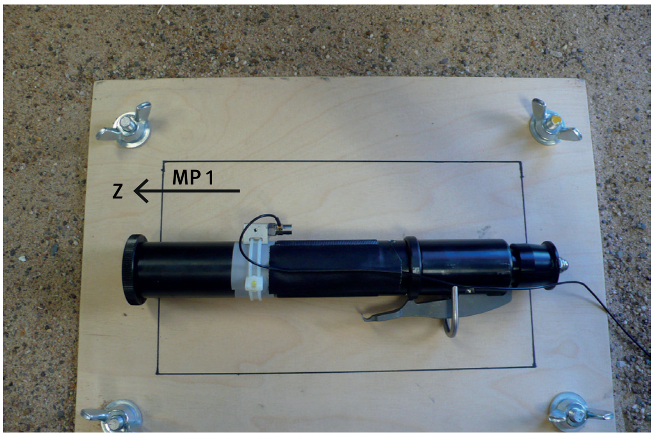


Figure 18:
Performance of the test involving the captive bolt gun

Figure 19:
Time signal of the $flat_h$-weighted acceleration on the captive bolt gun (measurement No 0310 34)

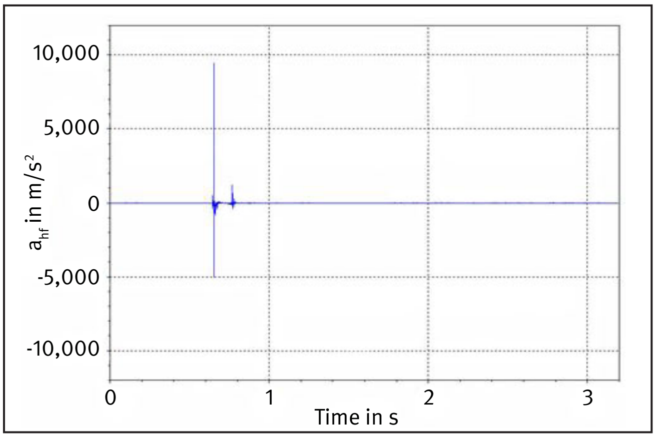


Figure 20:
Time signal of the W_h-weighted running root-mean-square value on the captive bolt gun (measurement No 0310 34)

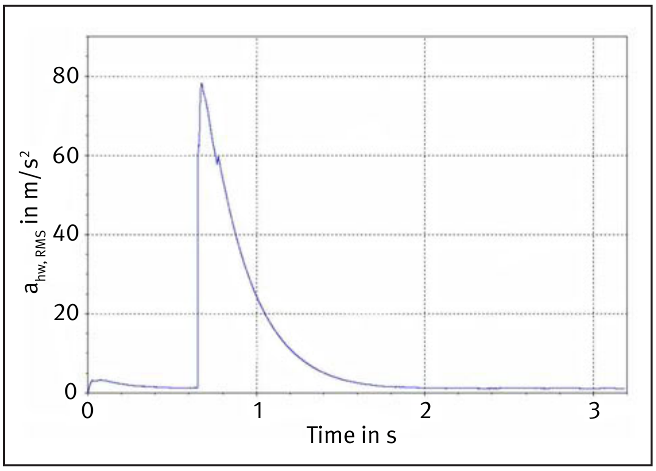
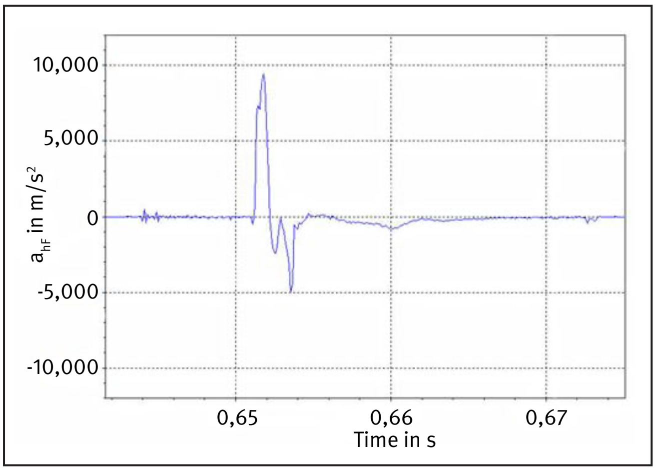


Figure 21:
Time signal (expanded scale) of the $flat_h$-weighted acceleration on the captive bolt gun (measurement No 0310 34)



Powder-actuated nail gun

These measurements were performed on a heavy-duty powder-actuated nail gun – a tool typical of those used in the construction sector. Both measurement points were measured in the direction of shooting only (see Figure 22). Measurement point 1 was located on the surface of the tool above the main handle, measurement point 2 at the bottom of the main handle.

According to the manufacturer‘s data, 400 to 700 shots are possible with the powder-actuated nail gun depending upon the ammunition employed before the user‘s exposure to vibration reaches the action value A(8) of 2.5 m/s². 1,600 to 2,800 shots are possible before the limit value A(8) of 5 m/s² is reached.

A typical work task involving the powder-actuated nail gun was performed for the purposes of the test. In this task, nails were driven into an ST37 steel plate (Figure 23). Here too, the steel plate was located in a sand pit for safety reasons and in the interests of better comparability between the individual processes.

The Figures 24 and 25 show the time signals of the $flat_h$-weighted acceleration and of the W_h-weighted running root-mean-square value at measurement point 1.

Figure 26 shows the time signal (expanded scale) of the $flat_h$-weighted acceleration on the powder-actuated nail gun. Here too, no artefacts are evident.

Figure 22:
Location of the sensors and directions of measurement on the powder-actuated nail gun

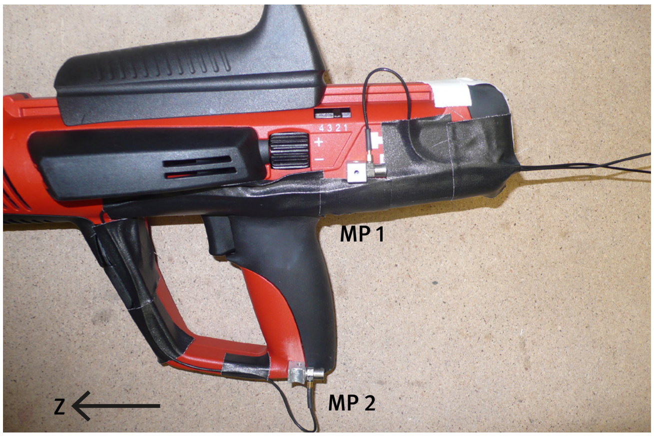


Figure 23:
Performance of the test involving the powder-actuated nail gun

Figure 24:
Time signal of the flat$_h$-weighted acceleration at measurement point 1 on the powder-actuated nail gun (measurement No 0291 3.3)

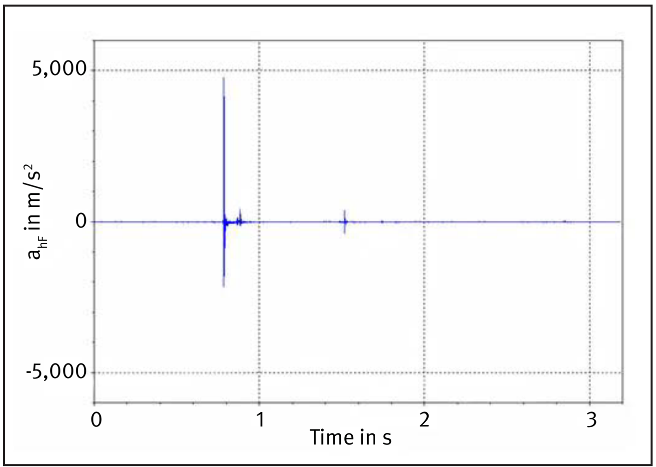


Figure 25:
Time signal of the W$_h$-weighted running root-mean-square value at measurement point 1 on the powder-actuated nail gun (measurement No 0291 3.3)

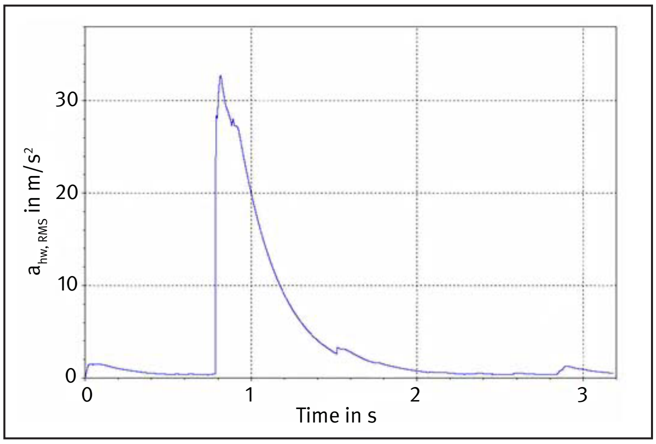
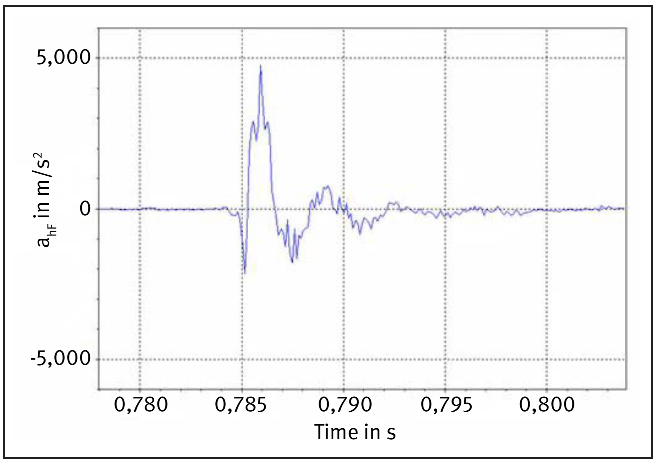


Figure 26:
Time signal (expanded scale) of the flat$_h$-weighted acceleration at measurement point 1 on the powder-actuated nail gun (measurement No 0291 3.3)

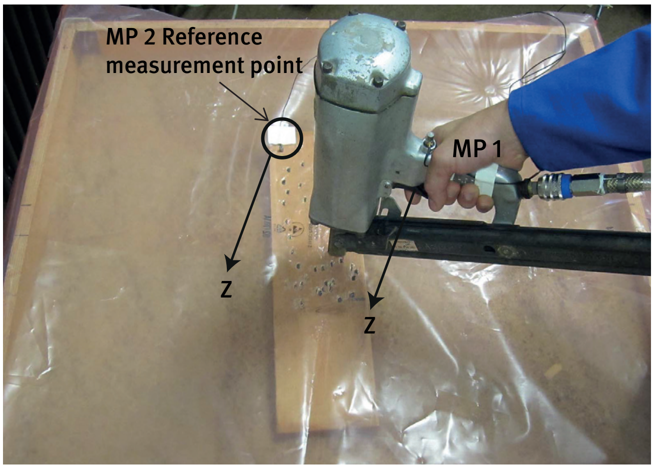


Pneumatic nail driver

The tests with the other tools were supplemented by measurements on a pneumatic nail driver (see Figure 27). In this partial test, nails were driven into a wooden board, which was placed in a sand pit in the interests of better absorption of the shock. The shot processes were triggered by contact: the user held the actuator on the tool depressed and triggered the individual shot processes by pressing the pneumatic nail driver dynamically against the workpiece.

The measurements and analyses for the pneumatic nail driver were less extensive than those for the tools described above. The aim of this measurement was to detect the user‘s own movement by means of a reference measurement point and to eliminate it from the acceleration characteristic. The procedure employed for this purpose is described in Section 3.2.3.

Figure 27:
Measurement points and performance of the test involving the pneumatic nail driver



3.2.3 Additional reference measurement points

Additional reference measurement points were attached to the workpiece used for the measurements on the locksmith's hammer and the pneumatic nail driver. The purpose of these measurement points was to detect the user's own movement during operation of the tool and to eliminate it from the acceleration characteristic. Since the user's own movement is also recorded as acceleration by the accelerometers and this acceleration component is not relevant to the vibration exposure, the component of the user's movement must be detected and filtered out of the acceleration characteristic. In order to achieve this, sensors were fitted both to the tool used and to the workpiece being worked. The sensors attached to the workpiece serve as reference measurement points. The precise point in time at which the tool impacts upon the workpiece can then be recognized on the acceleration characteristic for the reference measurement point.

Simultaneous measurement by the sensors attached to the tool and the reference measurement points permits comparison of the acceleration characteristics. Figure 28 shows the acceleration characteristics of an example measurement on the pneumatic nail driver, both from the sensor on the driver itself (upper curve) and from the reference measurement point (lower curve) attached to the workpiece.

The point in time of contact firing of the pneumatic nail driver can be clearly seen in Figure 28. This enables the component of the user's own movement to be eliminated from the evaluation of the vibration exposure.

Figure 29 shows the $flat_h$-weighted acceleration time signal for the locksmith's hammer and the reference measurement point on the workpiece (metal plate).

Figure 29 shows that the pulses on the locksmith's hammer and the reference measurement point occur approximately simultaneously (both at point t = 2.092 s). In addition, no movement by the user is evident in the signal characteristic. Elimination of the user's movement from the acceleration characteristic was not therefore necessary for the test with the locksmith's hammer.

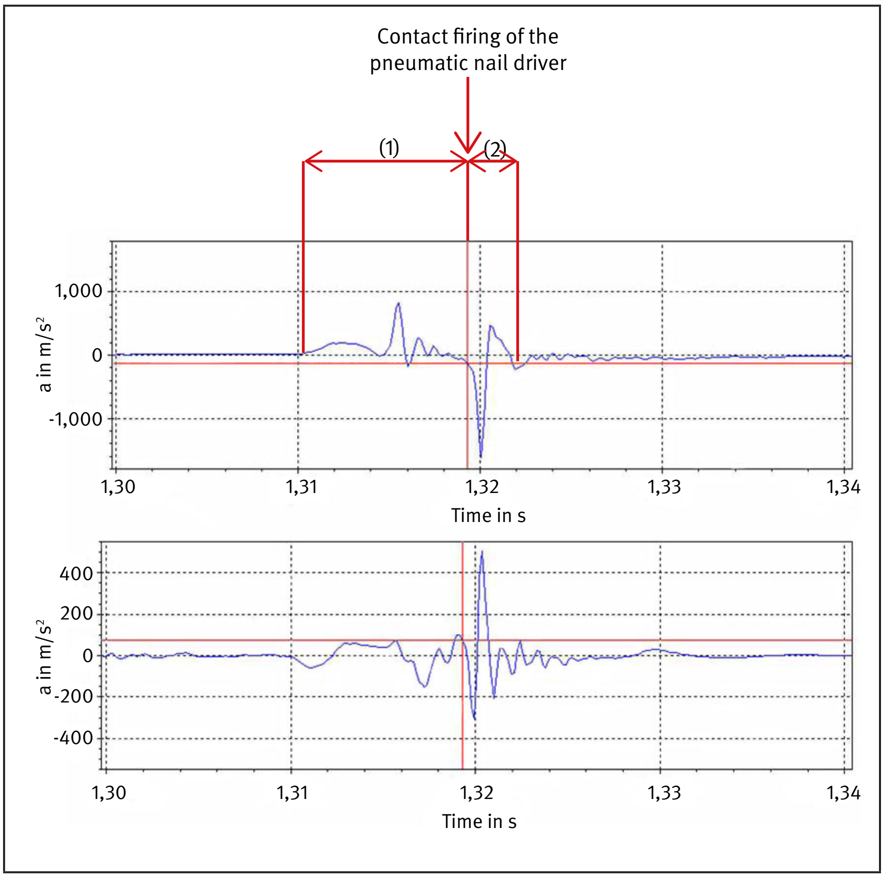


Figure 28:
$Flat_h$-weighted acceleration time signals for the pneumatic nail driver (top) and reference measurement point on the workpiece (bottom); (1): inherent movement of the user, (2) discrete shock caused by the pneumatic nail driver

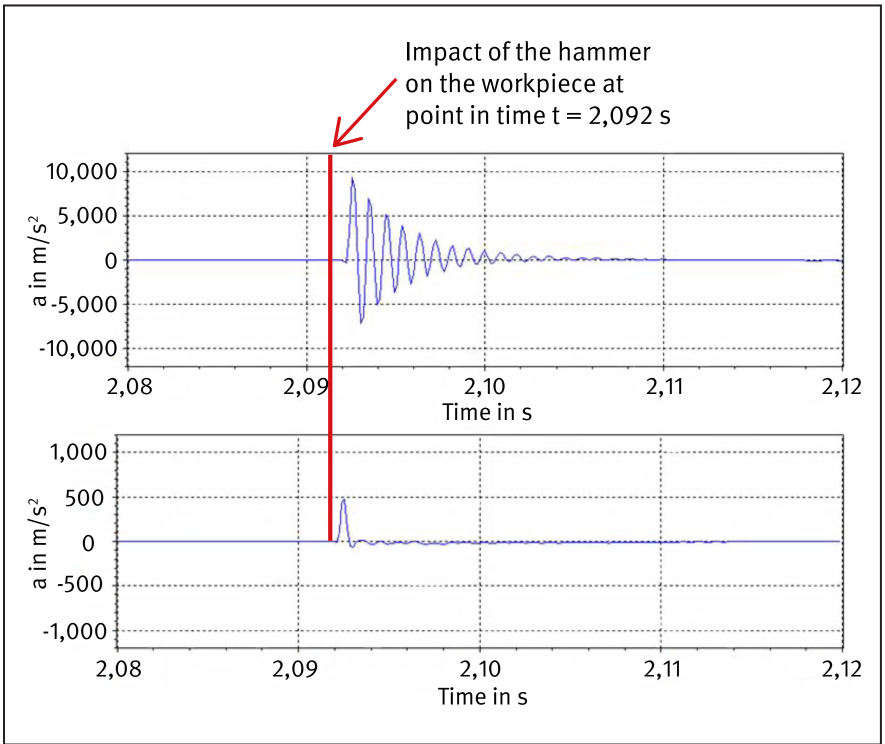


Figure 29:
Flat$_h$-weighted acceleration characteristics for the locksmith's hammer (top) and reference measurement point on the workpiece (bottom)

3.3 Presentation of the results – Comparison between tools

The results and anayses of the measurements are presented in brief for each tool. A comprehensive list of the test results can be found in the results tables in the annex. For each tool, the measurement point was considered that is definitive for the vibration exposure of the test subject. The measurement points that were analyzed for the tools are listed below.

Tool	Measurement point analyzed
Locksmith's hammer	2
Firearm	1
Captive bolt gun	1
Powder-actuated nail gun	1

The tables of results below show a summary of the measured values for the tools tested. In the interests of clarity, only the essential values are shown. The values marked in blue are comparable with those of the evaluation method used in EN ISO 5349-1. A comprehensive overview of all analyzed values can be found in the annex.

Locksmith's hammer

Table 1 shows a selection from the compiled measured values for the locksmith's hammer. At 415 m/s², the flat$_h$-weighted root-mean-square value over the time interval for the tasks involving the locksmith's hammer tested in this project represents the highest exposure of all the tools compared. However, since both the user and the work task have an essential influence upon the measurement result, substantially higher or for that matter lower values for an impact event can arise with hammers.

A further influence upon transmission of the shock effect and the associated exposure is the coupling force, which was not measured. The test arrangement permits coupling forces that were high and as constant as possible. A lower vibration exposure may be assumed for work with manually held hammers that require a lower coupling force [41].

Table 1:
Summarized presentation of the test results for the locksmith's hammer at measurement point 2

Parameter	Mean	Standard deviation	Unit
$a_{hF\ RMS}$ (T = 3 s)	184	± 5.4	m/s²
$a_{hF\ RMS}$ (T = 1 s)	415	± 35	m/s²
$a_{hw\ RMS}$ (T = 3 s)	40	± 15	m/s²
$a_{hw\ RMS}$ (T = 1 s)	67	± 21	m/s²
$a_{hwp\ RMS}$ (T = 3 s)	4	± 6.6	m/s²
$a_{hwp\ RMS}$ (T = 1 s)	106	± 21	m/s²
$a_{hF\ RMQ}$ (T = 3 s)	1,004	± 21	m/s²
$a_{hF\ MTVV}$	790	± 14.9	m/s²
$a_{hw\ MTVV}$	144	± 54	m/s²
$a_{hF\ PV}$	9,479	± 552	m/s²
$a_{hw\ PV}$	369	± 104	m/s²
CF_h	51	± 1.5	/
SC_h	5.6	± 0.12	/
$J_{hF\ RMS}$ (T = 3 s)	1,187,383	± 34,736	m/s³

Firearm

Table 2 shows a summary of the measured values for the firearm. The vibration exposure arising is lower for the firearm tested than for the manually held hammer. It is notable that the $flat_h$-weighted root-mean-square value is the second highest after that for the hammer, but that at 16.4 m/s² and 88 m/s² respectively, the W_h and W_p-weighted accelerations are the lowest of all tools tested. Since, among the tools studied, the frequency weighting with the W_h and W_p filter results in this case in the lowest values relative to the $flat_h$-weighted root-mean-square acceleration values, it can probably be assumed that the firearm tested exhibits a higher frequency component outside the filter limits than is the case with the other tools tested.

Table 2:
Summarized presentation of the test results for the firearm at measurement point 1

Parameter	Mean	Standard deviation	Unit
$a_{hF\,RMS}$ (T = 3 s)	143	± 4	m/s²
$a_{hF\,RMS}$ (T = 1 s)	281	± 35	m/s²
$a_{hw\,RMS}$ (T = 3 s)	8.2	± 1	m/s²
$a_{hw\,RMS}$ (T = 1 s)	16.4	± 3.8	m/s²
$a_{hwp\,RMS}$ (T = 3 s)	49	± 0.9	m/s²
$a_{hwp\,RMS}$ (T = 1 s)	88	± 14	m/s²
$a_{hF\,RMQ}$ (T = 3 s)	691	± 123	m/s²
$a_{hF\,MTVV}$	559	± 23	m/s²
$a_{hw\,MTVV}$	31	± 3.8	m/s²
$a_{hF\,PV}$	4,104	± 212	m/s²
$a_{hw\,PV}$	89	± 10.7	m/s²
CF_h	29	± 1.9	/
SC_h	4.8	± 0.7	/
$J_{hF\,RMS}$ (T = 3 s)	1,038,023	± 266,668	m/s³

Captive bolt gun

Table 3 shows a summary of the measured values for the captive bolt gun. The captive bolt gun used for this purpose was a high-power device; the values for a captive bolt gun are also correspondingly high. The captive bolt gun exhibited the highest W_p-weighted root-mean-square acceleration value (187 m/s²) of all the tools. If this is compared with the $flat_h$-weighted root-mean-square acceleration value of 250 m/s², it can be concluded that a high proportion of the frequencies for the captive bolt gun lie within the filter specifications of the W_p-weighting filter.

Powder-actuated nail gun

The measured values for the powder-actuated nail gun are summarized in Table 4. The powder-actuated nail gun studied exhibits the lowest $flat_h$-weighted root-mean-square values. It is notable here that the W_p-weighted acceleration is barely lower than the $flat_h$-weighted acceleration. It is possible that only a small frequency component of the acceleration lies outside the filter specifications of the W_p-weighting filter.

