Aus EINRICHTUNG INSTITUT FÜR ARBEITSMEDIZIN, PRÄVENTION
UND GESUNDHEITSMANAGEMENT (LIA)
der Universität zu Lübeck
Direktorin: Prof. Dr. Elke Ochsmann

HEALTH EFFECTS OF SINGLE IMPACTS ON THE HAND-ARM SYSTEM

Inauguraldissertation
zur Erlangung der Doktorwürde
der Universität zu Lübeck
- Aus der Sektion Medizin -

Vorgelegt von
ALEXANDRA OFELIA COROMINAS CISHEK
aus SANTIAGO DE LOS CABALLEROS / DOMINIKANISCHEN REPUBLIK

Lübeck 2025

1. Berichterstatter*in: Prof. Dr. med. Elke Ochsmann

   Ko-Betreuer*in: Prof. Dr. med. Karl-Friedrich Klotz
2. Berichterstatter*in: Prof. Dr. med. Justus Gille

Tag der mündlichen Prüfung: 15.07.2025

Zum Druck genehmigt. Lübeck, den 16.07.2025

-Promotionskommission der Sektion Medizin-

Table of content

List of Abbreviations

A1E	After 1st exposure
A2E	After 2nd exposure
A3E	After 3rd exposure
A4E	After 4th exposure
A5E	After 5th exposure
B2E	Before 2nd exposure
B3E	Before 3rd exposure
B4E	Before 4th exposure
B5E	Before 5th exposure
BMI	Body mass index
BS	Baseline
DGUV	Deutsche Gesetzliche Unfallversicherung e. V. / German Social Accident Insurance
E1	1st exposure
E2	2nd exposure
E3	3rd exposure
E4	4th exposure
E5	5th exposure
sEMG	Surface electromyography
FSBP	Finger systolic blood pressure
G1	Group exposed to 1 s^{-1}
G4	Group exposed to 4 s^{-1}
G20	Group exposed to 20 s^{-1}
GR	Group exposed to random vibration
HAVS	Hand-Arm Vibration Syndrome
HFD	Index of the fractal dimension
IFA	Institut für Arbeitsschutz der DGUV / Institute for Occupational Safety and Health of the German Social Accident Insurance
IR	Infrared
ISO	International Organization for Standardization

MDF	Index of the median frequency of the power density spectrum
TF-32	Test frequency of VPT at 32Hz
TF-125	Test frequency of VPT at 125Hz
TF-250	Test frequency of VPT at 250Hz
TF-500	Test frequency of VPT at 500Hz
TFMs	Test frequency measurements
MNF	Index of the mean frequency of the power density spectrum
MRI	Magnetic resonance imaging
MVIC	Maximum voluntary isometric contraction
OD	Occupational disease
peakPSD	Index of the maximum frequency of the power density spectrum
ROI	Region of interest
SD	Empirical standard deviation
SF	Shaker frequency
SNR	Signal-to-noise ratio
TTS	Temporary threshold shift
VPT	Vibration perception threshold

Chapter 1: Introduction and Research Questions

Occupational injuries related to handheld tools, particularly those producing vibration, have been a longstanding concern. In recent decades, there has been a significant increase in the attention paid to these injuries and the regulations aimed at preventing them [1]. This heightened focus on worker safety is driven by several factors, including the increasing recognition of the long-term health consequences of exposure to vibration, the growing public awareness of workplace hazards, and the increasing regulatory scrutiny of employers' safety practices. As a result, there has been a significant increase in the number and scope of regulations governing the use of handheld tools, particularly those that produce vibration.

These regulations have been implemented at both the national and international levels, and they cover a wide range of issues, including the design and manufacture of handheld tools, the training and education of workers, and the monitoring of exposure to vibration. The goal of these regulations is to protect workers from the harmful effects of vibration and to promote a safer and healthier workplace environment. A prime example is the European Union's Directive 2002/44/EC, implemented in 2005, which aims to protect workers from exposure to continuous and random vibration [2]. This directive, also known as the Physical Agents (Vibration) Directive, underscores the growing recognition of the importance of mitigating the risks associated with handheld tool use.

In line with this focus on worker safety, Germany implemented the LärmVibrationsArbSchV (Noise and Vibration Occupational Safety and Health Ordinance) in 2007. This ordinance provides a comprehensive framework for protecting workers from noise and vibration hazards, mandating employers to assess and control these risks. It includes conducting thorough risk assessments to evaluate the potential impact of hand-arm vibration exposure on their employees.

Workplace safety regulations effectively address the risks of continuous vibration exposure, often referred to as "random" vibration. However, they fail to account for a crucial reality: many workers regularly use tools that produce sharp, sudden jolts, known as "single-shock" vibrations. This oversight leaves a significant portion of the workforce vulnerable to the potentially harmful effects of these single-shock vibrations, which can include physical injuries and persistent discomfort like pain and fatigue. The regulations urgently need to distinguish between these two distinct types of vibration to ensure comprehensive worker protection.

This gap in regulation is compounded by a significant research deficit. Historically, most research on vibration exposure has concentrated on the effects of continuous vibration [3-6]. While a limited number of studies have acknowledged the potential dangers of single-shock vibrations [7, 8], a clear understanding of their specific impact remains elusive. This knowledge gap is also concerning given that the only very few studies directly comparing single-shock and continuous vibration effects, though the first one dates back to 1985 [7, 9, 10]. This lack of up-to-date research highlights an oversight in this vital