Table 3:
Summarized presentation of the test results for the captive bolt gun

Value	Mean	Standard deviation	Unit
$a_{hF\,RMS}$ (T = 3 s)	146	± 3.0	m/s²
$a_{hF\,RMS}$ (T = 1 s)	250	± 6.5	m/s²
$a_{hw\,RMS}$ (T = 3 s)	18.7	± 0.7	m/s²
$a_{hw\,RMS}$ (T = 1 s)	31.5	± 0.4	m/s²
$a_{hwp\,RMS}$ (T = 3 s)	108.8	± 1.6	m/s²
$a_{hwp\,RMS}$ (T = 1 s)	187	± 4.6	m/s²
$a_{hF\,RMQ}$ (T = 3 s)	1,040	± 8.7	m/s²
$a_{hF\,MTVV}$	688	± 16	m/s²
$a_{hw\,MTVV}$	71	± 10.6	m/s²
$a_{hF\,PV}$	9,504	± 241	m/s²
$a_{hw\,PV}$	599	± 11	m/s²
CF_h	65	± 2.8	/
SC_h	7.1	± 0.1	/
$J_{hF\,RMS}$ (T = 3 s)	566,605	± 36,069	m/s³

Table 4:
Summarized presentation of the test results for the powder-actuated nail gun at measurement point 1

Value	Mean	Standard deviation	Unit
$a_{hF\,RMS}$ (T = 3 s)	79	± 4.2	m/s²
$a_{hF\,RMS}$ (T = 1 s)	176	± 9.8	m/s²
$a_{hw\,RMS}$ (T = 3 s)	9.2	± 0.2	m/s²
$a_{hw\,RMS}$ (T = 1 s)	21	± 0.6	m/s²
$a_{hwp\,RMS}$ (T = 3 s)	71	± 7.5	m/s²
$a_{hwp\,RMS}$ (T = 1 s)	134	± 7.8	m/s²
$a_{hF\,RMQ}$ (T = 3 s)	461	± 15.1	m/s²
$a_{hF\,MTVV}$	336	± 19	m/s²
$a_{hw\,MTVV}$	33	± 0.4	m/s²
$a_{hF\,PV}$	4,417	± 356	m/s²
$a_{hw\,PV}$	233	± 13	m/s²
CF_h	57	± 7.1	/
SC_h	5.9	± 0.18	/
$J_{hF\,RMS}$ (T = 3 s)	354,733	± 7,031	m/s³

If the indirect information from the manufacturers is compared, tools with greater exposure exist. According to the manufacturers‘ data, 400 and 3,500 operations per day can be performed before the action value A(8) of 2.5 m/s² is exceeded. An exposure range for $a_{hw,\,RMS}$ (T = 3 s) of 4.1 to 12.2 m/s² can be derived from this figure.

Each of the diagrams below compares the different values for the tools under consideration for one measurement point (Figures 30 to 33).

The bar graphs show the mean and the standard deviation from three repeat measurements involving a single test subject. The standard deviation was calculated by means of the following formula:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} (a_{hv} - a_{hi})^2}{(n-1)}} \qquad (9)$$

Figures 30 and 31 show the root-mean-square in a time interval for intervals of one and three seconds. The root-mean-square values determined in a time interval are listed in this case for each tool with both the $flat_h$ frequency weighting and with the W_h and W_p frequency weightings.

The highest $flat_h$-weighted root-mean-square values in a time interval are observed for the locksmith's hammer. Note that the influence of the test subject upon the measurement result is very high in a hammering task. Substantially higher or lower values could therefore also be produced for the locksmith's hammer. Since for the other tools tested, the function is determined by the influence of the constant external energy and the same working process, the influence of the test subject upon the measurement result is substantially lower in these cases.

Figure 32 shows the crest factors (CFh) and the shock content quotients (SC) of the tools tested. igure 33 shows the pulse durations t_i and rise times t_a of the tools tested.

The longest pulse duration was observed for the firearm, whereas pulses with the captive bolt gun exhibited the shortest duration. The measured pulse durations and the rise times are broadly consistent with the data already published on the subject of isolated shocks [10].

Figure 30:
Comparison of the frequency-weighted root-mean-square values in a time interval (T = 1 s) for the tools tested

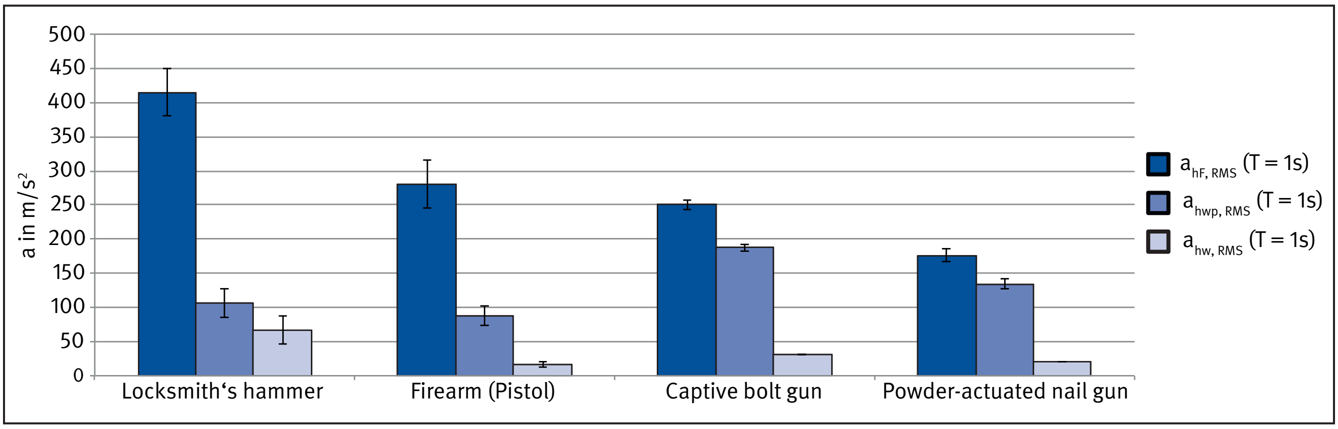


Figure 31:
Comparison of the frequency-weighted root-mean-square values in a time interval (T=3 s) of the tools tested

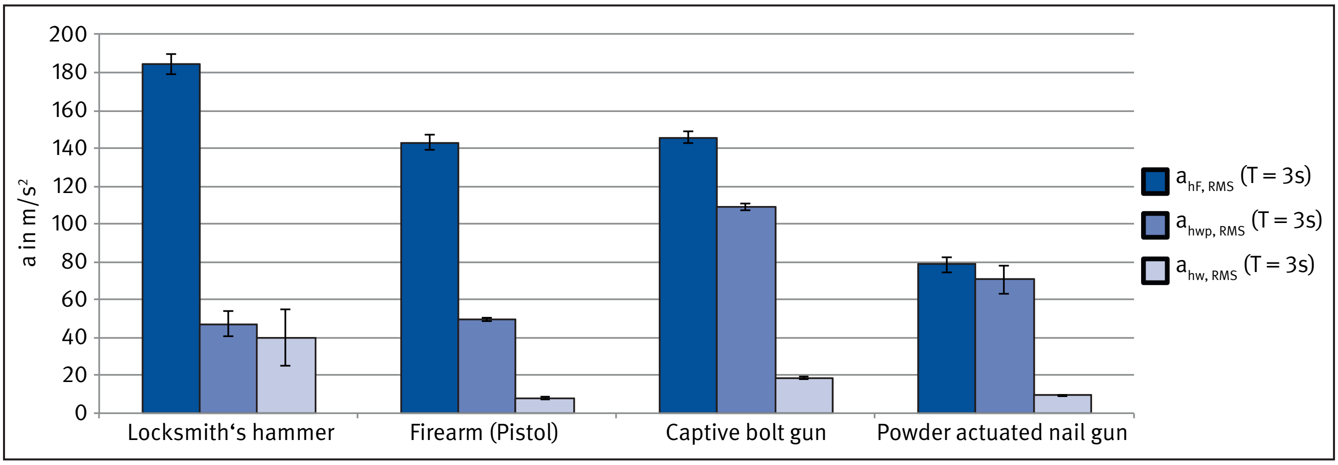


Figure 32:
Comparison of the crest factors (CFh) and the shock content quotients (SC) of the tools tested

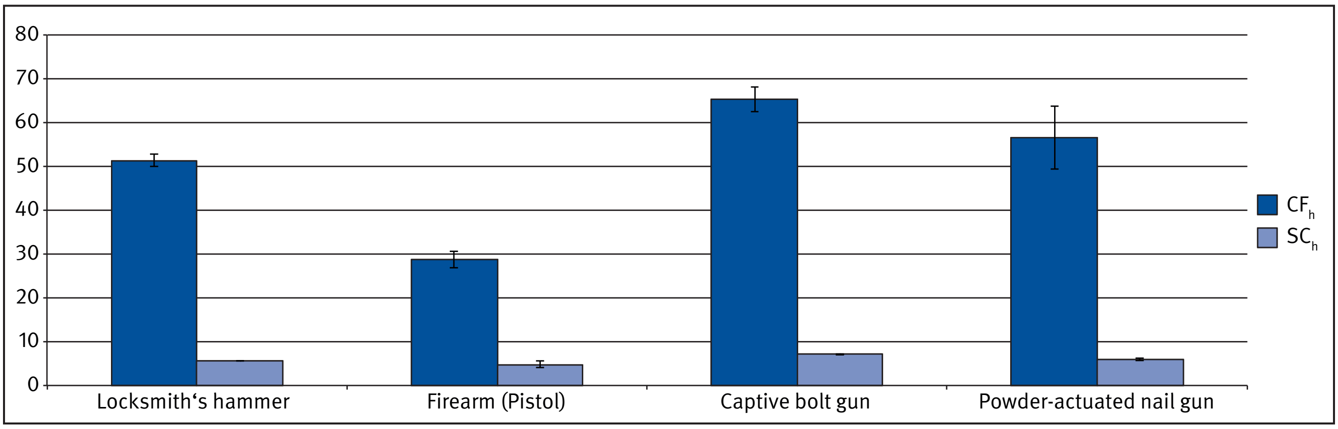
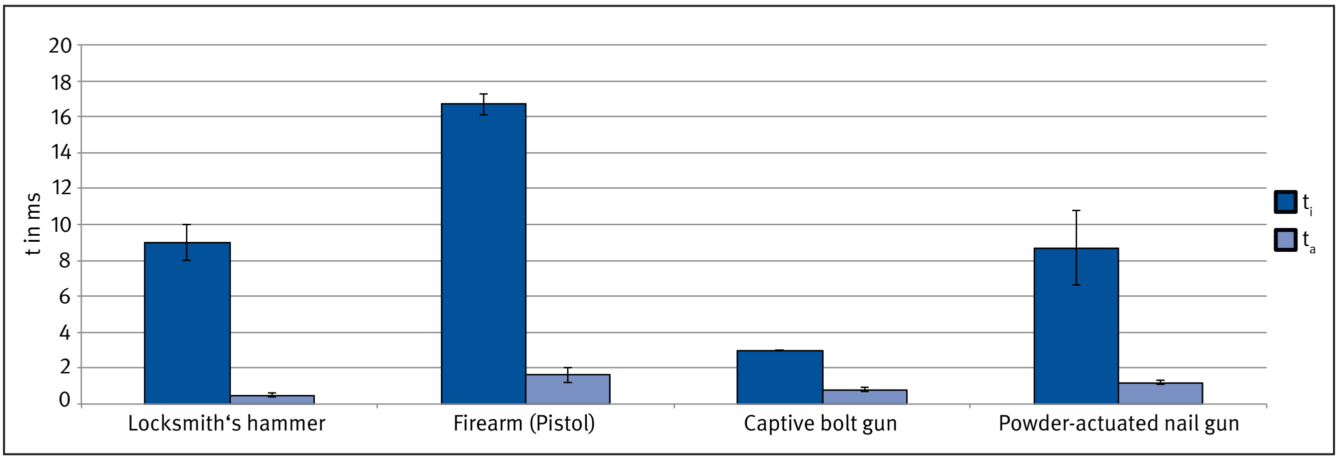


Figure 33:
Comparisons of the pulse durations t_i and rise times t_a of the tools tested



3.4 Summary of the test part

This part of the project studied typical tools the use of which is associated with the incidence of isolated shocks. For this purpose, tools were studied both for which movement is required on the part of the user prior to the isolated shock under analysis (locksmith‘s hammer and pneumatic nail driver), and for which no movement is required on the part of the user (pistol, captive bolt gun and powder-actuated nail gun). For tools requiring movement on the part of the user but not presenting vibration exposure, it was shown with reference to the example of the pneumatic air gun how such “falsification” of the measurement results can be avoided.

Substitute working methods were employed for the captive bolt gun and the locksmith‘s hammer in the interests of better reproducibility. This was not necessary for the other tools tested.

With reference to the existing standards, it was possible for a number of methods for determining the variables for the different forms of shock to be applied and trialled. Now available, these parameters can be referred to with regard to their suitability for assessing the risks of isolated shocks.

The variables for the tools determined in this way can be used in future studies, and extend the existing data on the subject of isolated shocks.

The measurement technology currently available enables isolated shocks to be measured and values for the vibration exposure to be determined in consideration of the underlying conditions.

The equipment specified in EN ISO 8041 (2005 edition with 2016 amendments) for measurement of human exposure to vibration continues to consider analogue measurement technology; the current measurement equipment is however based upon digital technology. Digital measurement equipment permits not only numerous computations of values, but often also analysis over time, and the combination of multiple additional measurement points.

The greatest source of uncertainty however continues to be the measurement sensor. Despite the facility for checking and harmonizing the phase response, measurements must be limited to one direction when shock exposure is high. If the direction of measurement can be maintained parallel to the direction of action, the relevant vibration exposure is then measured.

4 Part B: Laboratory experiments for the definition of shocks

4.1 Methods

4.1.1 Test arrangement

A standard test arrangement comprising a function generator (G), power amplifier (PA) and electrodynamic shaker (ES) was used for the laboratory tests. Figure 34 shows a block diagram of the test arrangement.

A handle was fitted to the vibrating plate of the electrodynamic shaker. The handle features force sensors for the gripping and pushing forces. Two accelerometers (A) were used to record the vibration signals on the vibrating plate of the electrodynamic shaker and on the handle. All measurement signals were recorded and analyzed by means of an eight-channel PC-based measurement system. During testing, the measurement signals were monitored at a suitable point on the screen/oscilloscope (OSC).

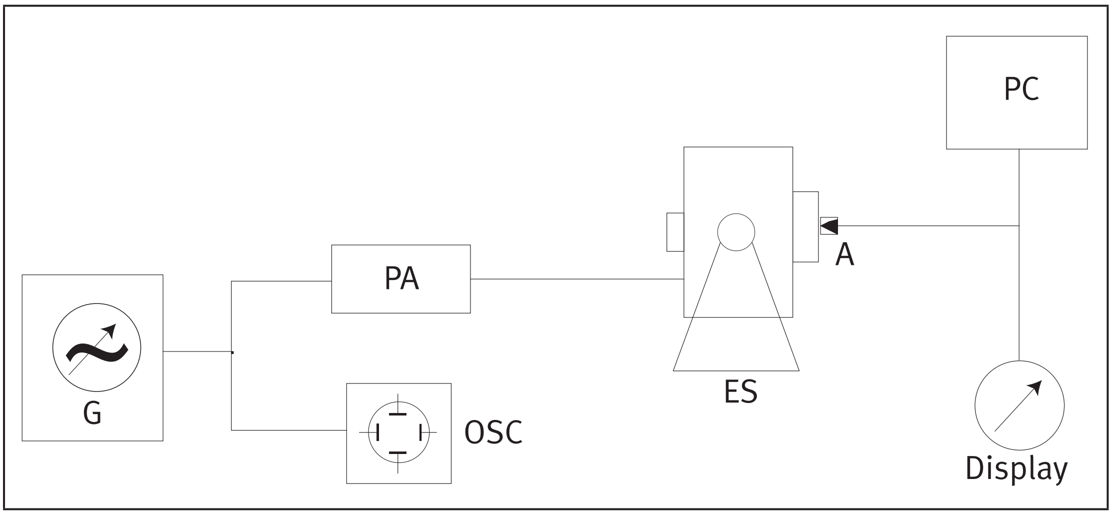


Figure 34: Block diagram of the test arrangement

The pilot tests and main tests were performed with essentially the same test arrangement, as described above, but with different types of electrodynamic shaker. The main tests were to be performed under conditions as similar as possible to those in practice. A relatively powerful shaker was therefore required in order to drive a handle with its mass and the applied pushing force, as far as possible without recoil. The pilot tests were performed for the purpose of obtaining more detailed information for selection of the underlying conditions for the main tests (signal form, signal parameters, influence of the point of load transfer, etc.). The use of the handle was not necessary in these tests, and no pushing forces requiring compensation arose. Use of a less powerful shaker was possible. The shaker used for the pilot tests had the advantage of possessing a smaller vibration plate. The test persons were thus able to rest their forearms or hands on a non-vibrating support and to place only the relevant finger or wrist on the vibration plate.

Figure 35 shows the test arrangement for the pilot tests, Figure 36 that for the main tests.

Vibration excitation systems employing the electrodynamic principle have many advantages with regard to their design, flexibility and scope of application, and are therefore very often used for vibration tests. However, the use of an electrodynamic shaker for shock exposure is in principle subject to tight limitations [42]. The limitation of low frequencies (high-pass effect) caused by the electronic drive results in quasi-static signal components being converted to a decaying, low-frequency vibration. This results for example in square-wave pulses increasingly being distorted in their signal form as the pulse duration increases. The clipping of higher frequencies (low-pass effect) caused by the mass and spring stiffness of the shaker components also gives rise to a frequency-dependent phase shift. At the frequency limit, this phase shift is 180°. Depending upon their duration, pulses may well contain frequency components close to or exceeding the upper frequency limit. The phase shift of the low-pass gives rise to changes in the signal characteristic over time, including changes to the peak values. Very short signals (pulses, shocks) are particularly affected by this phenomenon.

The suitability of electrodynamic shakers is therefore dependent not only upon the electrical and mechanical properties of the vibration excitation system, but also upon the characteristics of the test signal (duration, signal waveform, intensity). In the specific case here, the constraints described above apply primarily to shocks with realistic intensities and very short and very long pulses.

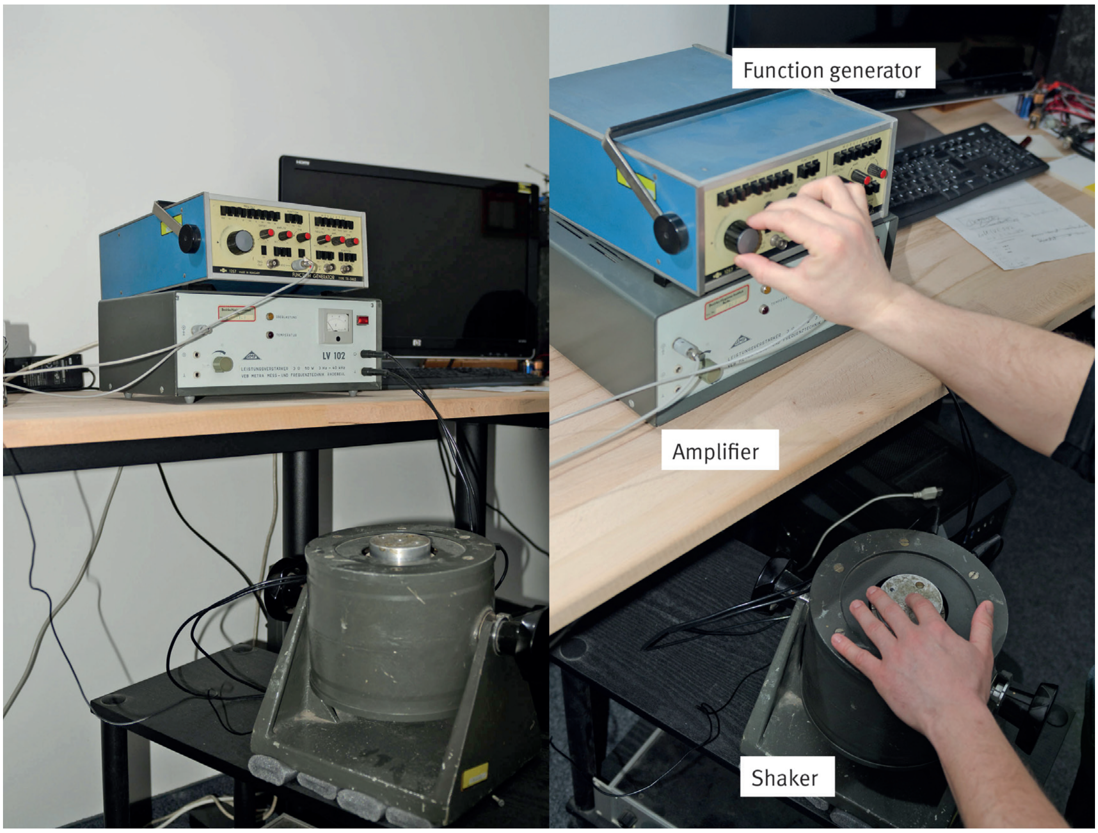


Figure 35:
Test arrangement used for the pilot tests

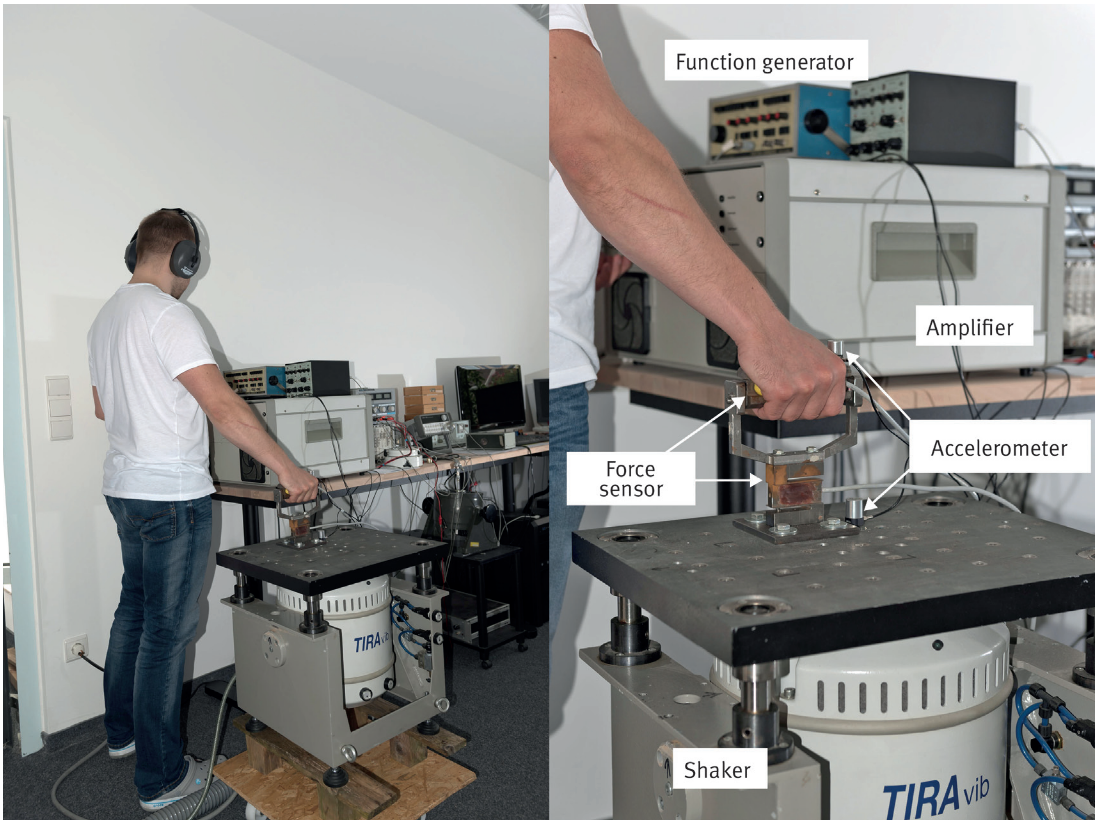


Figure 36:
Test arrangement used for the main tests

For the problem under consideration here however, realistic shock intensities are not required. In consideration of the cooperation required of the test subjects and the associated concentration required for the task, exposure at intensities encountered in the field would in fact have been more of an obstacle.

Figure 37 shows an example of semi-sinusoidal signals of 2 ms duration. The upper graph shows the vibration signal generated by the function generator. The middle graph shows the signal waveform measured on the shaker table in the form of an acceleration. It can be seen that the signal waveform generated by the function generator is still reproduced relatively well on the vibrating table at a peak value of 30 m/s², but that clear undershoot occurs as a result of the mass inertia of the table. For the tests to be performed here, this undershoot is however not considered disadvantageous, since comparison with the measured characteristic of a powder-actuated nail gun (bottom graph) shows that a similar vibration behaviour is quite common for shock signals on real-case machines.

It can therefore be reasonably assumed that under the underlying conditions described, the electrodynamic vibration excitation system is suitable for use in the studies planned here. In the pilot tests, detailed studies were conducted of the signal waveforms, signal durations, etc. to be employed in the main tests.

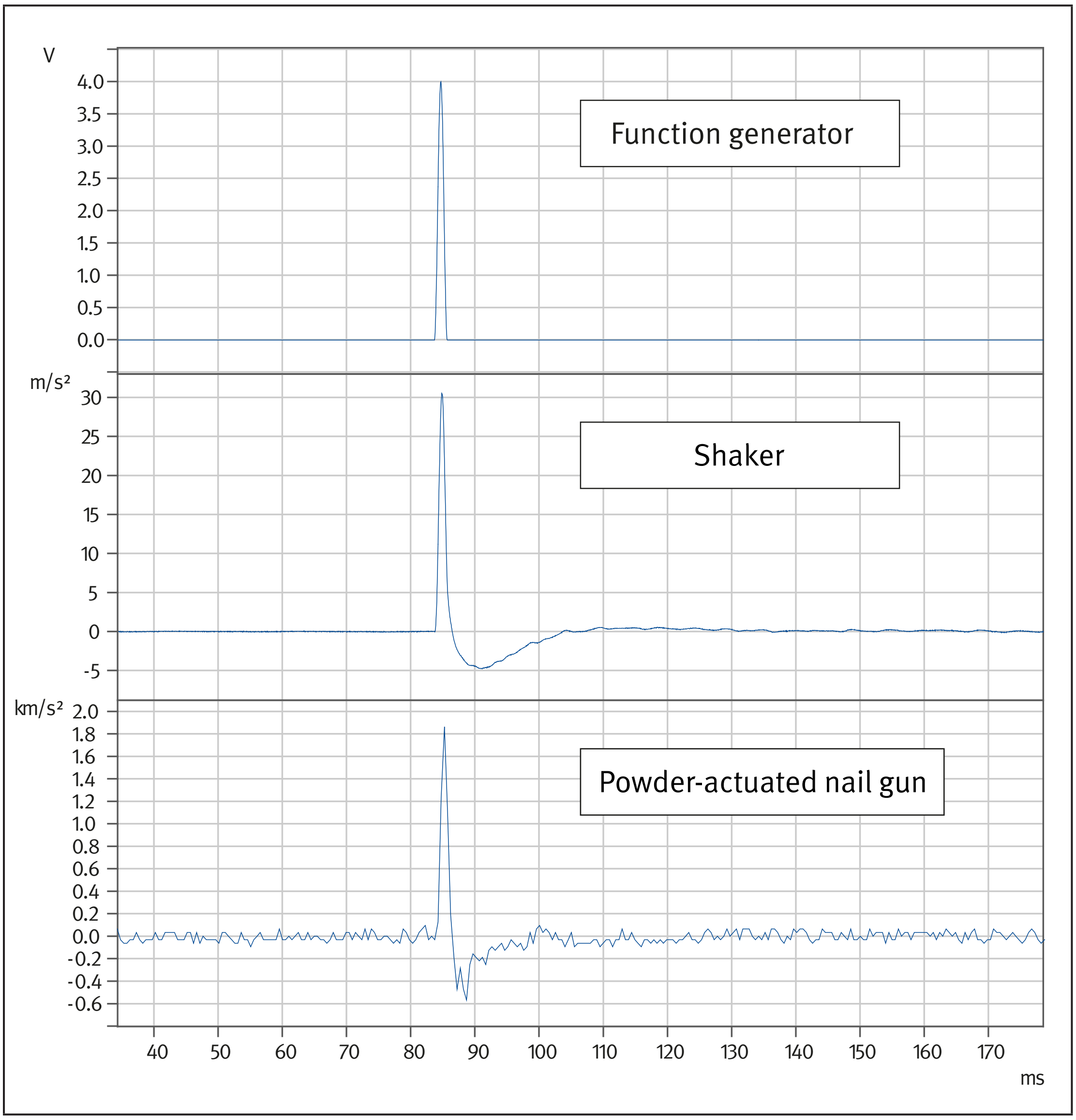


Figure 37:
Semi-sinusoidal signal characteristic on the generator output and on the shaker table in comparison with the signal characteristic on a powder-actuated nail gun

4.1.2 Test subjects

The tests were performed with a total of 24 male test subjects aged between 26 and 76 (mean: 51.2). Nine test subjects had manual occupations, 15 were primarily employed in office work.

The height of the test subjects lay between 174 and 193 cm (mean: 182 cm), the body weight between 73 and 120 kg (mean: 87.5 kg).

Annex D contains a table showing the individual properties of the test subjects. The pilot tests were performed with only the first seven of the test subjects shown in the table. All test subjects took part in the main tests.

4.2 Pilot tests

4.2.1 Performance of the tests

The pilot tests were performed in order to obtain basic information for the design of the underlying conditions and selection of the parameters for the main tests. For this purpose, tests were performed in accordance with Chapter 2, Problem 1, i.e. the test subjects were required to determine the subjective threshold between isolated pulses and series of pulses. These tests were repeated with different settings for the intensity and duration of the pulses, with different pulse waveforms, and with different points of load transfer.

Answers were sought to the following questions:

- What signal waveform is most suitable for subjective assessment of shock exposure?
- Does the subjective assessment differ at different intensities and different pulse durations?
- Do differences arise with respect to transfer to different parts of the hand (finger, heel of the hand)?
- Does the sequence have an effect (repeat effects)?

Pulses with repeated triangular pulses and semi-sinusoidal waveforms were used in the pilot tests. These repeated triangular pulses and semi-sinusoidal pulses were generated on the electrodynamic shaker with a range of pulse durations of 2, 10 and 30 ms, and with a specified peak intensity of approximately 20 m/s² (Figure 34, small shaker). The selected intensity of 20 m/s² is just above the sensation threshold. Since, at this low intensity, high concentration is required of the test subjects for the subjective perception, an additional test series was conducted with semi-sinusoidal pulses with a peak intensity of 100 m/s².

Initially, additional use of the square-wave pulse waveform was also considered. The initial results however revealed highly inconsistent reactions on the part of the test subjects. Owing to the difficulty of reproducing square-wave signals by means of electrodynamic shakers (see Section 4.1.1) and the improbability of square-wave pulses occurring under practical shock exposure conditions, square-wave pulses were not used in the further tests.

In order for the exposure to the test pulses to be subject to as little influence as possible, a handle was not used in the pilot tests. The mass of the handle, natural resonances, etc. were not therefore influencing factors. The test pulses were transferred through the 4 fingertips and the outer wrist bone (pisiform bone, *os pisiforme*) of the left and right hands. The test subjects were required to lay their fingers/wrists gently on the plate of the shaker without applying additional pressure.

The test arrangement enabled the test subjects to adjust the strike rate of the series of pulses, i.e. the interval between consecutive pulses, on the function generator. When the periods between the individual events (pulses) are relatively long, they can be sensed clearly. This is the range of repeated isolated pulses/shocks. When the period between the individual events becomes shorter (i.e. the strike rate increases) and a certain threshold is crossed, the isolated pulses can no longer be distinguished from each other. The limit at which this occurs was to be set by the test subjects.

Prior to performance of the test, the test subjects were provided with written instructions for the test (see Annex E) to ensure that they all received the same preparation for it. Any questions were then answered by the test supervisor. In order to provide a better understanding of the test and to familiarize the test subjects with the test apparatus, three trial settings were performed that were not assessed.

All measurements were repeated again twice, i.e. three measurements in total per test condition. The strike rate in s^{-1} set by the test subjects as the threshold at which discrete pulses (isolated shocks) could be differentiated from series of pulses was analyzed. The results were analyzed by means of the StatSoft STATISTICA software application, Version 6. Single-factor and multi-factor variance analyses were performed.

4.2.2 Results of the pilot tests

The statistical values of the mean, standard deviation, minimum and maximum (see Table 5) and the frequency distribution (Figure 38) were obtained, providing an initial overview of the data.

The mean value for the strike rate set by the test subjects as the threshold for distinction between isolated pulses and series of pulses was 18.3 pulses per second. Relatively large spread, not expected in this form, was observed, with a standard deviation of almost 5 s^{-1}. The minimum and maximum values are approximately 10 s^{-1} below/above the mean. The frequency distribution (Figure 38) clearly indicates non-random spread of a two-peak distribution with local maxima at approximately 14 and 25 s^{-1}.

Further statistical analysis was performed in the way of study of the influencing factors of test repetition (1st to 3rd measurement), left vs. right hand, pulse duration (2, 10 or 30 ms), pulse intensity (20 or 100 m/s²) and pulse waveform (repeated triangular or semi-sinusoidal) (Table 6). No significant differences as a function of these influencing factors were observed in the strike rate selected as a threshold.

Table 5:
Statistical values of pilot tests (summary of the complete body of data)

	Mean	Minimum	Maximum	Standard deviation
Threshold between discrete pulses and pulse series	18.30	9.75	30.05	4.81

Figure 38:
Frequency distribution of the strike rate for the threshold between isolated pulses and series of pulses

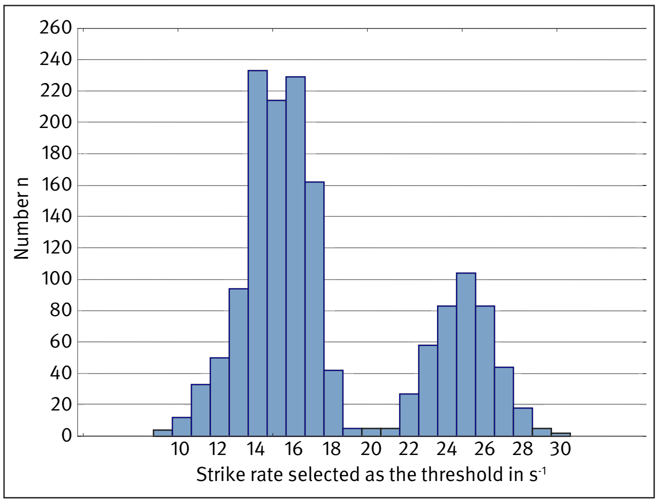


Table 6:
Statistical values of the threshold between distinct pulses and pulse series in s^{-1}; influencing factors of test repetition, left vs. right hand, pulse duration, pulse intensity, pulse waveform

	Mean	Standard deviation	Minimum	Maximum
1st measurement	17.88	4.83	9.01	30.03
2nd measurement	18.18	4.86	9.80	30.05
3rd measurement	18.03	4.82	10.05	29.71
Right hand	18.03	4.88	9.01	29.76
Left hand	18.03	4.78	9.80	30.05
2 ms	18.05	4.74	9.80	30.03
10 ms	17.94	5.03	9.83	30.05
30 ms	18.10	4.74	9.01	29.12
20 m/s²	17.86	4.97	9.01	30.05
100 m/s²	18.37	4.54	10.26	28.45
Semi-sinusoidal	17.78	4.92	9.80	29.12
Sawtooth	18.16	4.79	9.01	30.05

A significant dependency of the selected threshold upon the point of load transfer was however observed (significance level $\alpha \leq 0.005$). The results of the statistical analysis are shown in Table 7 and Figure 39. In the graphical presentation in the figure (and in further descriptions below in the text), means are compared to the corresponding values for scatter for the individual test conditions. The mean in each case is presented by a dot/small square. The range for ± 1 standard deviation is shown by the closed rectangle around this point, and the full range of values between the minimum and maximum by "T" bars.

The results show somewhat lower mean values for the point of load transfer directly on the thin layer of skin over the pisiform bone compared to transfer through the fingertip. For all points of load transfer, the scatter was however in the same order of magnitude as for the body of data as a whole.

Based upon the means, it can also be concluded that the differences – relatively low despite their statistical significance – between the values for the fingers and the pisiform bone cannot be the cause of the two peaks in the study results.

If the measured values for the point of load transfer through the pisiform bone are eliminated from the statistical analysis, no statistically significant differences between the individual fingers on the left and right hands remain for the remaining measured values of the point of load transfer through the fingertips.

The final influencing factor, that of the statistical values of the individual test subjects, was also studied (Table 8, Figure 40).

Table 7:
Effect of the point of load transfer upon the selected threshold between isolated pulses and series of pulses

Point of load transfer	Abbreviation	Mean	Standard deviation	Minimum	Maximum
Right, 2nd digit	R2	18.15	4.96	10.05	29.76
Right, 3rd digit	R3	18.44	4.94	9.79	29.71
Right, 4th digit	R4	18.26	4.78	9.83	28.43
Right, 5th digit	R5	18.32	4.87	10.79	28.16
Right-hand pisiform bone	RHPB	17.00	4.78	9.01	26.88
Left, 2nd digit	L2	18.20	4.74	10.71	29.24
Left, 3rd digit	L3	18.51	4.80	9.80	30.05
Left, 4th digit	L4	18.28	4.70	9.80	28.38
Left, 5th digit	L5	18.22	4.74	10.88	30.03
Left-hand pisiform bone	LHPB	16.93	4.83	9.95	27.73

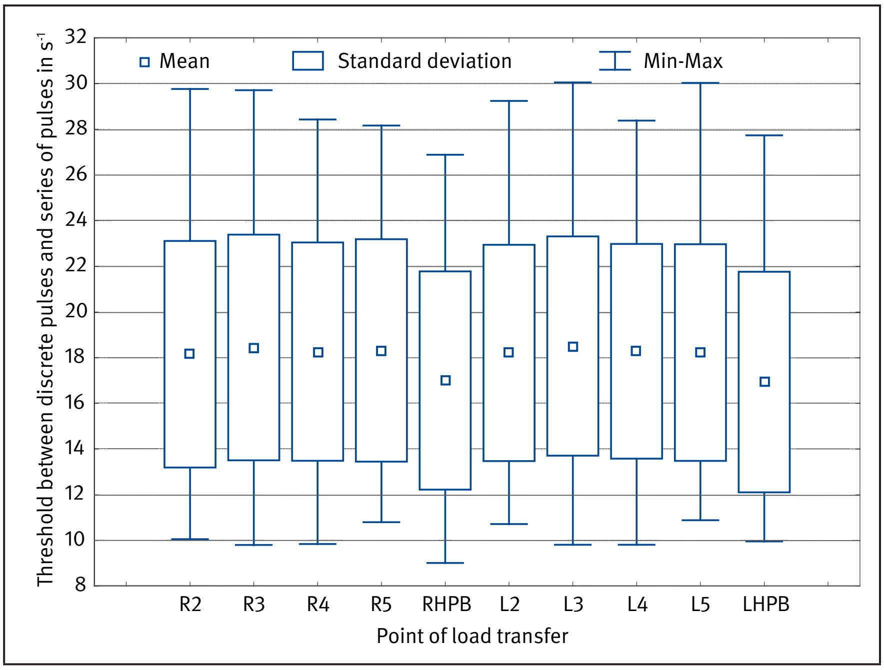


Figure 39:
Effect of the point of load transfer upon the selected threshold between isolated pulses and series of pulses

Table 8:
Statistical values for the influence of the test subjects

Test subject No.	Mean	Standard deviation	Minimum	Maximum
1	24.34	1.52	18.36	28.79
2	13.45	1.73	9.01	17.68
3	16.47	1.69	10.88	20.52
4	15.20	1.42	11.47	19.77
5	15.74	1.42	11.56	19.11
6	15.14	1.45	10.03	18.48
7	25.88	1.68	20.79	30.05

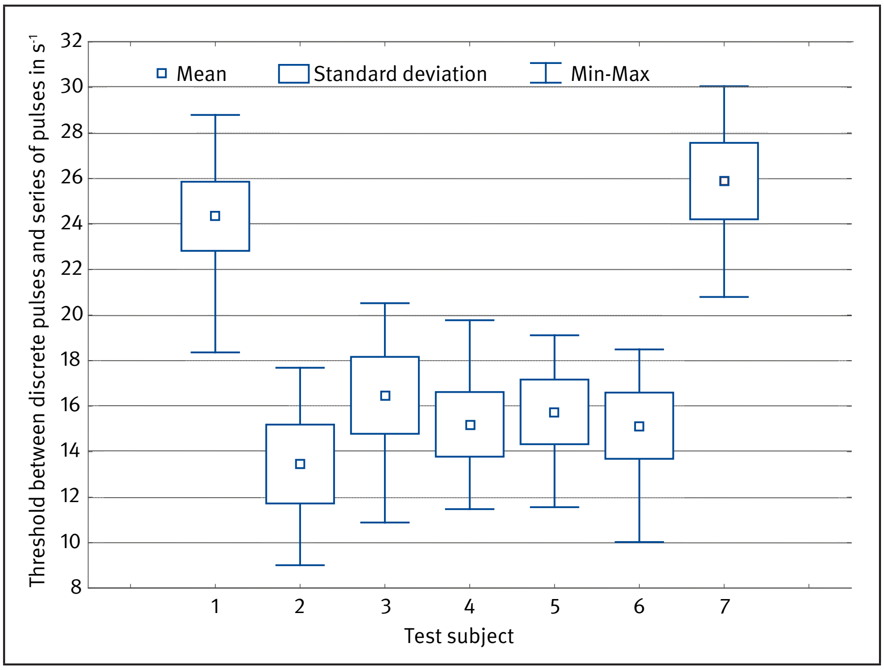


Figure 40:
Influence of the test subjects upon the selected threshold between isolated pulses and series of pulses

It can be seen that test subjects 1 and 7 selected substantially higher pulse strike rates than the other test subjects. The high scatter of the body of data as a whole is therefore caused by the major variation between the test subjects. The scatter in the values for each individual test subject is substantially lower than for the body of data as a whole. The two peaks in the frequency distribution of the body of data as a whole are caused by test subjects 2 to 6 with means in the range from 13 to 16 s^{-1} on the one hand and by test subjects 1 and 7 with means in the range from 24 to 26 s^{-1} on the other. At a significance level $\alpha \leq 0.001$, the differences are highly significant.

These observed differences cannot be explained by the underlying conditions of the test arrangement and performance of the tests. More intensive discussions were therefore held with the test subjects in order to determine the cognitive method they employed for selecting the threshold. It was found here that test subjects 2 to 6 concentrated on the isolated pulses and the periods between them. The criterion for selection of the threshold was the point at which the periods between the pulses were no longer perceived. Test subjects 1 and 7 pursued a different strategy for selecting the threshold: they regarded everything as an isolated pulse that produced the sense of brief changes (pulses) in perception. Only when these changes at short intervals transitioned to a perception of more or less diffuse vibration, a "tingling", were they regarded as a series of pulses.

There are therefore evidently three subjectively perceived ranges of sequences of pulses succeeding each other at a greater or lesser rate:

- Isolated pulses
- Series of pulses
- Perceived stochastic/diffuse vibration

The written instructions for the test were prepared before this observation was made, and so requested only **one** threshold demarcating the two different ranges of isolated pulses and series of pulses. Owing to this lack of clarity in the formulation of the test instructions, the test subjects reached different decisions.

It can therefore be concluded that the written test instructions, with their request to demarcate two subjectively perceived ranges, were open to misunderstanding. New test instructions with clear formulations were to be drawn up for the main tests.

Discussions with the test subjects further revealed that the specification of a certain strike rate as the threshold between isolated pulses and series of pulses is evidently primarily a conscious rational decision rather than an issue of peripheral sensory perception. Besides other influencing factors (interest, curiosity, intelligence, etc.), all influencing factors with a bearing upon the test subjects' concentration (fatigue, noise, etc.) are therefore also relevant. For this reason, the duration of testing should be limited to a maximum of 30 minutes. The test subjects should not be overtaxed by an excessive number of variations (e.g. differences in pulse waveform) and diversion of their attention to other underlying conditions (e.g. additional observation of a pushing force display).

For the main tests, it was also significant that the point of load transfer to the human body, i.e. the hand-arm system, evidently influences the choice of demarcation point between isolated pulses and series of pulses. Only one transfer point was therefore selected for the main tests: transfer through a handle, which most closely resembles real-case shock exposure.

Since transfer through the right vs. the left hand evidently has no influence upon the test results, it was possible to limit transfer to the right hand for the purposes of the main tests. The pulse duration and pulse waveform also have no influence within the selected value range. In consideration of the shock parameters arising in real-case exposure, 3 ms repeated triangular pulses were selected as test pulses for the main tests.

The test subjects were able to draw relatively reliable conclusions even at very low pulse intensities. Variation of the intensity or selection of higher intensities was not therefore necessary in the subsequent tests.

4.3 Main tests

4.3.1 Performance of the tests

The results of the pilot tests as described in the previous section were used for the design of the main tests. Two main tests were performed:

- Main test 1:
  Study of the influence of the strike rate upon the perception of shock

- Main test 2:
  Study of the influence of the event duration and intensity upon the perception of shock

Main test 1

In main test 1 the test subjects were presented, through the handle of the shaker, with series of pulses with adjustable periods between the isolated pulses. Repeated triangular pulses with a pulse duration of 3 ms were used in all cases.

Prior to the tests, the test subjects were required to adjust the intensity of the pulses such that they lay slightly above the perception threshold whilst still being easily detectable. The intensity of all isolated pulses was constant during the tests.

The test subjects were able to adjust the strike rate of the pulse series, i.e. the interval between the successive pulses, on the function generator. When the periods between the individual events (pulses) are relatively long, they can be sensed clearly. This describes the range in which repeated isolated pulses/isolated shocks occur. When the periods between the individual events become shorter (i.e. the strike rate becomes greater) a "threshold A" is crossed. Then the range of the pulse series is reached, in which the individual events are still perceived as pulses, but the period between them is no longer perceptible. When the time periods are reduced further still and the "threshold B" is crossed, the isolated pulses can no longer be perceived as discrete events; the pulse series are then perceived only as diffuse vibration, i.e. “tingling”.

The test subjects had the task of setting the two different thresholds for the strike rate, threshold A and threshold B, according to their subjective perception. Threshold A distinguishes between the range of the repeated isolated pulses (shocks) and the range of the pulse series (sequence of shocks). Threshold B distinguishes between the range of the pulse series and the range of perceived diffuse (stochastic) vibration. There are therefore three ranges of different perception in total to be demarcated.

The tests were performed at three different pushing forces:

- Virtually no pushing force (only loose contact of the hand enclosing the handle)
- Light pushing force
- Medium pushing force

The pushing force exerted was determined by the test subjects subjectively in these three ranges in accordance with the instructions and following a number of pilot tests. Since the test subjects were not to be distracted from the test task proper, i.e. selection of threshold A and threshold B, the pushing force was not adjusted with the aid of a force meter, which would be the normal procedure in such tests. The pushing force actually exerted in the individual tests was recorded separately.

All test subjects were prepared for the test task by means of written test instructions, which were modified in consideration of the results of the pilot test (see Annex F). Any questions were then answered by the test supervisor. In order to provide a better understanding of the test and to familiarize the test subjects with the test apparatus, three trial settings were performed that were not assessed. All tests were performed a total of three times (repeated twice) by each test subject.

The strike rates in s^{-1} selected by the test subjects as threshold A and threshold B were analyzed. The StatSoft STATISTICA software application, Version 6, was used for this purpose. Single-factor and multi-factor variance analyses were performed.

Main test 2

In the second main test, repeated triangular pulses of different pulse duration were transmitted through the handle of the shaker into the hand-arm system of the test subjects.

Pulse duration:
1 ms, 2 ms, 5 ms, 10 ms, 20 ms, 30 ms, 50 ms, 80 ms and 100 ms

The test subjects had the task of varying the intensity of the pulse until the threshold of shock perception was just reached. At very low movements, the intensity was therefore to be increased until the movement was perceived as a shock. Conversely, if the shock was felt clearly, the intensity was to be reduced again until the transition to a non-shock, i.e. to a simple movement of the handle, was reached. The tests were performed at two different pushing forces:

- Virtually no pushing force (only loose contact of the hand enclosing the handle)
- Light pushing force

The pushing forces were exerted by the test subjects subjectively in accordance with the instructions and following a number of pilot tests. Since the test subjects were not to be distracted from the test task proper, i.e. differentiation between “shock” and “non-shock”, the pushing force was not adjusted with the aid of a force meter, which would be the normal procedure in such tests. The pushing force actually exerted in the individual tests was recorded separately.

All test subjects were prepared for the test task by means of written test instructions (see Annex G). Any questions were then answered by the test supervisor. In order to provide a better understanding of the test and to familiarize the test subjects with the test apparatus, three trial settings were performed that were not assessed. All tests were performed a total of three times (repeated twice) by each test subject. The different pulse durations were presented in a random order which differed between test passes but was the same for all test subjects.

The acceleration in the form of root-mean-square values and positive peak values measured on the handle was evaluated for each combination of pulse duration and intensity declared by the test subjects as a “shock”. The root-mean-square (RMS) values were measured with an integration time of 1 s in accordance with DIN 45661-A1 [43] and with an integration time of 3 s in accordance with ISO/TS 15694 [12]. The root-mean-quad (RMQ) values were also measured with an integration time of 3 s in accordance with ISO/TS 15694. All RMS and RMQ values were measured with different frequency weighting functions:

- Linear in accordance with the available frequency range of the measurement technology used (pass band 2 Hz to 20 kHz)
- $Flat_h$ frequency weighting in accordance with ISO/TS 15694 (pass band 6.3 Hz to 1.25 kHz)
- W_p weighting in accordance with ISO/PWI 18570 (pass band 20 to 400 Hz) [44]
- W_h weighting in accordance with EN ISO 5349-1 [4]

The results were analyzed by means of the StatSoft STATISTICA software application, Version 6. Single-factor and multi-factor variance analyses were performed.

4.3.2 Results of the main tests

Results of main test 1

This section describes the results of main test 1, which studied the influence of the strike rate of a pulse series (sequence of isolated pulses/shocks), i.e. the interval between successive pulses, upon the subjective distinction between its perception as repeated isolated pulses, series of pulses and diffuse vibration.

The raw data obtained were first subjected to a descriptive analysis. This revealed that the data from test subject 14 were completely inconsistent and therefore had to be excluded from analysis. The measurement data for threshold A and B were recorded a total of three times for each test subject (i.e. the test was repeated). The differences between the values measured in the three test runs were not significant under otherwise identical underlying conditions. An influence by the sequence of this test repetition was not therefore detected. The measured values for the three repeats were therefore averaged for each individual test subject and for the individual test conditions. Only the averaged data were used for subsequent analysis.

The frequency distribution of all averaged data for threshold A (distinction between isolated pulses and series of pulses) and for threshold B (distinction between series of pulses and perceived diffuse vibration) is shown in Figure 41. The distributions for the values of threshold A and threshold B approximate a normal distribution. It can be seen that although the two distributions overlap in a sub-range, they are otherwise clearly distinguishable from each other. The scatter for the values of threshold B is somewhat greater than for threshold A.

Table 9 shows the statistical values measured.

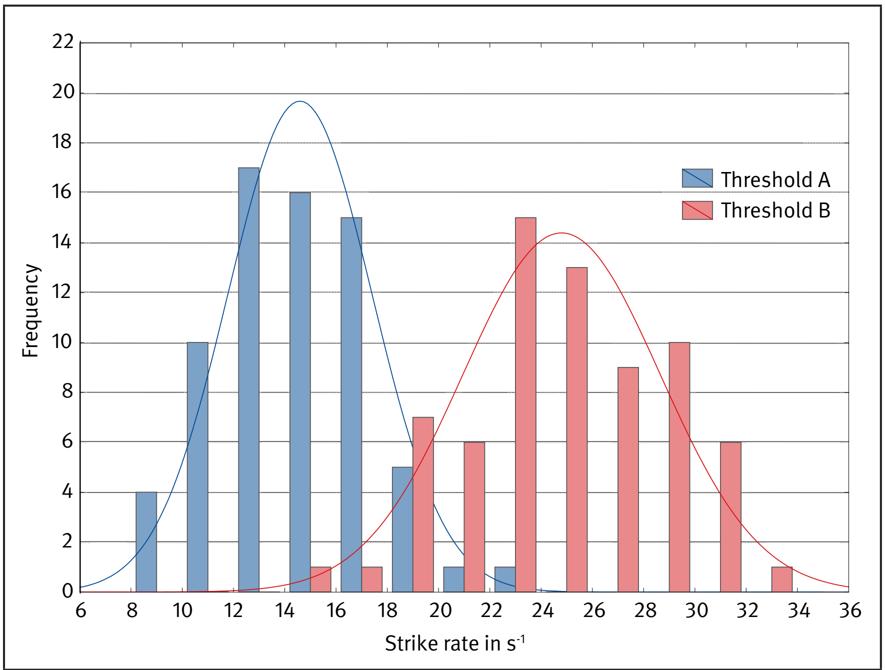


Figure 41:
Frequency distribution of the strike rate for threshold A and threshold B

Table 9:
Statistical values of main test 1 (overview of the complete body of data)

Threshold	Mean	Minimum	Maximum	Standard deviation
A	14.55	9.82	23.29	2.78
B	24.71	14.61	32.07	3.83

The strike rate set by the test subjects as the threshold between isolated pulses and series of pulses (threshold A) is on average around 15 s^{-1}, with a minimum of around 9.8 s^{-1}. It is therefore seen that the test subjects are still able to distinguish repeated isolated pulses clearly from each other when their strike rate lies substantially above 5 or 5.6 s^{-1}.

The strike rate set by the test subjects as the threshold between pulse series and perceived diffuse vibration (threshold B) is on average approximately 25 s^{-1}.

At a significance level of $\alpha \leq 0.001$, the difference between the strike rates for threshold A and threshold B is statistically highly significant.

Figure 42 shows the three different perception ranges with the two thresholds A and B in combination with the measured values.

A significant statistical relationship (correlation coefficient ($r = 0.65$, $\alpha \leq 0.05$) exists between the values for threshold A and threshold B. Figure 43 shows the values set by each test subject for threshold A and threshold B in the form of a scatter plot with the linear regressions (thick red line) derived from the values and the 95% confidence interval (thin red lines). The regression equation is:

$$\text{threshold A} = 0.47392 \cdot \text{threshold B} + 2.8421$$

With an offset of approximately 3 s^{-1}, threshold A is therefore set by the individual test subjects at around half the value of threshold B.

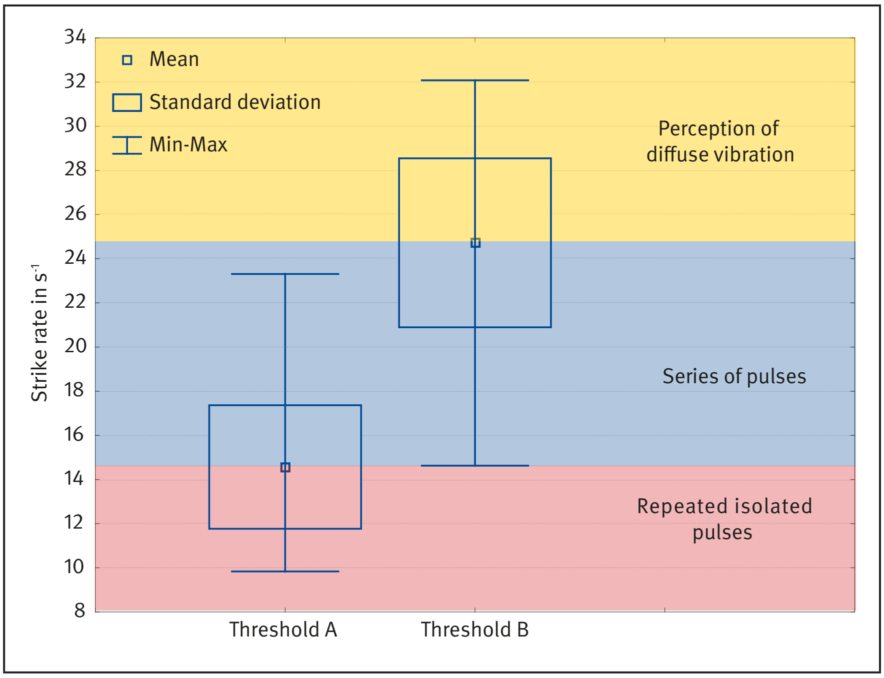


Figure 42:
Three perception ranges to be distinguished, demarcated by threshold A and threshold B

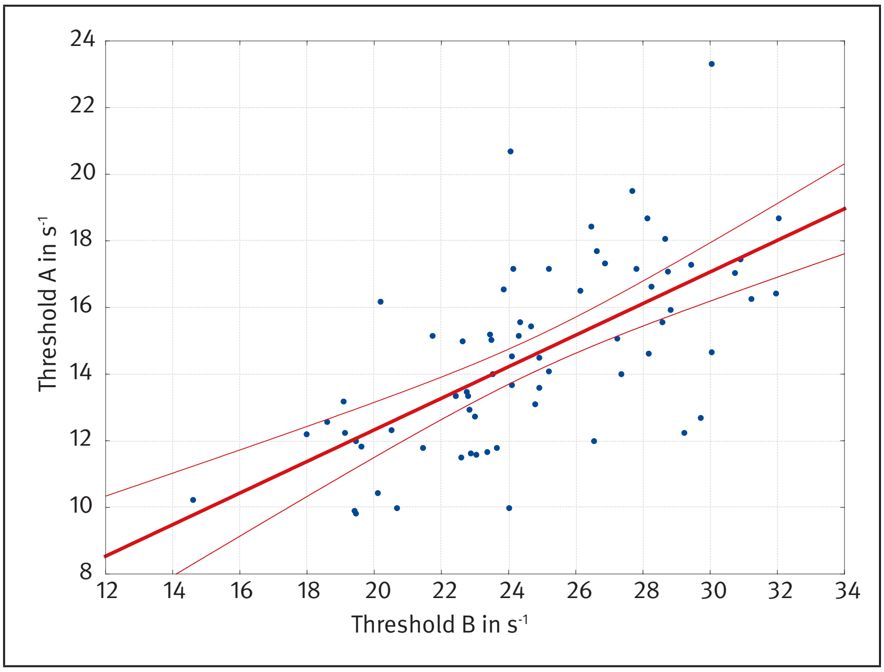


Figure 43:
Relationship between threshold A and threshold B

For further clarification of the relatively high scatter, the influence of the individual test subjects was studied. Tables 10 and 11 and Figure 44 show the mean values, standard deviations and extreme values for the individual test subjects, broken down for threshold A and threshold B.

It can be seen that the individual test subjects set mean values for threshold A and threshold B that differ, in some cases widely ($\alpha \leq 0.001$), and that also exhibit substantial variation in the scatter of their individual values. At the same time however, the relationship between threshold A and threshold B discussed above is also evident. It can be concluded that the values set for threshold A and threshold B can be considered valid values specific to individuals. The scatter arising in the overall means described above is caused primarily by the scatter between the test subjects, and less by the scatter for an individual test subject themselves (with some exceptions, such as test subject 19).

The setting of threshold A and threshold B differed significantly however ($\alpha \leq 0.001$) in the test groups depending upon the group of workers to which the individual belonged: those primarily performing office work, and those primarily performing manual work. Office workers set lower values for threshold A and threshold B. The scatter among manual workers is substantially lower, such that the distributions for threshold A and threshold B no longer overlap (see Table 12 and Figure 45).

Table 10:
Threshold A

Test subject No.	Mean	Standard deviation	Minimum	Maximum
1	14.83	1.53	13.17	16.16
2	10.05	0.34	9.82	10.44
3	11.65	0.11	11.57	11.78
4	15.66	1.47	14.61	17.34
5	14.52	1.41	12.92	15.57
6	13.28	0.50	12.72	13.67
7	16.46	1.13	15.15	17.16
8	17.20	1.08	16.54	18.44
9	12.41	2.50	9.97	14.97
10	11.26	0.92	10.20	11.80
11	12.33	0.20	12.18	12.56
12	16.14	2.66	13.10	18.05
13	14.26	0.84	13.58	15.20
15	16.05	1.37	14.51	17.14
16	13.18	1.30	12.22	14.65
17	11.21	1.07	9.99	12.00
18	15.68	1.49	14.08	17.03
19	15.33	2.89	13.35	18.65
20	19.39	3.39	17.17	23.29
21	12.26	0.96	11.47	13.33
22	16.71	0.65	16.25	17.46
23	19.62	1.01	18.69	20.69
24	15.17	0.54	14.55	15.54

Table 11:
Threshold B

Test subject No.	Mean	Standard deviation	Minimum	Maximum
1	20.33	1.33	19.07	21.73
2	19.65	0.40	19.40	20.12
3	23.20	0.41	22.90	23.67
4	26.19	2.41	23.50	28.18
5	26.21	3.02	22.82	28.59
6	23.29	0.73	22.77	24.12
7	25.73	2.62	24.13	28.75
8	26.19	2.22	23.85	28.25
9	21.27	1.18	20.50	22.63
10	18.57	3.55	14.61	21.47
11	18.57	0.59	17.97	19.15
12	27.63	2.50	24.78	29.43
13	23.96	0.83	23.43	24.92
15	26.29	1.46	24.92	27.82
16	29.67	0.41	29.23	30.05
17	24.64	1.67	23.36	26.54
18	28.26	2.81	25.21	30.75
19	27.41	4.63	22.80	32.07
20	27.29	2.48	25.22	30.04
21	21.49	1.76	19.46	22.58
22	31.37	0.53	30.91	31.95
23	26.63	2.23	24.07	28.14
24	24.38	0.29	24.11	24.69

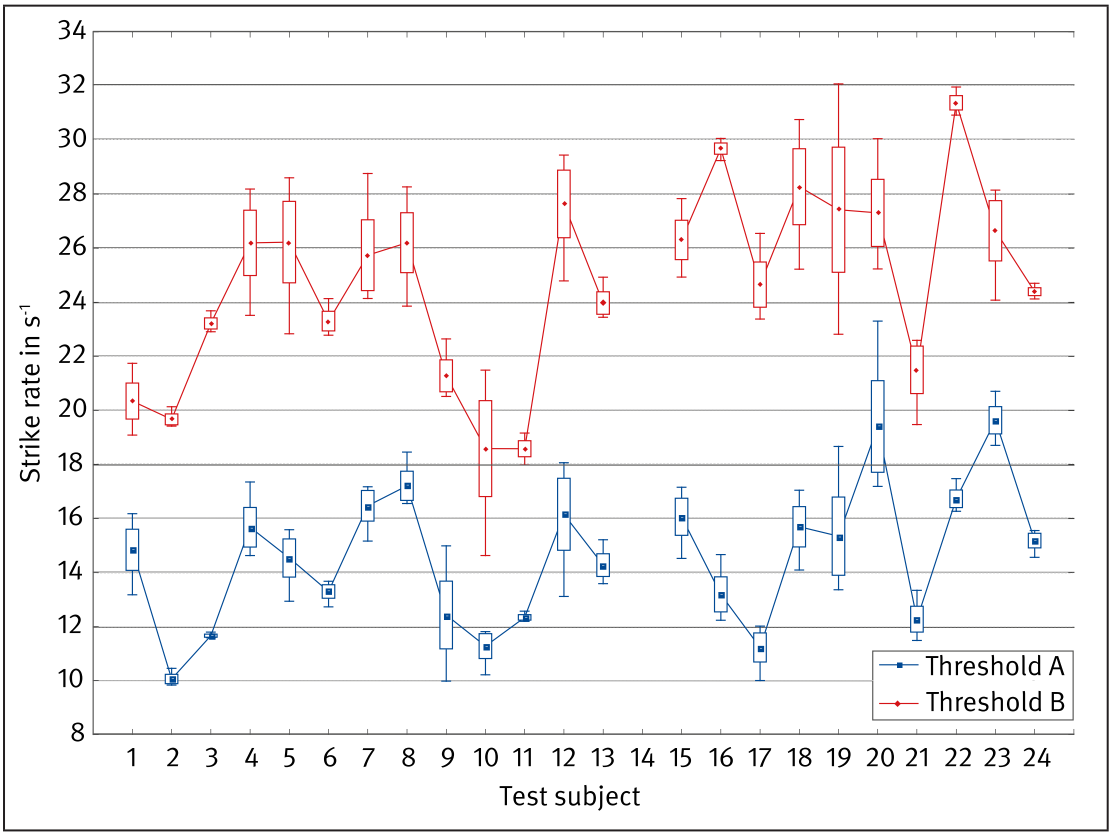


Figure 44:
Mean values, standard deviations and extreme values for the individual test subjects for threshold A and threshold B

Further analysis of the person-specific influencing factors (Tables 13 and 14) revealed a significant influence of body mass (α ≤ 0.01) and age (α ≤ 0.01) upon the values for threshold A, but not upon the values for threshold B. The influence of body height and of the pushing force was not significant in any of the cases.

Table 12:
Statistical values for the influence of the type of work performed

	Mean	Stndard deviation	Minimum	Maximum
Threshold A				
Office workers	13.84	3.06	9.82	23.29
Manual workers	15.88	1.55	12.92	18.44
Threshold B				
Office workers	23.64	3.94	14.61	32.07
Manual workers	26.70	2.70	22.82	31.95

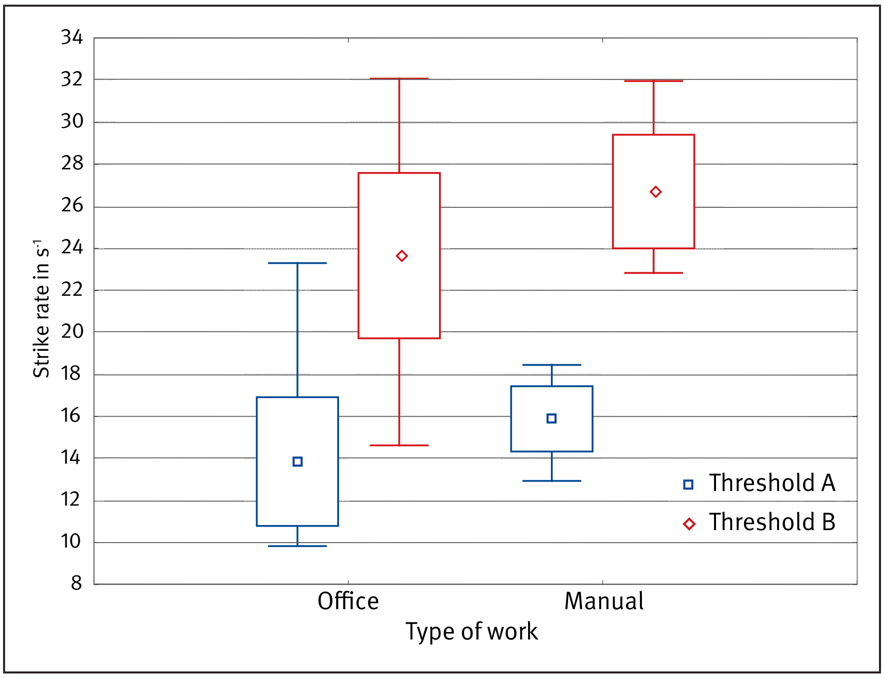


Figure 45:
Effect of the type of work performed upon threshold A and threshold B

Table 13:
Threshold A

	Mean	Standard deviation	Minimum	Maximum
Body height				
Short	15.15	2.62	9.99	23.29
Medium	14.10	2.97	9.82	20.69
Tall	14.04	2.56	9.97	17.34
Body weight				
Light	15.43	1.96	12.72	18.65
Medium	14.47	3.13	9.82	23.29
Heavy	12.86	2.28	10.20	17.34
Age				
Young	13.08	2.39	9.82	18.65
Medium	14.35	2.82	10.20	20.69
Old	16.04	2.44	11.47	23.29
Pushing force				
None	13.71	2.46	9.88	19.48
Light	14.61	2.83	9.82	20.69
Strong	15.34	2.96	10.20	23.29

Table 14:
Threshold B

	Mean	Standard deviation	Minimum	Maximum
Body height				
Short	25.28	2.97	19.07	32.07
Medium	24.36	4.57	14.61	31.95
Tall	23.73	3.19	20.50	28.18
Body weight				
Light	26.06	3.92	19.07	32.07
Medium	24.45	3.57	17.97	30.75
Heavy	22.65	3.96	14.61	28.18
Age				
Young	24.17	4.12	19.07	32.07
Medium	23.97	4.32	14.61	31.95
Old	25.91	2.74	19.46	30.75
Pushing force				
None	24.52	3.26	19.07	31.24
Light	24.21	3.54	17.97	30.91
Strong	25.39	4.62	14.61	32.07

Results of main test 2

The results of main test 2 were analyzed with the aim of producing curves of equivalent shock perception based upon the respective combinations of pulse duration and pulse intensity which were perceived by the test subjects as “shock”. These curves were to be determined separately for the different measurement parameters with the respective different frequency weighting curves.

Since it was shown in the statistical analyses that the pushing force and measurement repetition were not significant influencing factors, it was possible for the measured values to be averaged across the individual test conditions. The initial analyses further revealed substantial outliers in the direction of very high intensities for some test subjects. These values were excluded from the analyses.

All individual results are presented graphically in the annex as mean values across test subjects, pushing force conditions and repeats with the associated 95% confidence ranges. All graphs show the intensity just sufficient to be perceived by the test persons as a “shock” at a given pulse duration.

Presentation and interpretation of the results was accompanied by the problem that for four of the measurement parameters (three different time-averaged values and the peak value) in combination with the four different frequency weighting functions, a relatively confusing number of graphical presentations was required. In this context, graphs are advantageous that show on the one hand, the influence of the measurement parameter at a given frequency weighting, and on the other, the influence of the frequency weighting at a given measurement parameter. It was further shown that the different graphical presentations of the data, firstly on a linear scale and secondly on a double logarithmic scale, yielded additional information. In order for clarity nevertheless to be assured, individual parameters representative of a large volume of similar data have been selected, presented and interpreted in this section. In the interests of completeness, all individual results are however presented in Annex H.

Figure 46 shows the mean characteristic of the perceived shock for the different measurement parameters of the peak value, the RMS value with time constant of 1 and 3 s, and the RMQ value when the linear frequency weighting (pass band 2 Hz to 20 kHz) is applied. It can be seen that at longer pulse durations, even very low intensities (approx. 5 m/s² peak-to-peak) are sufficient for a movement of the handle on the shaker to be perceived as a “shock”. If the movements (the pulses) are shortened, higher intensities are required in order for them to be perceived as shocks. However, even at very short pulse durations, peak values of approximately 100 m/s² are sufficient for the test subjects to perceive the pulses (movements) as shocks.

The curve of the perceived shock exhibits an almost exponential drop at higher pulse durations. The numerical values for the shock intensity are by their nature most pronounced at the peak values. The next highest numerical values are attained when the RMQ values are used, as a consequence of use of the fourth power in averaging. Owing to the averaging of a very short, time-limited event over a short period of time, the numerical values are next highest for the RMS values with an averaging time of 1 s. The lowest values are exhibited by the RMS values with an averaging time of 3 s.

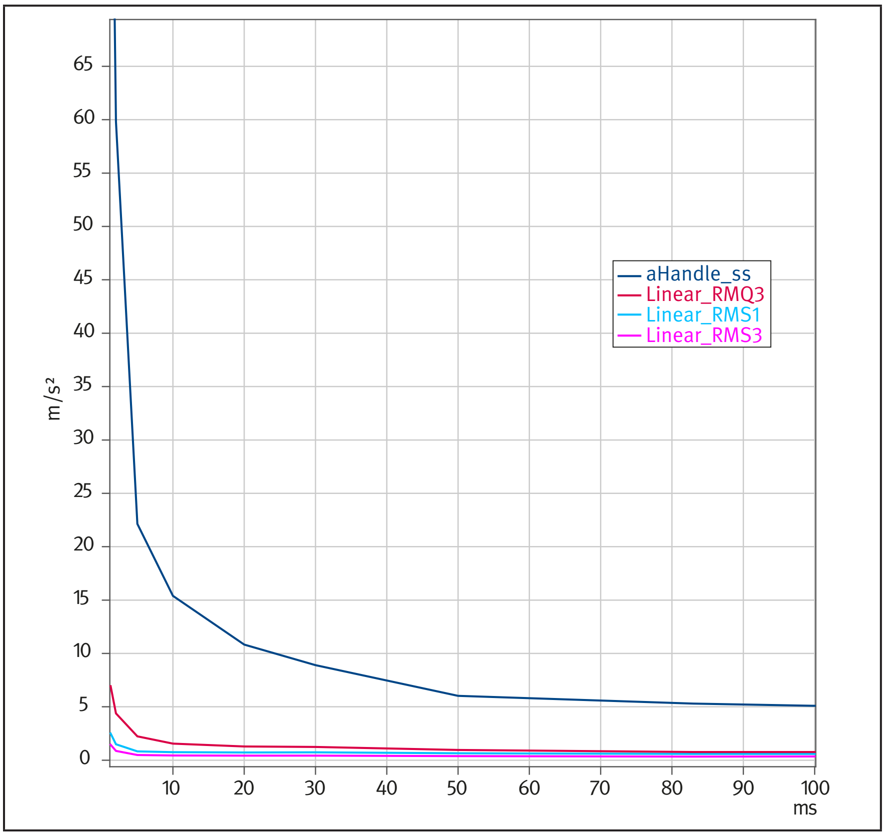


Figure 46:
Mean shock perception as a function of the pulse duration

This curve is fundamentally the same for all measured parameters (peak values and time-averaged values). The different frequency weighting functions likewise do not for the most part modify the curve. An exception however is the frequency weighting to EN ISO 5349-1. Figure 47 shows this with reference to the example of the RMQ values, and Figure 48 in direct comparison with the time-averaged values with the linear frequency curve. Compared to the other frequency weighting functions, the measured values at short pulse durations are attenuated considerably more strongly up to approximately 30 s by the frequency weighting to EN ISO 5349-1.

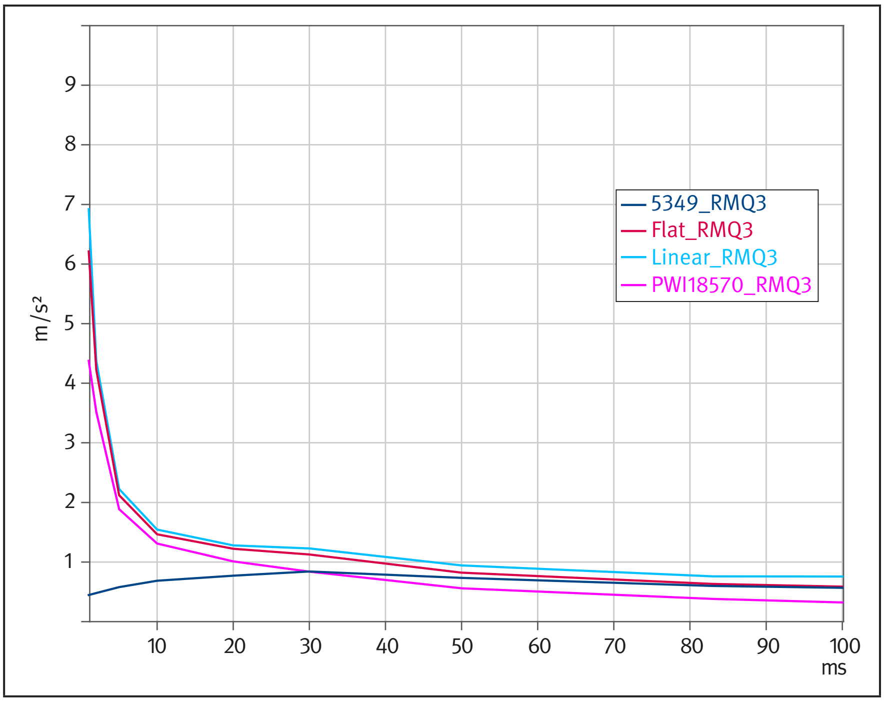


Figure 47:
Mean shock perception in the form of RMQ values with different frequency weightings

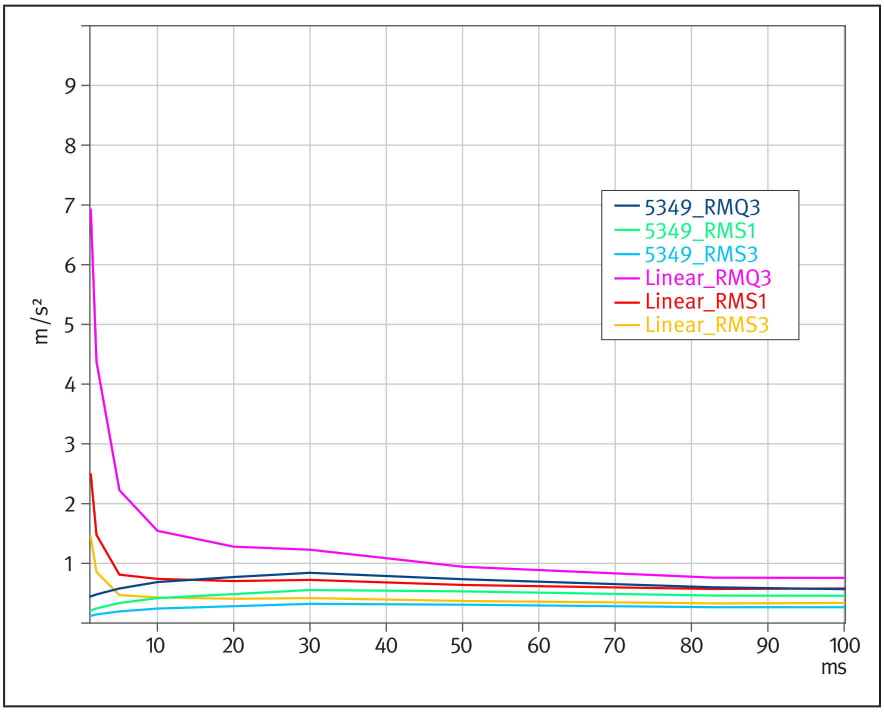


Figure 48:
Mean shock perception in the form of time-averaged values with linear frequency weighting and frequency weighting to EN ISO 5349

Since the other frequency weighting functions all principally constitute band-pass filters with different corner frequencies, the associated shock perception curves merely exhibit a parallel shift. The highest numerical values are represented by the curves with the widest band-pass filters (linear and $flat_h$). The band-pass filter to ISO/PWI 18570 developed specially for the alternative evaluation of hand-arm vibration in consideration of possible vibration-induced circulatory disturbances exhibits the lowest numerical values.

Figure 49 shows the measurement results with reference to the example of the RMS values with an averaging time of 1 s and for the peak-to-peak values on the double logarithmic scale. The measured value curves are seen to become more or less kinked straight lines. The gradient of the straight lines, with the exception in this case of the frequency-weighting curve to EN ISO 5349, is approximately 10 dB/decade, and thus approximately reflects the energy equivalence principle (represented by the thick red line in the middle of the graph).

All measured values, i.e. all measurement parameters together with the full complement of frequency weighting functions (including the frequency weighting function to EN ISO 5349) are correlated with each other. The correlation coefficients for all combinations are significant, i.e. all measurement parameters react approximately the same way. There is therefore no preference for a particular measurement parameter or a particular frequency weighting curve.

The statistical analysis of the data revealed that the combinations of pulse duration and intensity described as "shock" differ significantly between test subjects. It must therefore be assumed that the process of classifying a movement/pulse as a "shock" is specific to the individual. The influence of the person-specific covariables (body weight, height, age) was however not significant in any case.

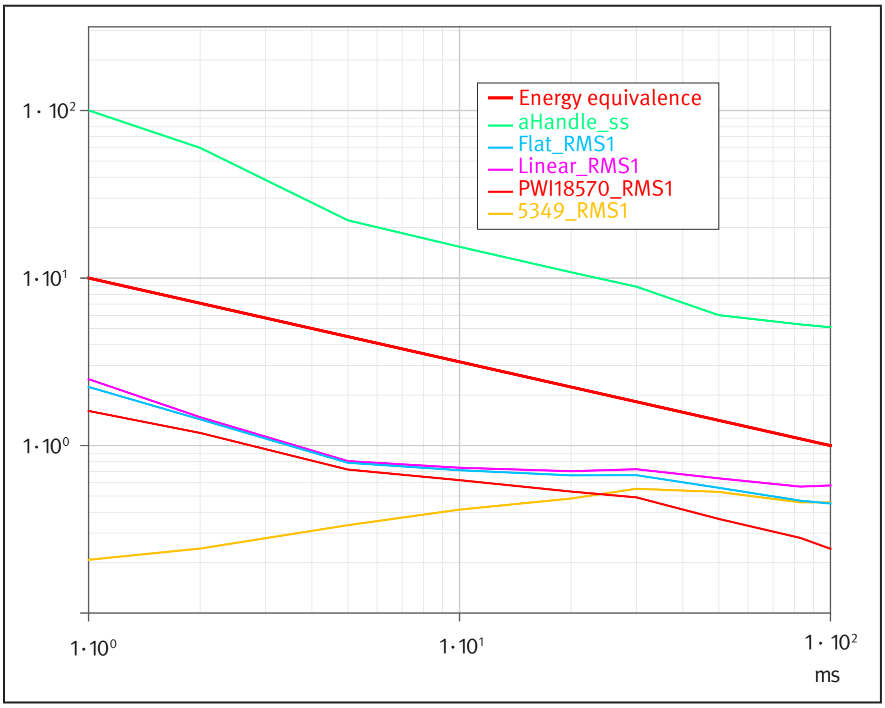


Figure 49:
Mean shock perception on the double logarithmic scale

5 Synoptic presentation of the results

5.1 Part A

In Project Part A, essential problems were studied concerning the measurement of isolated shocks on typical tools the use of which is associated with such shocks. For this purpose, tools were studied both for which movement is required on the part of the user prior to the isolated shock under analysis (locksmith‘s hammer and pneumatic nail driver), and for which no movement is required on the part of the user (pistol, captive bolt gun and powder-actuated nail gun). For tools requiring movement on the part of the user but not presenting vibration exposure, it was shown with reference to the example of the pneumatic air gun how such “falsification” of the measurement results can be avoided.

The results of the studies show that adequately representative variables for the description of different forms of shock can be determined with the necessary accuracy using the technology currently available and with reference to the existing standards, provided consideration is given to certain underlying conditions. Which of these measurement variables should be used for evaluation of the potential hazard or relevance to health of shock exposure is the preserve of further studies into the medical and biological cause-and-effect relationships.

The digital measurement technology currently available not only enables numerous values to be measured, but also permits analysis in the time domain and the combination of a range of additional measurement points.

The greatest contribution to the uncertainty however continues to be the measurement sensor and coupling of it. Despite the facility for checking and harmonizing the phase response, measurements must be limited to one direction when shock exposure is high. If the direction of measurement can be maintained parallel to the direction of action, the relevant vibration exposure is then measured.

5.2 Part B

The results of the studies into the subjectively perceived shock can be summarized as follows:

There are evidently three subjectively perceived ranges of sequences of pulses acting upon the hand-arm system and succeeding each other at a greater or lesser rate (see Section 4.2.2):

- Isolated pulses
- Series of pulses
- Perceived stochastic/diffuse vibration

These three ranges can be differentiated by two thresholds, threshold A and threshold B. The actual values defined for these thresholds are subject to scatter within a certain range as a function of the person exposed (standard deviation approx. 3 to 4 s^{-1}). The values for the two thresholds differ however with statistical significance. Threshold B is approximately double the value of threshold A.

The causes of the scatter in the values are not completely clear. Besides the cognitive characteristics of the person concerned, situational underlying conditions are doubtless also at play that have an influence upon their ability to concentrate. It was also demonstrated that the thresholds were selected differently depending upon whether the individual‘s vocation was more manual or office-based in nature. The person‘s age and constitution may also have an influence upon demarcation of the three ranges.

The values for threshold A are substantially above 5 s^{-1}/5.6 s^{-1}. The lowest measured value was 9.8 s^{-1}, the mean 14.6 s^{-1} and the highest measured value 23.3 s^{-1}.

Whether or not a person perceives a certain mechanical deflection, a movement, as a shock, is dependent upon the interaction of pulse duration and intensity. When exposure to the movement (pulse) is longer in duration, in the order of 50 to 100 ms, even very low accelerations (peak value approx. 5 m/s^2) are sufficient to bring about the perception of shock. Where the exposure duration is shorter, i.e. in the case of the movement durations from 10 to 30 ms that are much more frequently encountered in practice, the intensity required in order for shock to be perceived lies in the range from 10 to 15 m/s^2 (peak value). Even at a very short exposure duration of 2 ms (occurring in practice for example on powder-actuated nail guns), a peak acceleration value of approx. 80 to 100 m/s^2 is sufficient for shock to be perceived. This may also be considered very low when compared to the peak values occurring in the field on powder-actuated nail guns, namely in the order of 10,000 m/s^2 (see Chapter 3).

The interrelationship between the exposure duration (pulse duration) and acceleration gives rise to an approximately exponentially decaying curve on the diagram with linear axis scaling. This curve is very similar for almost all measurement parameters studied. An exception is the curve for the W_h frequency weighting to EN ISO 5349, which exhibits differences from the curves of the other measurement parameters in the range of shorter exposure durations. The results for all measurement parameters (including for the measured values with Wh weighting) correlate statistically significantly with each other.

If the relationship between the accelerations and durations of exposure required for perception as shock are presented on the double logarithmic scale, the results are approximate straight lines. An exception here is the relationship based upon the Wh frequency weighting in accordance with EN ISO 5349. The drop in the straight lines with rising exposure duration is approximately 10 dB per decade, and thus corresponds to the energy equivalence principle.

6 Evaluation of the results; conclusions

The results of the study into the essential measurement problems showed that it is already possible, with existing measurement technology and with reference to existing standards, to determine a great number of different measurement variables/parameters with adequate accuracy. For the machines serving as examples in the study, the values obtained are suitable for further use. Measured values have already been published for a number of further machines [10; 11]. This body of measured data should be extended for future research activity in the area of exposure to isolated shocks.

The results of the study concerning the distinction of shock exposure from other forms of hand-transmitted vibration show that three perceived ranges must be distinguished with regard to the strike rate of shocks. Real-case workplaces involving exposure to shock or vibration can be assigned to these three ranges as shown in Table 15.

Table 15:
Distinction between the three perceived ranges, with examples of practical work tasks

	Range	Examples
I	Repeated (discrete) shocks	Powder-actuated nail guns, nail drivers, pneumatic and electric hammers
II	Continuous series of shocks	Impact screwdrivers, pneumatic and electric hammers, percussive drilling machines
III	Stochastic vibration	Grinding machines, chainsaws

The machines listed in the last column serve only as examples for the exposure concerned. Depending upon their specific design for a particular purpose, pneumatic and electric hammers may be assigned to the ranges of either isolated shocks or series of shocks. The pattern is for smaller hammers to be associated more with impacts in quick succession (range II, e.g. chisel hammers) and for larger, heavier hammers to be associated more with impacts in slower succession (range I, e.g. pneumatic picks).

The study results described here based upon the subjective perception indicate that the threshold between the range of isolated shocks and that of series of shocks lies at approximately 15 shocks per second. The results do not therefore confirm the strike rate of 5 s^{-1} proposed by some experts as the threshold between isolated shocks and series of shocks.

The authors point out again that the threshold of 15 s^{-1} was determined based upon studies of the subjective perception. No studies were performed of the biological or medical impact of exposure to shock at different strike rates. At the same time, the strike rate of 5 s^{-1} proposed as a threshold is not based upon any known results of scientific studies.

If it is now assumed that series of shocks with a strike rate of less than 15 per second are to be considered as isolated shocks, work with certain heavy pneumatic picks, paving breakers, road breakers and tampers must also be assumed to involve exposure to isolated shocks. Before now, exposure of this kind has been recorded, evaluated and assessed based upon the methodological rules for "normal" hand-transmitted vibration (e.g. EN ISO 5349-2), without fundamental objections. If this procedure is accepted, the same procedure must also be accepted for exposure associated with nail drivers, powder-actuated nail guns and similar tools, based upon the study results presented here. This reasoning is supported by the fact that the subjective assessment of shocks is also evidently consistent with the energy equivalence principle.

Conversely, if the view is taken that the existing methods for the assessment of isolated shocks are unsuitable or insufficient, it must also be concluded that certain types of pneumatic and electric hammers and tampers have also not been assessed adequately before now.

The study results show that depending upon the exposure duration (shock duration), very low intensities suffice in order for a simple movement to be perceived as a shock. It does not therefore appear appropriate to set a lower intensity threshold above which a movement can be regarded as a shock. The measurement variable used to describe the intensity is largely irrelevant in this context. Since the measurement parameters studied here are all correlated with each other, there is no reason, in the absence of further information, for preference to be given to a particular parameter. The frequency weighting W_h to EN ISO 5349 is an exception. In the absence of further studies however, this conclusion is valid for the time being only for variables based upon the physical variable of acceleration. Other physical values were not measured in the present study, and no conclusions can therefore be drawn concerning them.

Based upon the results presented here concerning the principles of measurement and the subjective distinction between various forms of shock exposure and other forms of hand-transmitted vibration, purposeful medical research can now be conducted into cause-and-effect relationships concerning various forms of shock exposure.

7 Implementation of the results

Exposure to hand-transmitted vibration at the workplace continues to be associated with considerable risks to performance, well-being and health. Shock exposure constitutes a special case. In contrast to the widespread, “normal” vibration exposure, it has been studied only rarely and unsystematically in recent decades.

The results presented here serve as a basis for systematic measurement of shock exposure in the field. By use of the criteria described in this report, it is possible to distinguish exposure to isolated shocks from exposure to continual series of shocks. As a result, future medical and biological studies of shock exposure will be better able to classify the different exposure conditions, and on this basis, to develop dose-effect models in the long term as a function of the strike rate of the shock exposure. This in turn will enable effective prevention measures to be developed for reducing the health hazard at workplaces associated with shock exposure.

In the medium term, this can be expected to lead to improvements in the knowledge of possible health hazards at workplaces involving shock exposure and to greater legal security in the evaluation of such exposure.

The study results described here will be presented in the near future at suitable scientific events and in the scientific literature. They have already been presented for the first time, at the International Conference on Hand-Arm Vibration in October 2015 in Beijing, China.

The study results will be incorporated continuously into the work of national and international standards committees.

References

[1] *Louda, L.; Rouskova, H.; Svoboda, L.; Muff, V.*: Disease and disorders resulting from hand-arm shocks. In: *Dupuis, H.; Christ, E.; Sandover, J.; Taylor, W.; Okada, A.* (eds.): Proceedings, 6th International Conference on Hand-Arm Vibration, Bonn, 19-22 May 1992, pp. 271-277

[2] *Schenk, Th.; Heine, G.*: Effects of shocks on the peripheral nervous system. In: *Dupuis, H.; Christ, E.; Sandover, J.; Taylor, W.; Okada, A.* (eds.): Proceedings, 6th International Conference on Hand-Arm Vibration, Bonn, 19-22 May 1992, pp. 319-325

[3] *Bovenzi, M.*: Health effects of mechanical vibration. Gazz. Ital. Med. Lav. Erg. 2005

[4] EN ISO 5349-1: Measurement and evaluation of human exposure to hand-transmitted vibration. 2001

[5] *Brubaker, R. L.; MacKenzie, C. J. G.; Hutton, S. G.*: Vibration-induced white finger among selected underground rock drillers in British Columbia. Scand. J. Work Environ. Health 12 (1986), pp. 296-300

[6] *Engström, K.; Dandanel, R.*: Exposure conditions and Raynaud‘s phenomenon among riveters in the aircraft industry. Scand. J. Work Environ. Health. 12 (1986), pp. 293-295

[7] ISO/TC 118/SC 3: Compressors and pneumatic tools, machines and equipment. Resolution 83 (WG 3 Milan 9), 2011.

[8] ISO/TC 108/SC 4: Human exposure to mechanical vibration and shock. Resolution 2/2011, 2011.

[9] *Schenk, Th.; Kummer, W.; Köckritz, S.*: Besonderheiten bei arbeitshygienischen Schwingungsmessungen an schlagenden handgeführten Maschinen. Z. ges. Hyg. 37 (1991), pp. 22-26

[10] *Schenk, Th.*: Measurement of single shocks, affecting the hand-arm system. In: *Dupuis, H.; Christ, E.; Sandover, J.; Taylor, W.; Okada, A.* (eds.): Proceedings, 6th International Conference on Hand-Arm Vibration, Bonn, 19-22 May 1992, pp. 607-612

[11] *Kaulbars, U.*: Determination of vibration emission values for fastener driving tools (nailers). Cent. Eur. J. Publ. Health 3 (1995), pp. 126-128

[12] ISO/TS 15694: Mechanical vibration and shock – Measurement and evaluation of discrete shocks transmitted from hand-held and hand-guided machines to the hand-arm system. July 2004

[13] *Gridin, N. M.; Gorodnova, N. W.*: Clinical and hygienic assessment of pulsed vibration and noise during free forging and manual straightening of metal. Theses of the scientific and practical conference concerning issues of prophylaxis in vibration disease. Leningrad, 23-25 December 1970 (in Russian)

[14] *Zuravljov, A. B.; Komleva, L. M.; Nioradse, D. P.*: Clinical and physiological effects of exposure to local pulse vibration. Gig. trud. i prof. zabol. (1987), *9*, pp. 17-20 (in Russian)

[15] *Starck, J.*: High impulse acceleration levels in hand-held vibratory tools. Scand. J. Work Environ. Health 10 (1984), pp. 171-178

[16] *Starck, J.*: Characteristics of vibration, hand grip force and hearing loss in vibration syndrome. Diss., University of Kuopio, Finland 1984

[17] *Starck, J.; Pyykkö, I.*: Impulsiveness of vibration as an additional factor in the hazards associated with hand-transmitted vibration. Scand. J. Work Environ. Health 12 (1986) pp. 323-326

[18] *Lösch, R.*: Expositionsfolgen der Teilkörpervibration unter Berücksichtigung der Berufstätigkeiten in der Natursteinbearbeitung. Diss. A, Humboldt-Universität Berlin 1982

[19] *Zuravljov, A. B.; Sinev, V. G.*: Concerning the influence of local pulse vibration upon the organism at different distributions of the pulses over time. Gig. trud. i prof. zabol. (1985),7 S. 28-31 (in Russian)

[20] *Zuravljov, A. B.; Sinev, V. G.*: Hygienic assessment of local pulse vibration under production and experimental conditions. Gig. trud. i prof. zabol. (1987),1, pp. 30-34 (in Russian)

[21] *Lindell, H.; Lönnroth, I.; Ottertun, H.*: Transient vibrations from impact wrenches: Vibration negative effect on blood cells and standards for measurement. In: Proceedings, 8th International Conference on Hand-Arm Vibration, Umea, Sweden 1998, pp. 113-117

[22] *Schenk, Th.; Kruse, P.; Wendt, G.*: Effects of combined exposure to shock-type hand-transmitted vibration and impulse noise. In: Proceedings, 8th International Conference on Hand-Arm Vibration, Umea, Sweden 1998, pp. 463-469

[23] *Schäfer, N.; Dupuis, H.; Hartung, E.*: Acute effects of shock-type vibration transmitted to the hand-arm-system. Int. Arch. Occup. Environ. Health 55 (1984), pp. 49-59

[24] *Dupuis, H.; Schäfer, N.*: Effects of impulse vibration on the hand-arm-system. Scand. J. Work Environ. Health 12 (1986), pp. 320-322

[25] *Riedel, S.; Münch, H.*: Measurement and assessment of hand-transmitted vibration caused by fastener driving tools. In: Proceedings, 8th International Conference on Hand-Arm Vibration, Umea, Sweden 1998, pp. 455-461

[26] *Ying, Y.; Mauro, M.; Bovenzi, M.; Griffin, M. J.*: Acute effects of mechanical shocks on finger blood flow: influence of shock repetition rate and shock magnitude. Int. Arch. Occup. Environ. Health 85 (2012), pp. 605-614

[27] *Bovenzi, M.; Petronio, L.; Di Marino, F.*: Epidemiological survey of shipyard workers exposed to hand-arm vibration. Int. Arch. Occup. Environ. Health. 46 (1980), pp. 251-266

[28] *Koradecka, D.*: Periphere Kreislaufreaktionen durch Arbeiten mit vibrierenden Werkzeugen. Schriftenreihe Arbeitsschutz No 32. Published by: Bundesanstalt für Arbeitsschutz und Unfallforschung, Dortmund, 1982

[29] *Micksch, W.*: Eine Methode zur mathematisch-statistischen Analyse der Ursache-Wirkung-Beziehung bei Berufskrankheiten mit physikalischer Ursache – dargestellt am Beispiel der Berufskrankheit durch Teilkörpervibration im Bauwesen der DDR. Dissertation A, TU Dresden, Sektion Arbeitswissenschaften, 1985

[30] ISO 2041: Vibration and shock – Vocabulary. 1990

[31] ISO 9688: Mechanical vibration and shock – Analytical methods of assessing shock resistance of mechanical systems – Information exchange between suppliers and users of analyses. 1990

[32] Handbuch der Schock- und Vibrationsmeßtechnik. ENDEVCO Eigenverlag, Heidelberg 1992

[33] *Schenk, Th.*: Zum Stand der arbeitshygienischen Bewertung der Einwirkung von mechanischen Stößen auf das Hand-Arm-System des Menschen. Arbeitshygienische Information Bauwesen, Berlin (East) 24 (1988) No. 6, pp. 159-163

[34] *Zuravljov, A. B.*: The particular aspects of exposure of the organism to local pulse vibration. Gig. truda i prof. zabol. (1988), 4 pp. 32-35 (in Russian)

[35] EN ISO 5349-2: Mechanical vibration – Measurement and evaluation of human exposure to hand-transmitted vibration. 2001

[36] EN ISO 8041 : Human response to vibration – Measuring instrumentation. 2006

[37] ISO/PWI 18570 Mechanical Vibration – Measurement and evaluation of human exposure to hand-transmitted vibration – Supplementary method for assessing risk of vascular injury. In preparation

[38] EN ISO 8041/A1:2015-05: Human response to vibration – Measuring instrumentation – Corrigendum 1 (ISO 8041:2005/DAM 1:2015); German and English version EN ISO 1:2005/prA1:2015

[39] *Riedel, S.; Gillmeister, F.; Louagie, J.*: Untersuchung eines schwingungsgeminderten Handhammers. ASU Protect: Das Magazin für Arbeitsschutzmanagement. Germany: Gentner Verlag 2009-01

[40] *Schäfer, N.*: Akute Wirkungen stoßhaltiger Schwingungen auf das Hand-Arm-System. Forschungsbericht HA 85-020 Humanisierung des Arbeitslebens. Fachinformationszentrum Karlsruhe. 1985

[41] *Kaulbars, U.; Raffler, N.*: Study of Vibration Transmission on a Paver‘s Hand Hammer. Twelfth International Conference on Hand-Arm Vibration, 13-17 June 2011, Ottawa – paper. In: Canadian Acoustics 39 (2011) No 2, pp. 52-53

[42] *Schenk, Th.*: Untersuchungen zu Möglichkeiten der Simulation von Stoßereignissen auf das menschliche Hand-Arm-System mit Hilfe von elektrodynamischen Schwingerregern (Shakern). Unpublished study report commissioned by HILTI AG, Liechtenstein, April 1999

[43] DIN 45661-A1: Schwingungsmesseinrichtungen – Begriffe; Amendment A1 Draft 2015-04

[44] Mechanical Vibration – Measurement and evaluation of human exposure to hand-transmitted vibration – Supplementary method for assessing risk of vascular injury. Preliminary work item ISO/PWI 18570, ISO/TC 108/SC 4/ WG 3 N 266; 2014-06-20

Annex A:
Frequency weightings

Figure A.1:
$Flat_h$ weighting filter to CEN ISO/TS 15694

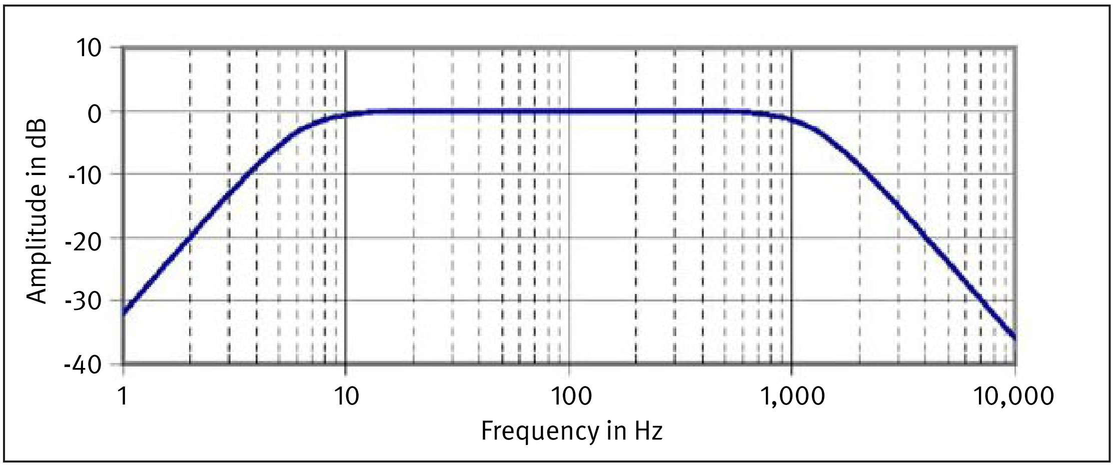


Figure A.2:
Characteristic of the W_h weighting factor for hand-transmitted vibration over the frequency f in accordance with EN ISO 5349-1

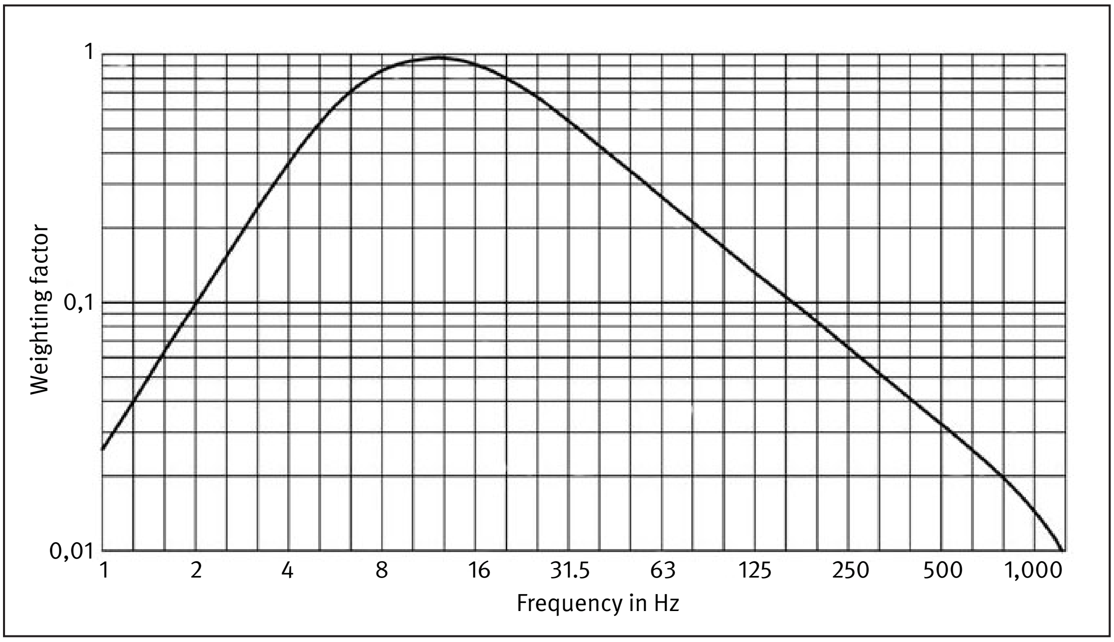
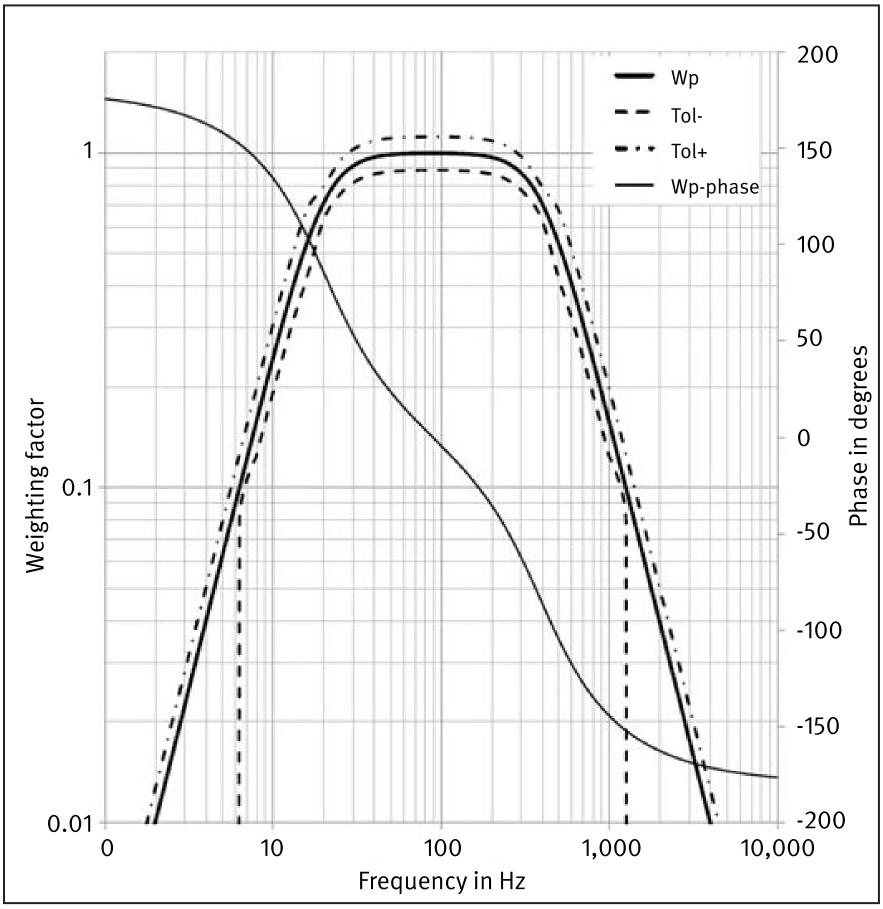


Figure A.3:
Characteristic of the W_p weighting factor for hand-transmitted vibration over the frequency f in accordance with ISO/PWI 18570



Annex B:
Description of the measurement system

The Wölfel “MEDA RedSens” measurement system was employed for this project. The data sheet is shown in Figure B.1. This measurement system was supplemented by the “MatLab” software application for calculation of the jerk and the root-mean-quad value.

Figure B.1:
Data sheet for the “MEDA RedSens” measurement system

Synchronous wireless measurement with external sensors

RedSens extern

Number of channels per node, input for external sensors	3
Signal input selectable by channel	Voltage or IEPE
Signal coupling selectable by channel	AC or DC
Frequency range	DC – 4 kHz
Offset	1 mV
Noise, wide-band	20 µV@ ±1 | 40 µV@ ±10 V
Resolution	24 bit
Dynamic range	110 dB
Scanning over all channels	Simultaneous
Max. synchronicity deviation	1 µs
Data transfer rate	1 Mbit/s
Sensor nodes per system	1 to 10
Free-field range, 802.11g	140 m
Power supply	Internal rechargeable battery or external power supply
Measurement time with rechargeable battery	8 h
Battery charge time	3 h
Dimensions excl. antenna	(114 x 64 x 30) mm^3
Weight	220 g
Temperature range	0 °C to 60 °C
Ingress protection	IP64

MEDA RedSens consists essentially of the MEDA software application, a suitable PC with antenna (in this case a Toughbook CF-31), and two RedSens nodes. The measurement system provides a wireless link between the RedSens nodes and the Toughbook. The measured signals are transmitted by WLAN in real time.

The individual components of the system are described in greater detail below.

MEDA (Version 2014-3)

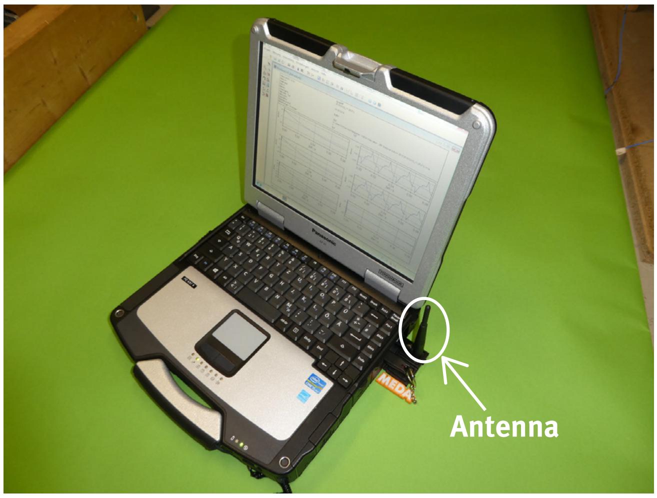
The MEDA software application is a multi-channel, computer-based system for the measurement, evaluation and documentation of shocks and noise. It enables measurement to be performed on up to 6 channels simultaneously.

The application offers numerous options for the analysis of acceleration characteristics imported or measured with MEDA. The $flat_h$, W_h and W_p frequency weighting filters are already stored in MEDA and can be applied to all measurements during post-measurement processing. MEDA also enables interval calculations to be performed for a time interval defined in advance. This function enables the values required for this project (e.g. root-mean-square values in a time interval) to be generated.

Toughbook CF-31

The measurements were performed by means of a Panasonic Toughbook CF-31. Figure B.2 shows the Toughbook employed with antenna attached.

Figure B.2:
Toughbook CF-31 with antenna attached

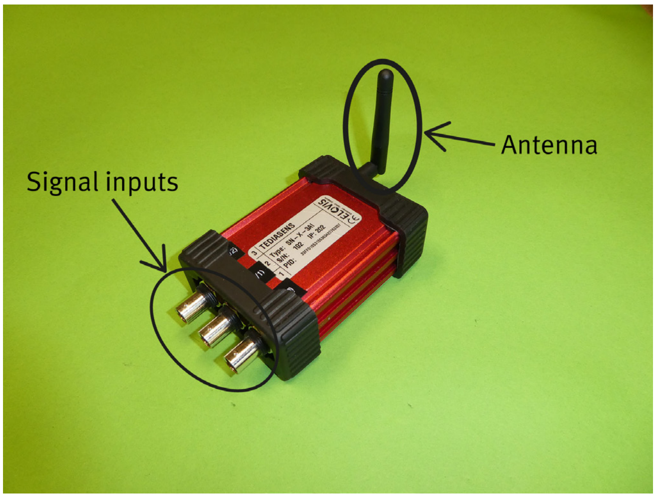


RedSens nodes

The RedSens nodes form the interface between the connected sensors and the PC. Each RedSens node has three signal inputs, an integrated A/D converter and an antenna (see Figure B.3). This enables IEPE sensor input to be switched on or off for individual channels. Simultaneous measurements with both charge sensors and ICP sensors are thus possible.

The integrated A/D converter digitizes the incoming voltage signals and transfers them to the PC by WLAN.

Figure B.3:
Wölfel RedSens node



MatLab R2014a (supplementary use)

The use of MEDA was supplemented by MatLab (Version R2014a) for analysis of the measured accelerations. Measurements were imported into MatLab in ASCII format for this purpose.

Annex C: Measured values

Table C.1:
Table of results of the $flat_h$-weighted values for the locksmith's hammer

Measurement No.	MP	$a_{hf\ RMS}$ (T = 1 s)	$a_{hf\ RMS}$ (T = 3 s)	$a_{hF,\ RMQ}$ (T = 3 s)	$j_{hf\ RMS}$ (T = 1 s)	$j_{hf\ RMS}$ (T = 3 s)	$j_{hf,\ peak\ to\ peak}$	$a_{hf\ MTVV}$	$a_{hf,\ PV}$	CF_h	SC_h	t_a in ms	t_i in ms
0328 14.2	1	229.5	106.9	606.7	1,231,668	711,141	33,977,526	450.8	6,083.0	56.9	5.7	0.5	9
	2	398.7	182.1	1,039.4	2,100,405	1,212,733	72,438,449	791.7	9,291.7	51.0	5.7	0.5	8
	3	12.1	6.3	47.0	53,034	30,627	4,939,445	25.3	479.1	76.0	7.5	0.5	/
	4	9.1	4.4	20.8	19,336	11,164	1,382,503	17.1	188.8	42.6	4.7	0.6	/
0328 14.3	1	245.4	102.6	554.0	1,244,951	718,811	50,387,800	437.8	4,811.3	46.9	5.4	0.6	10
	2	455.4	190.3	1,041.6	1,987,925	1,147,789	74,428,068	803.6	10,100.8	53.1	5.5	0.4	10
	3	5.1	2.1	10.8	16,128	9,332	1,042,507	8.6	104.8	49.2	5.1	0.5	/
	4	6.5	2.7	11.2	11,221	6,479	726,460	10.3	108.0	39.5	4.1	0.6	/
0328 14.4	1	218.1	99.9	567.0	1,190,380	687,320	38,088,516	431.3	5,479.6	54.8	5.7	0.6	9
	2	391.6	180.1	1,004.3	2,081,119	1,201,629	69,174,059	774.0	9,044.1	50.2	5.6	0.6	9
	3	11.3	5.9	43.8	37,978	21,936	3,085,586	23.4	444.3	75.8	7.5	0.5	/
	4	4.6	2.7	11.2	10,454	6,036	719,215	9.8	106.6	39.8	4.2	0.6	/
Mean	1	231.0	103.1	575.9	1,222,333	705,757	40,817,947	440.0	5,458.0	52.9	5.6	0.6	9.3
	2	415.2	184.2	1,028.4	2,056,483	1,187,384	72,013,525	789.8	9,478.9	51.4	5.6	0.5	9.0
	3	9.5	4.8	33.9	35,713	20,632	3,022,513	19.1	342.7	67.0	6.7	0.5	/
	4	6.7	3.3	14.4	13,671	7,893	942,726	12.4	134.4	40.6	4.3	0.6	/
Standard deviation	1	13.7	3.5	27.4	28,458	16,421	8,538,830	9.9	636.1	5.3	0.2	0.1	0.6
	2	35.0	5.4	20.9	60,151	34,736	2,652,654	14.9	552.7	1.5	0.1	0.1	1.0
	3	3.9	2.3	20.0	18,557	10,707	1,949,234	9.1	206.8	15.4	1.4	0.0	/
	4	2.3	1.0	5.5	4,922	2,842	380,875	4.1	47.1	1.7	0.3	0.0	/

Table C.2:
Table of results of the W_h-weighted values for the locksmith's hammer

Measurement No.	MP	$a_{hw\ RMS}$ (T = 1 s)	$a_{hw\ RMS}$ (T = 3 s)	$a_{hw\ MTVV}$	$a_{hw,\ PV}$	CF_w
0328 14.2	1	63.2	32.0	114.3	280.3	8.8
	2	50.0	26.2	93.2	277.3	10.6
	3	1.8	1.1	4.3	17.2	16.2
	4	3.2	1.7	5.4	15.0	9.0
0328 14.3	1	40.8	26.2	90.3	230.8	8.8
	2	90.7	56.0	201.1	482.7	8.6
	3	0.5	0.3	1.2	4.7	15.2
	4	2.1	1.3	4.5	15.1	11.6
0328 14.4	1	29.1	18.0	64.4	177.8	9.9
	2	61.7	38.1	136.8	346.9	9.1
	3	1.7	1.0	4.2	16.0	15.6
	4	2.1	1.3	4.5	14.1	10.6
Mean	1	44.4	25.4	89.7	229.6	9.2
	2	67.5	40.1	143.7	369.0	9.4
	3	1.3	0.8	3.2	12.6	15.6
	4	2.5	1.4	4.8	14.7	10.4
Standard deviation	1	17.4	7.0	25.0	51.3	0.6
	2	21.0	15.0	54.2	104.4	1.0
	3	0.7	0.4	1.8	6.9	0.5
	4	0.6	0.2	0.5	0.6	1.3

Table C.3:
Table of results of the W_p-weighted values for the locksmith's hammer

Measurement No.	MP	$a_{hwp\ RMS}$ (T = 1 s)	$a_{hwp\ RMS}$ (T = 3 s)
0328 14.2	1	57.6	27.5
	2	89.7	41.3
	3	7.1	4.1
	4	7.4	3.5
0328 14.3	1	55.1	23.0
	2	130.1	54.4
	3	3.7	1.5
	4	4.6	1.9
0328 14.4	1	40.5	19.1
	2	98.3	45.9
	3	6.6	3.7
	4	3.3	1.8
Mean	1	51.1	23.2
	2	106.0	47.2
	3	5.8	3.1
	4	5.1	2.4
Standard deviation	1	9.3	4.2
	2	21.3	6.6
	3	1.9	1.4
	4	2.1	1.0

Tabelle C.4:
Table of results of the flat$_h$-weighted values for the firearm (pistol)

Measurement No.	MP	$a_{hf\,RMS}$ (T = 1 s)	$a_{hf\,RMS}$ (T = 3 s)	$a_{hf,\,RMQ,}$ (T = 3 s)	$j_{hf\,RMS}$ (T = 3 s)	$a_{hf\,MTVV}$	$a_{hf,\,PV}$	CF_h	SC_h	t_a in ms	t_i in ms
0254 5.2	1	241.4	147.3	833.5	1,345,749	584	3,929	26.7	5.7	1.3	17
	2	13.5	8.5	45.7	17,492	34	87	10.3	5.4	4.5	17
	3	734.7	372.7	2,445.1	5,585,229	1,587	27,562	74.0	6.6	1.4	3
	4	399.7	221.3	1,331.2	2,467,820	930	13,012	58.8	6.0	1.3	12
0254 5.3	1	309.4	139.4	618.3	874,656	537	4,045	29.0	4.4	2	17
	2	18.1	8.0	34.5	14,193	32	66	8.3	4.3	4.1	19
	3	766.0	335.7	2,023.4	3,595,898	1,417	25,575	76.2	6.0	1.5	5
	4	490.2	216.7	977.9	1,519,889	896	13,508	62.3	4.5	1.6	14
0254 5.4	1	292.3	142.2	622.0	893,663	556	4,340	30.5	4.4	1.5	16
	2	20.4	9.7	33.5	12,823	39	102	10.5	3.5	4.1	27
	3	726.5	334.3	1,776.4	3.113,804	1,406	19,778	59.2	5.3	1.6	5
	4	431.4	201.0	1,072.0	1,552,850	839	15,521	77.2	5.3	1.6	4
Mean	1	281.0	143.0	691.3	1,038,023	559	4,104	28.7	4.8	1.6	16.7
	2	17.4	8.7	37.9	14,836	35	85	9.7	4.4	4.2	21.0
	3	742.4	347.6	2,081.7	4,098,310	1,470.2	24,305	69.8	6.0	1.5	4.3
	4	440.5	213.0	1,127.0	1,846,853	888.2	14,014	66.1	5.3	1.5	10.0
Standard deviation	1	35.4	4.0	123.2	266,668	23.6	212	1.9	0.7	0.4	0.6
	2	3.5	0.9	6.8	2,400	3.6	18	1.2	1.0	0.2	5.3
	3	20.8	21.8	338.1	1,310,076	101.6	4,045	9.3	0.6	0.1	1.2
	4	45.9	10.7	182.9	538,025	46.2	1,329	9.8	0.8	0.2	5.3

Table C.5:
Table of results of the W_h-weighted values for the firearm (pistol)

Measurement No.	MP	$a_{hw\ RMS}$ (T = 1 s)	$a_{hw\ RMS}$ (T = 3 s)	$a_{hw\ MTVV}$	$a_{hw,\ PV}$	CF_w
0254 5.2	1	19.8	9.4	35.1	92	9.78
	2	6.6	3.2	12.1	27	8.33
	3	12.9	7.1	27.9	174	24.60
	4	9.3	5.8	21.9	238	41.32
0254 5.3	1	17.3	7.6	28.1	78	10.29
	2	7.1	3.1	11.8	26	8.37
	3	22.2	9.7	37.3	166	17.18
	4	28.7	12.6	45.5	225	17.88
0254 5.4	1	12.3	7.7	29.2	99	12.82
	2	5.5	3.2	12.3	27	8.41
	3	15.4	7.9	29.7	112	14.24
	4	27.3	16.3	60.2	328	20.13
Mean	1	16.4	8.2	31	89	10.96
	2	6.4	3.2	12	27	8.37
	3	16.8	8.2	31.6	151.0	18.67
	4	21.8	11.5	42.5	263.4	26.44
Standard deviation	1	3.8	1.0	3.8	10.7	1.63
	2	0.8	0.1	0.3	0.5	0.04
	3	4.8	1.3	5.0	33.9	5.34
	4	10.8	5.3	19.3	56.4	12.93

Table C.6:
Table of results of the W_p-weighted values for the firearm (pistol)

Measurement No.	MP	$a_{hwp\ RMS}$ (T = 1 s)	$a_{hwp\ RMS}$ (T = 3 s)	$a_{hwp,\ PV}$	CF_{wp}
0254 5.2	1	81.5	50.5	1,589	31.5
	2	13.6	7.5	138	18.3
	3	110.8	55.4	2,746	49.6
	4	88.2	49.3	1,784	36.2
0254 5.3	1	78.0	48.9	1,697	34.7
	2	11.2	7.0	126	17.9
	3	89.0	55.8	1,916	34.3
	4	76.1	47.8	1,609	33.7
0254 5.4	1	104.1	48.8	1,442	29.5
	2	18.4	8.8	153	17.4
	3	121.9	55.4	2,512	45.4
	4	95.7	44.1	1,733	39.3
Mean	1	87.9	49.4	1,576	31.9
	2	14.4	7.8	139	17.9
	3	107.2	55.5	2,391.4	43.1
	4	86.7	47.1	1,708.5	36.4
Standard deviation	1	14.2	0.9	128.4	2.6
	2	3.7	0.9	13.5	0.5
	3	16.7	0.3	428.0	7.9
	4	9.9	2.7	90.0	2.8

Tabelle C.7:
Table of results of the $flat_h$-weighted values for the captive bolt gun

Measurement No.	MP	$a_{hf\,RMS}$ (T = 1 s)	$a_{hf\,RMS}$ (T = 3 s)	$a_{hf,\,RMQ}$ (T = 3 s)	$j_{hf\,RMS}$ (T = 1 s)	$j_{hf\,RMS}$ (T = 3 s)	$j_{hf,\,peak\,to\,peak}$	$a_{hf\,MTVV}$	$a_{hf,\,PV}$	CF_h	SC_h	t_a in ms	t_i in ms
310 3.3	1	244.1	143.5	1,046.2	918,354	536,801	84,947,025	677.4	9,771	68.1	7.3	0.8	3
310 3.4	1	248.4	144.1	1,029.3	1,049,041	606,701	94,208,537	680.2	9,439	65.5	7.1	0.9	3
310 3.5	1	256.9	149.0	1,041.4	961,379	556,312	71,330,007	707.0	9,302	62.4	7.0	0.8	3
Mean	1	249.8	145.5	1,039.0	976,258	566,605	83,495,190	688.2	9,504	65.3	7.1	0.8	3.0
Standard deviation	1	6.5	3.0	8.7	66,602	36,069	11,508,156	16.3	241	2.8	0.1	0.1	0.0

Table C.8:
Table of results of the W_h-weighted values for the captive bolt gun

Measurement No.	MP	$a_{hw\ RMS}$ (T = 1 s)	$a_{hw\ RMS}$ (T = 3 s)	$a_{hw,\ RMQ}$ (T = 3 s)	$a_{hw\ MTVV}$	$a_{hw,\ PV}$	CF_w	SC_w
310 3.3	1	31.3	19.4	80.3	77.6	606	31.2	4.1
310 3.4	1	32.0	18.5	80.0	58.8	600	32.4	4.3
310 3.5	1	31.3	18.1	77.7	76.4	584	32.2	4.3
Mean	1	31.5	18.7	79.3	70.9	597	32.0	4.2
Standard deviation	1	0.4	0.7	1.4	10.6	11	0.7	0.1

Table C.9:
Table of results of the W_p-weighted values for the captive bolt gun

Measurement No.	MP	$a_{hwp\ RMS}$ (T = 1 s)	$a_{hwp\ RMS}$ (T = 3 s)	$a_{hwp,\ RMQ}$ (T = 3 s)	$a_{hwp\ MTVV}$	$a_{hwp,\ PV}$	CF_{wp}	SC_{wp}
310 3.3	1	182.3	107.7	656.9	502.1	5,567	51.7	6.1
310 3.4	1	187.3	108.2	653.1	505.7	5,439	50.3	6.0
310 3.5	1	191.5	110.6	665.5	522.2	5,376	48.6	6.0
Mean	1	187.0	108.8	658.5	510.0	5,461	50.2	6.1
Standard deviation	1	4.6	1.6	6.3	10.7	97	1.6	0.0

Tabelle C.10:
Table of results of the $flat_h$-weighted values for the powder-actuated nail gun

Measurement No.	MP	$a_{hf\ RMS}$ (T = 1 s)	$a_{hf\ RMS}$ (T = 3 s)	$a_{hf\ RMS}$	$a_{hF,\ RMQ,}$ (T = 3 s)	$j_{hf\ RMS}$ (T = 1 s)	$j_{hf\ RMS}$ (T = 3 s)	$j_{hf,\ peak\ to\ peak}$	$a_{hf\ MTVV}$	$a_{hf,\ PV}$	CF_h	SC_h	t_a in ms	t_i in ms
0291 03.2	1	186.8	82.2	73.8	478.4	611,360	358,230	43,604,000	354	4,434	53.9	5.8	1.3	7
	2	274.1	125.1	113.4	978.5	201,390	117,480	188,090,000	514	10,854	86.8	7.8	0.5	6
0291 03.3	1	167.3	73.9	66.4	449.6	582,280	346,640	44,531,000	315	4,766	64.5	6.1	1.1	8
	2	276.7	126.2	114.4	965.2	1,707,700	1,000,300	134,770,000	525	10,591	83.9	7.6	0.4	5
0291 03.4	1	175.1	79.4	71.2	456.2	614,790	359,330	58,984,000	339	4,053	51.1	5.7	1.3	11
	2	268.0	126.0	114.2	914.7	2,065,100	1,203,900	180,180,000	515	10,591	84.0	7.3	0.3	5
Mean	1	176.4	78.5	70.4	461.4	602,810	354,733	49,039,667	336	4,417	56.5	5.9	1.2	8.7
	2	272.9	125.8	114.0	952.8	1,324,730	773,893	167,680,000	518	10,679	84.9	7.6	0.4	5.3
Standard deviation	1	9.8	4.2	3.8	15.1	17,862	7,031	8,624,509	19.4	356.7	7.1	0.2	0.1	2.1
	2	4.5	0.6	0.5	33.7	989,117	577,514	28,774,000	6.0	152.2	1.6	0.3	0.1	0.6

Table C.11:
Table of results of the W_h-weighted values for the powder-actuated nail gun

Measurement No.	MP	$a_{hw\ RMS}$ (T = 1 s)	$a_{hw\ RMS}$ (T = 3 s)	$a_{hw\ RMS}$	$a_{hw,\ RMQ}$ (T = 3 s)	$j_{hw\ RMS}$ (T = 1 s)	$j_{hw\ RMS}$ (T = 3 s)	$j_{hw,\ peak\ to\ peak}$	$a_{hw\ MTVV}$	$a_{hf,\ PV}$	CF_h	SC_h
0291 03.2	1	21.4	9.4	8.4	336.1	13,188	7,624	631,985	33.5	283.8	30.3	35.9
	2	21.3	9.6	8.6	277.8	13,654	7,909	885,798	32.1	239.2	24.9	28.9
0291 03.3	1	20.8	9.1	8.2	303.4	11,441	6,626	561,525	32.7	256.9	28.2	33.3
	2	19.0	8.6	7.7	275.5	11,201	6,501	844,882	29.9	233.7	27.2	32.1
0291 03.4	1	20.2	9.1	8.2	319.4	12,331	7,128	601,921	33.3	269.2	29.6	35.1
	2	20.6	9.3	8.4	270.9	12,213	7,074	895,519	32.3	227.5	24.4	29.1
Mean	1	20.8	9.2	8.2	319.6	12,320	7,126	598,477	33.2	270.0	29.3	34.7
	2	20.3	9.2	8.2	274.7	12,356	7,161	875,400	31.4	233.4	25.5	30.0
Standard deviation	1	0.6	0.2	0.1	16.3	873.6	499.0	35,356.0	0.4	13.5	1.1	1.3
	2	1.2	0.5	0.5	3.5	1,233	708	26,872	1.3	5.9	1.5	1.8

Table C.12:
Table of results of the W_p-weighted values for the powder-actuated nail gun

Measurement No.	MP	$a_{hwp\ RMS}$ (T = 1 s)	$a_{hwp\ RMS}$ (T = 3 s)	$a_{hwp\ RMS}$	$a_{hwp\ MTVV}$	$a_{hwp,\ PV}$	CF_{wp}
0291 032	1	142.7	62.5	55.9	271	2,676	42.8
	2	107.3	47.1	42.2	202	2,489	52.9
0291 033	1	127.5	72.2	50.0	241	2,476	34.3
	2	104.5	59.3	41.1	198	2,451	41.3
0291 034	1	132.2	77.1	53.3	257	2,574	33.4
	2	103.7	60.5	41.9	201	2,373	39.2
Mean	1	134.2	70.6	53.1	256	2,575	36.8
	2	105.2	55.6	41.7	200	2,437	44.5
Standard deviation	1	7.8	7.5	3.0	15.1	99.8	5.2
	2	1.9	7.4	0.5	2.3	58.9	7.4

Annex D:
List of test subjects

Test subject	Age in years	Height in cm	Weight in kg	Occupation/Sector
1	38	175	78	Engineer
2	30	193	85	Engineer
3	50	185	105	Engineer
4	41	189	82	Engineer
5	76	182	82	Engineer
6	38	174	74	Engineer
7	62	189	84	Engineer
8	38	176	73	Machine construction
9	45	178	76	Engineer
10	66	175	95	Foundry
11	62	184	80	Building industry
12	70	178	74	Electrician
13	59	175	86	Driver
14	59	182	81	Engineer
15	68	174	83	Building industry
16	26	183	95	Student
17	28	178	95	Engineer
18	61	179	92	Engineer
19	56	180	78	Electrician
20	60	188	92	Janitor
21	28	189	90	Student
22	51	185	115	Engineer
23	55	193	120	Electrician
24	62	186	85	Engineer

Annex E:
Test instructions, pilot tests

The tests conducted here are intended to yield a better understanding of the effect of certain mechanical influences upon the human sense of touch.

During the test, sequences of low-intensity pulsed movements are generated by means of the test apparatus. You can detect these movements when your finger or hand is placed upon the test apparatus. The magnitude of the movement is far too low to produce a sense of pain.

You can adjust the interval between the isolated pulses by means of the knob. With the knob on a very low setting, you are able to sense individual pulsed movements. Turning the knob anticlockwise causes the periods between the pulses to become shorter. The pulses come in quicker succession and eventually merge.

Your task is to determine the point at which, in your opinion, successive isolated pulses become a continuous series of pulses.

Turn the knob back and forth until you feel that this threshold has been set, then inform your test supervisor.

The tests are performed for the fingers of the right and left hands and for a particular point on the wrist (the pisiform bone). Each measurement is repeated again twice (i.e. three measurements in total per point of load transfer).

Place your fingertips and your wrist gently upon the shaker. Concentrate on your sense of touch and not on the noise made by the test apparatus.

Before the test proper is performed, a number of trials are performed in order to familiarize you with the test movements, the resulting sensation, and control by means of the knob.

Annex F:
Test instructions, main test 1

The tests conducted here are intended to yield a better understanding of the effect of certain mechanical influences upon the human sense of touch.

During the test, sequences of low-intensity pulsed movements are generated by means of the test apparatus. You sense these through the handle. The magnitude of the movement is far too low to produce a sense of pain.

You can adjust the interval between the isolated pulses by means of the knob. With the knob on a very low setting, you can clearly sense the individual movement pulses and the breaks between them. Turning the knob anticlockwise causes the periods between the pulses to become shorter. The pulses come in quicker succession, until you are no longer able to properly perceive the breaks between them. Turning the knob further still results in the gaps between the pulses becoming so short that you are only able to sense a diffuse tingling.

There are therefore three ranges of perception:

1. The range in which isolated pulses and periods between them are perceptible
2. The range of quicker pulse sequences (the periods between the pulses are no longer clearly perceptible, but pulses as such can still be sensed)
3. The range of perception of diffused vibration (tingling)

Your task is to determine the thresholds between these three ranges of perception:

Threshold A Threshold between isolated pulses and series of pulses

Threshold B Threshold between series of pulses and diffuse vibration

Turn the knob back and forth until you feel that the threshold concerned (A or B as applicable) has been reached, then inform your test supervisor.

The tests are performed only for the right hand.

Grip the handle very loosely (but sufficiently firmly for the movement still to be reliably sensed) or somewhat more firmly, as instructed by the test supervisor. The tests are also performed both without pushing force and with light pushing force. Under no circumstances should strong force be exerted. Do not concentrate on the gripping or pushing forces, but on the sensory perception.

Threshold A is determined several times in the first test pass. Following a break, threshold B is determined several times in the second test pass.

Before the test proper is performed, a number of trials are performed in order to familiarize you with the test movements, the resulting sensation, and control by means of the knob.

Annex G:
Test instructions, main test 2

The tests conducted here are intended to yield a better understanding of the effect of certain forms of mechanical exposure upon the human perception. The aim is to establish how strong a movement acting upon a human being must be in order to be perceived as a shock.

During the test, a low-intensity movement is generated by means of the test apparatus. You sense this movement through the handle. The magnitude of the movement is far too low to produce a sense of pain.

You perceive this movement either as a shock, or only as a movement, depending upon its intensity.

You can adjust the intensity by means of the knob. Change the setting on the knob by turning it back and forth until you feel that the threshold has been reached at which a movement just becomes a shock.

The tests are performed only for the right hand.

Grip the handle very loosely (but sufficiently firmly for the movement still to be reliably sensed) or somewhat more firmly, as instructed by the test supervisor. The tests are also performed both without pushing force and with light pushing force. Under no circumstances should strong force be exerted. Do not concentrate on the gripping or pushing forces, but on the sensory perception.

The form of the movement is specified by the test supervisor. This movement is repeated again and again after a short interval. You can therefore concentrate on your perception and on changing the setting. When you feel that the threshold for the perception of shock has been correctly set, please inform the test supervisor.

Before the test proper is performed, a number of trials are performed in order to familiarize you with the test movements, the resulting sensation, and control by means of the knob.

Annex H: Individual results for the combination of pulse duration and intensity assessed as a “shock” (main test 2)

Thick line: mean value, thin lines: 95% confidence interval

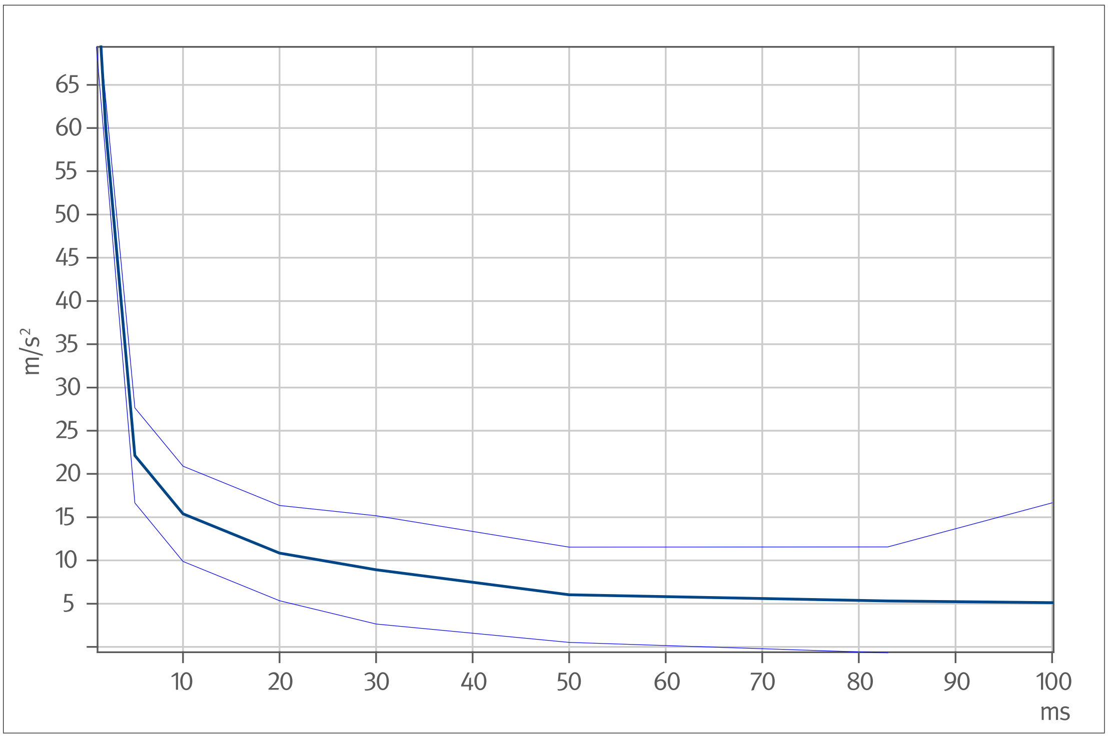


Figure H.1:
Handle_peak-to-peak

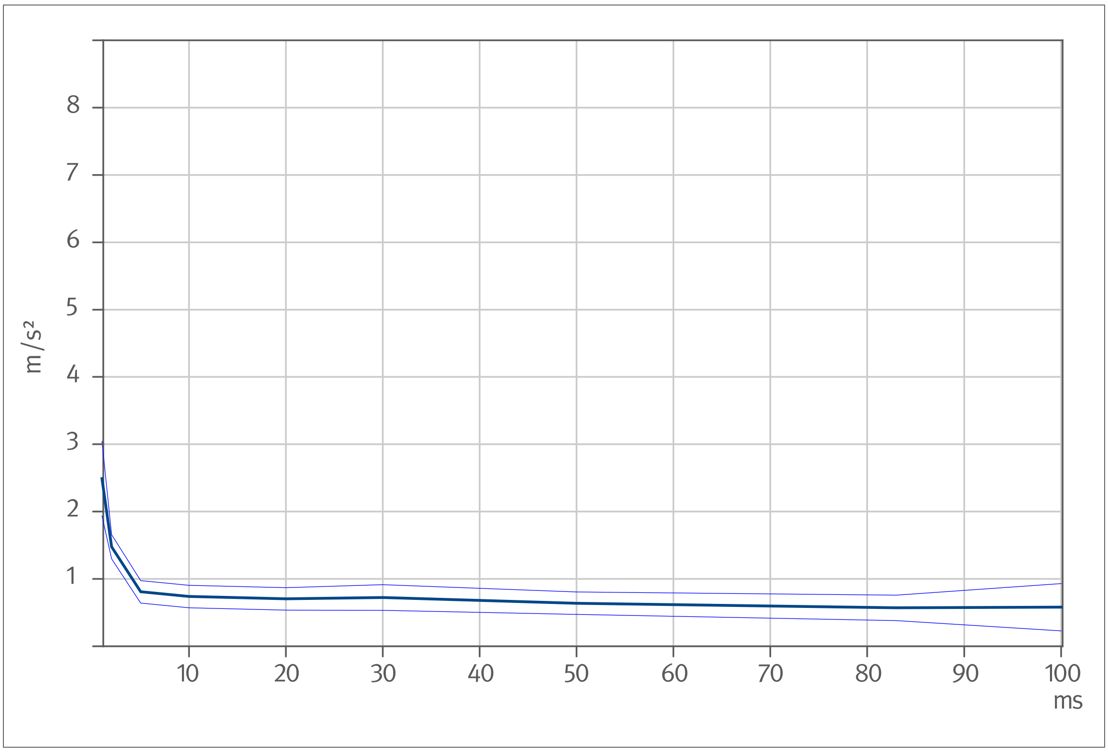


Figure H.2:
Linear RMS1

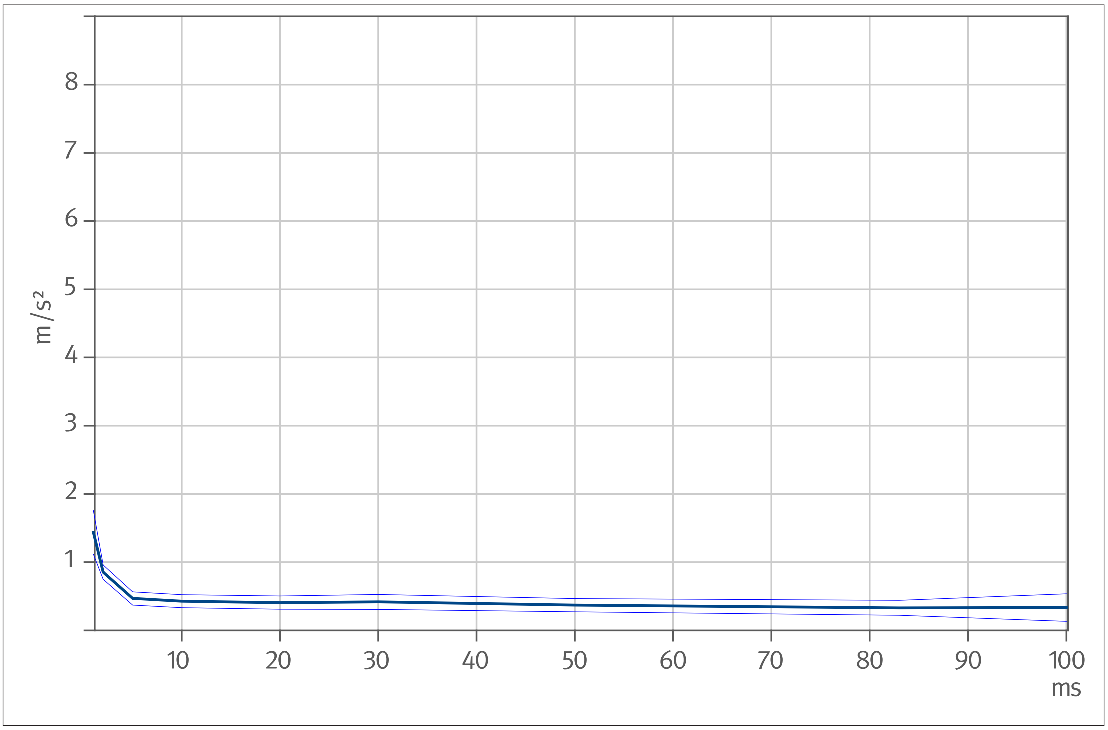


Figure H.3:
Linear RMS3

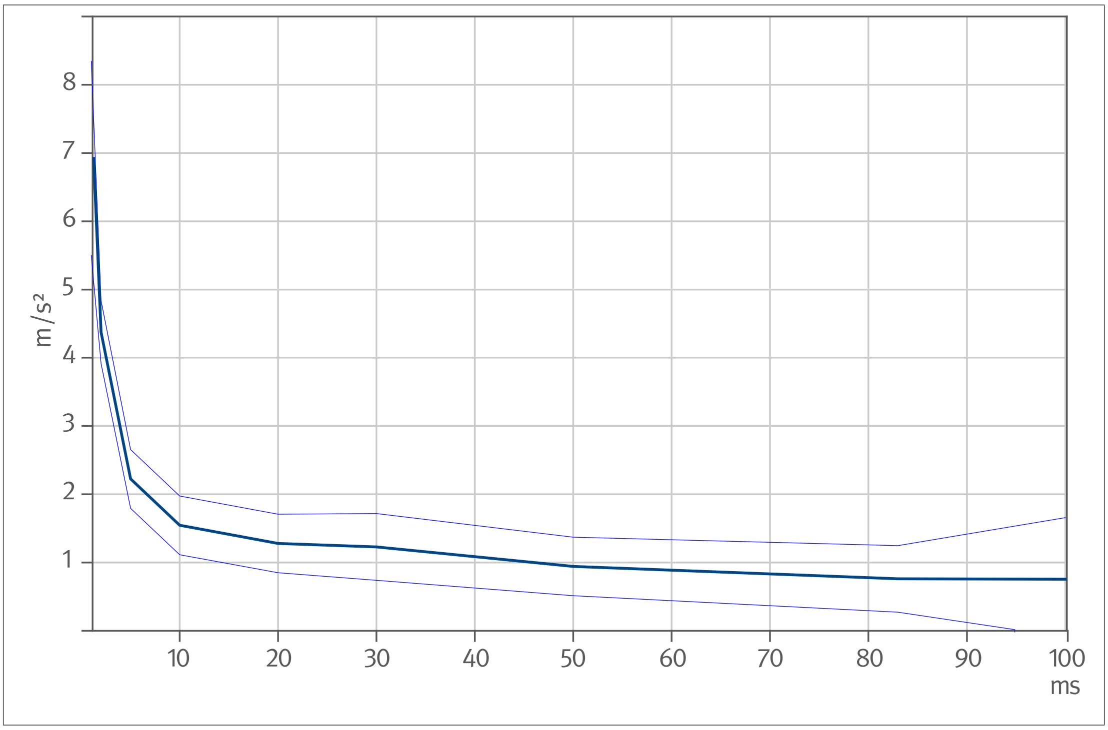


Figure H.4:
Linear RMQ3

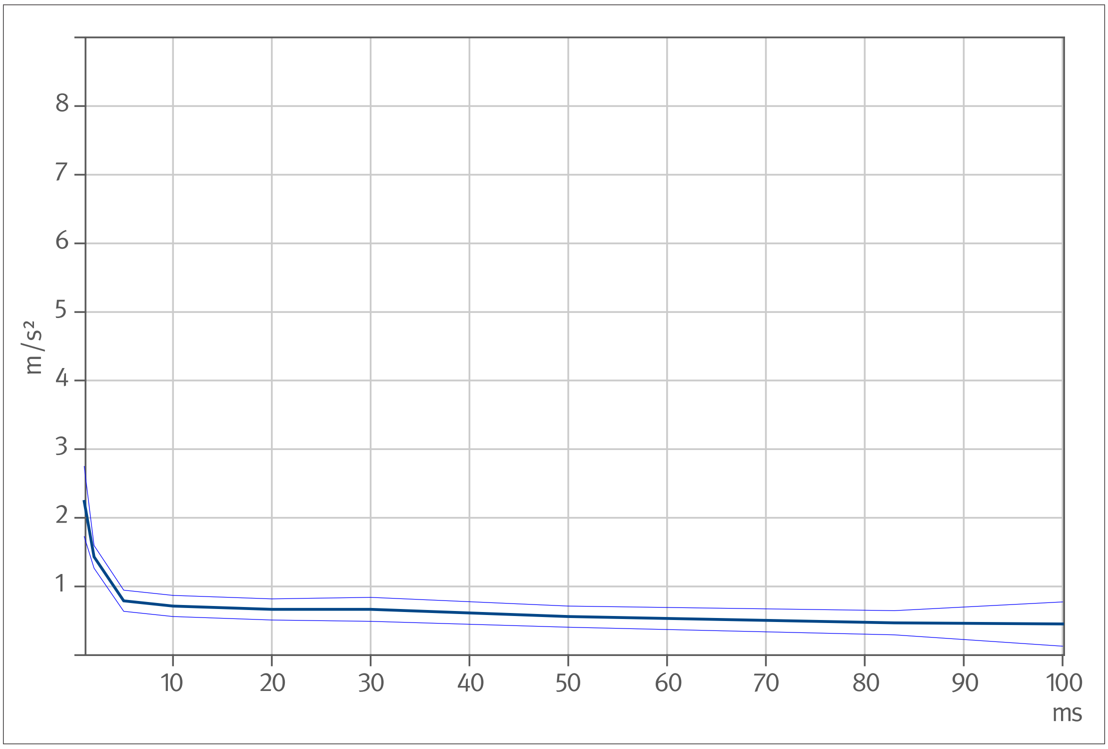


Figure H.5:
$Flat_h$ RMS1

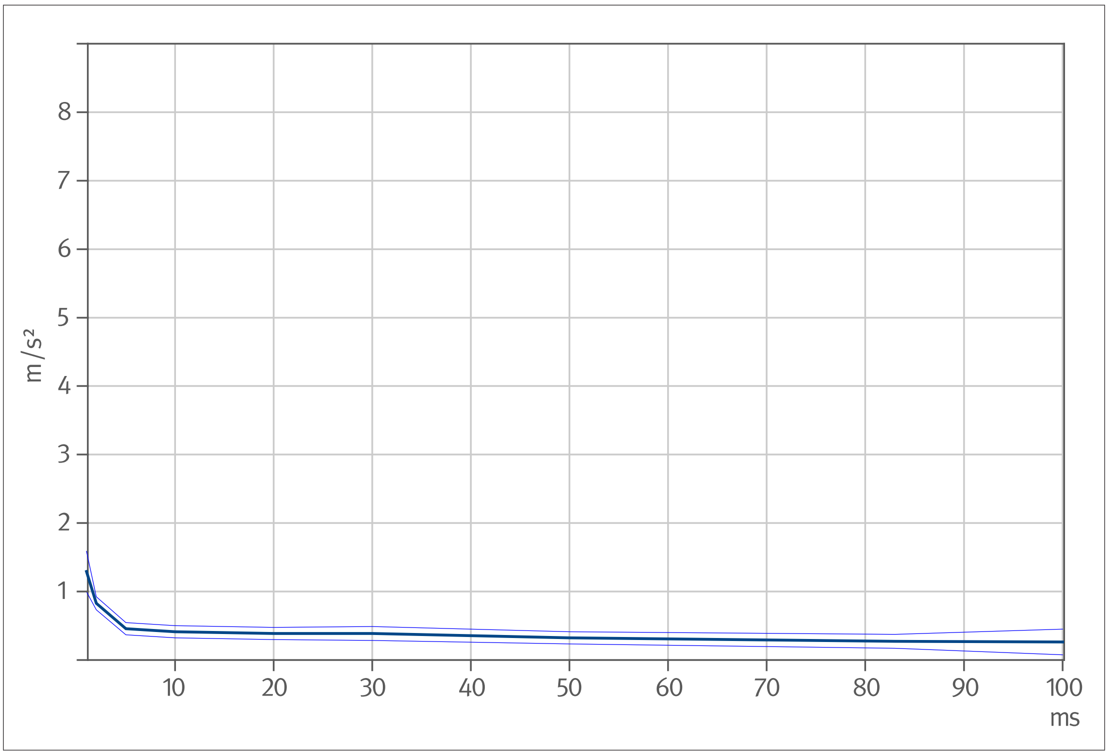


Figure H.6:
$Flat_h$ RMS3

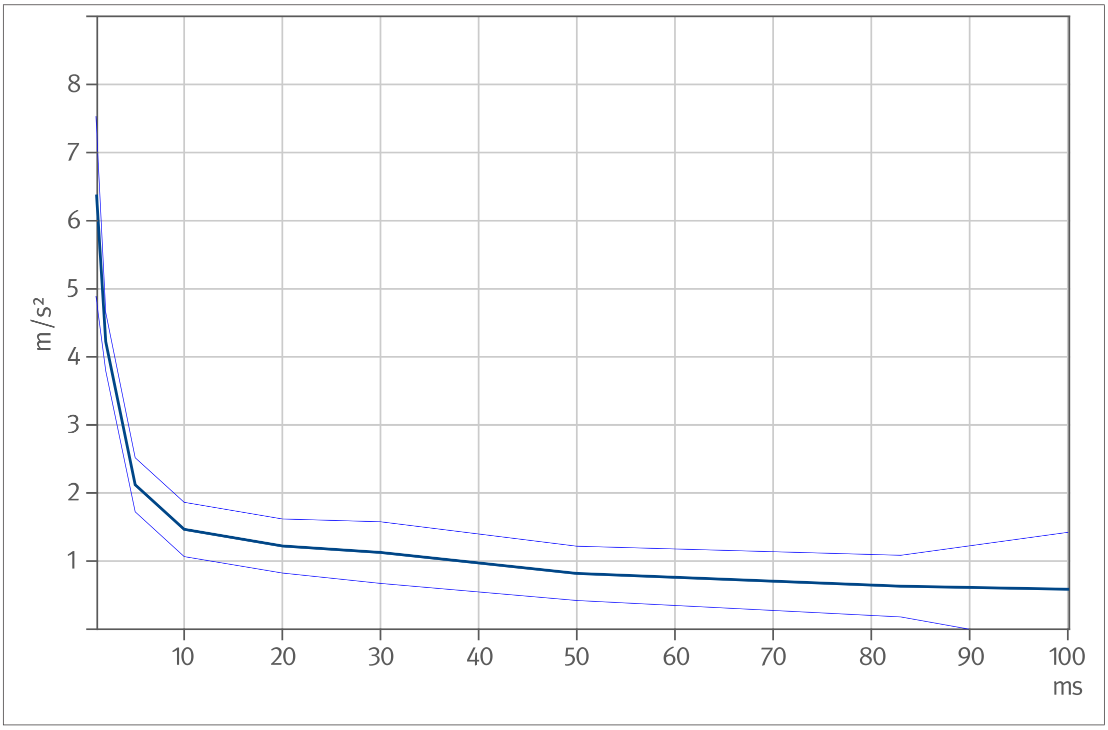


Figure H.7:
$Flat_h$ RMQ3

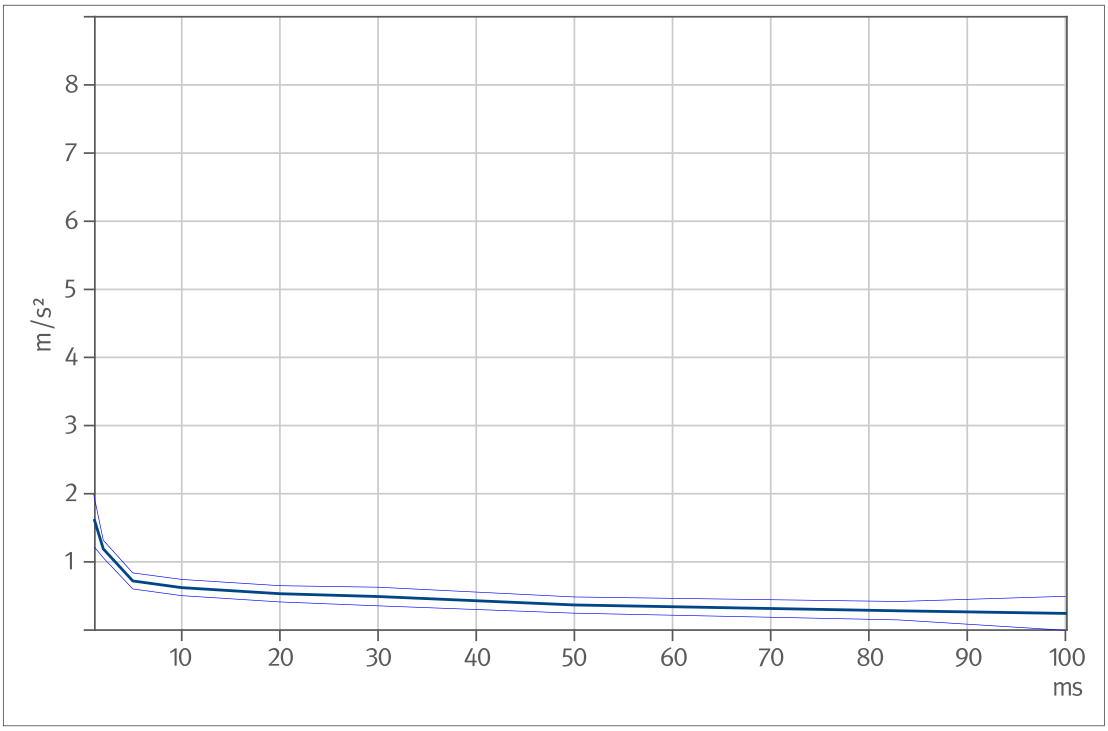


Figure H.8:
PWI18570 RMS1

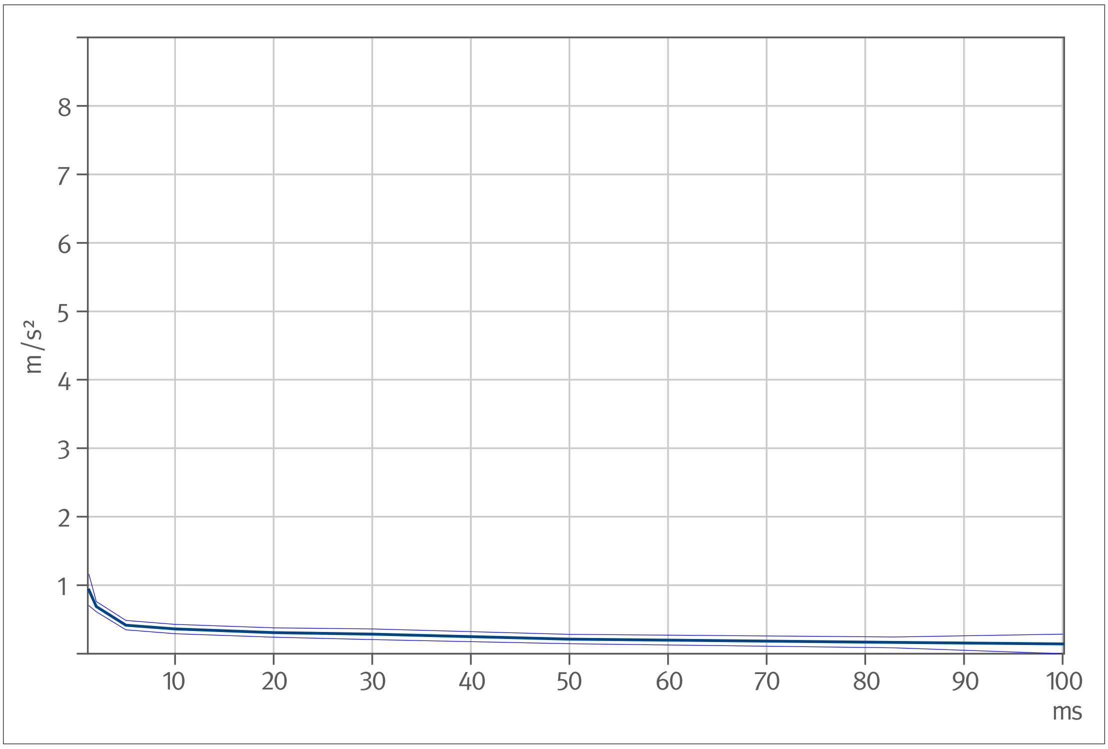


Figure H.9:
PWI18570 RMS3

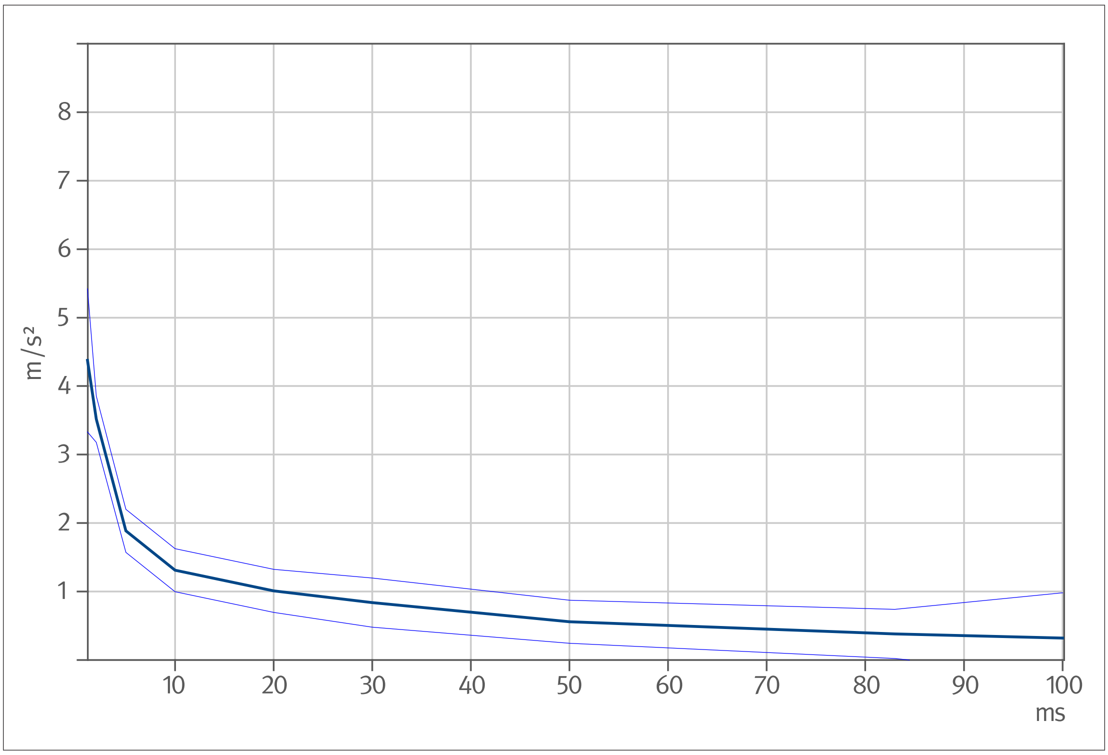


Figure H.10:
PWI18570 RMQ3

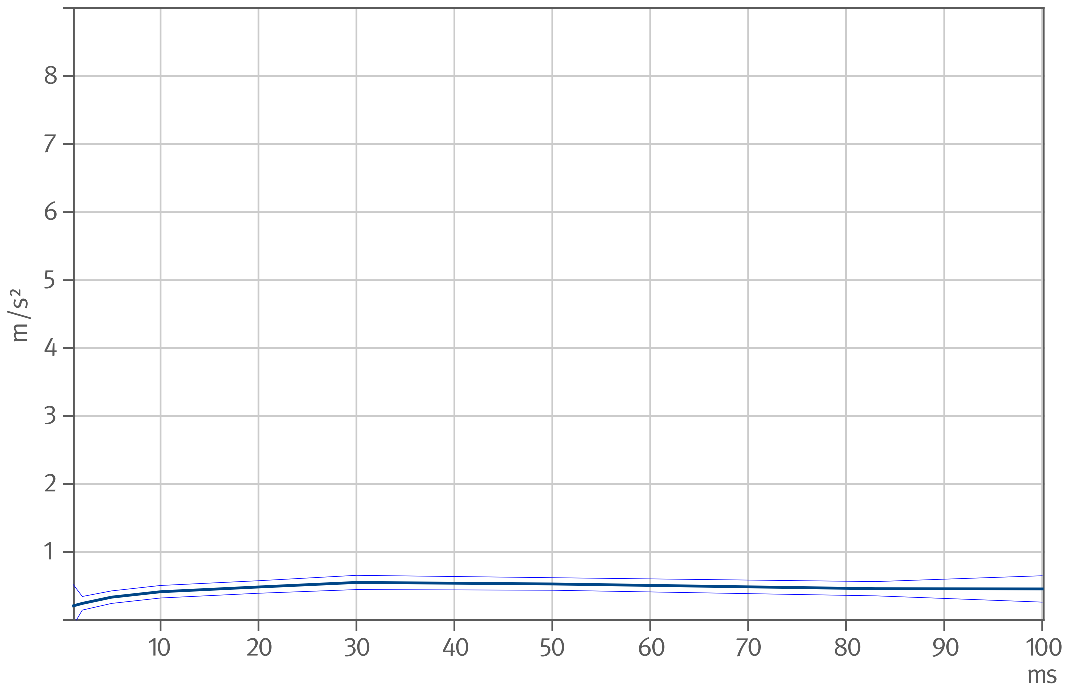


Figure H.11:
EN ISO 5349 RMS1

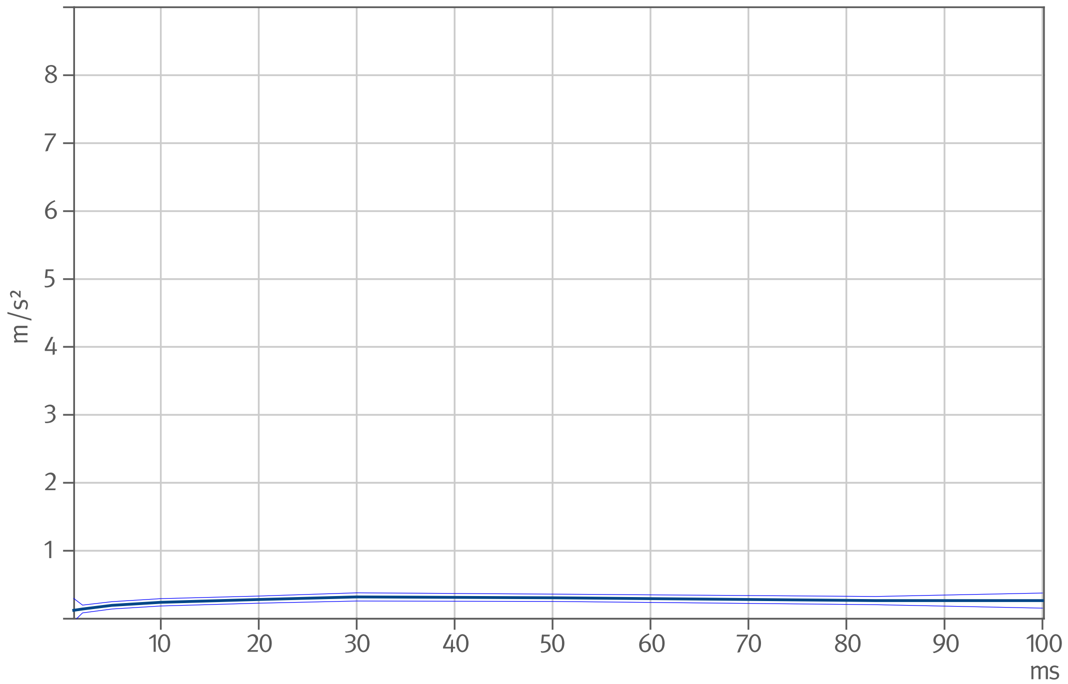


Figure H.12:
EN ISO 5349 RMS3

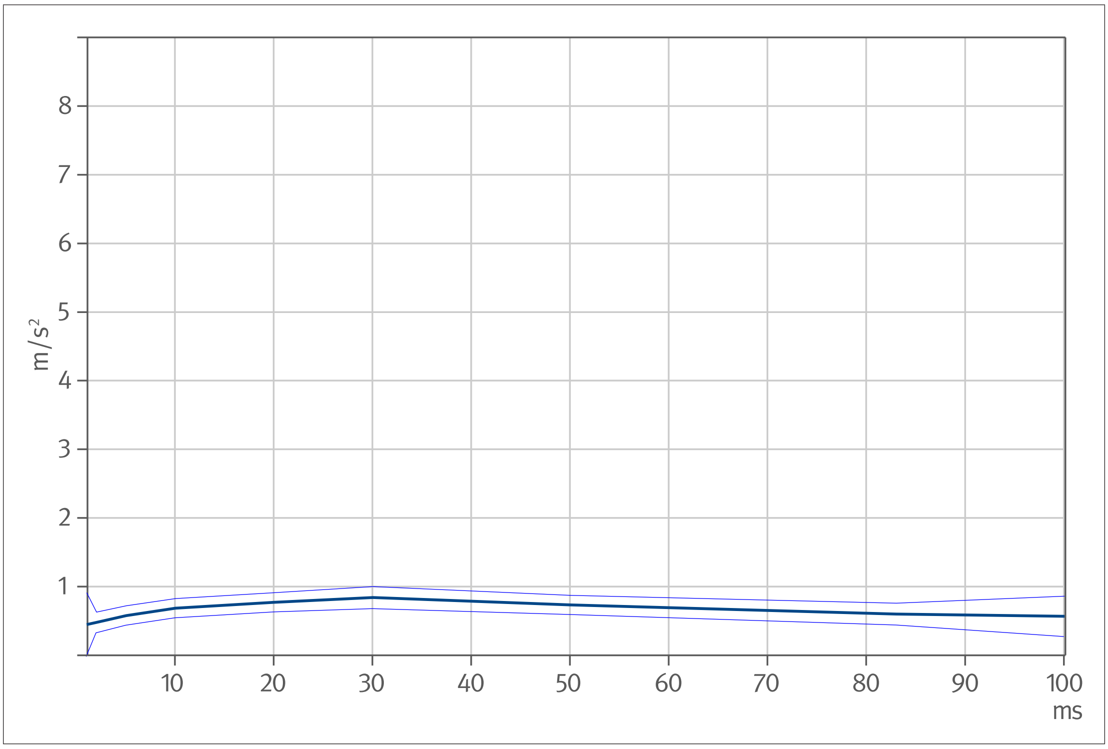


Figure H.13:
EN ISO 5349 RMQ3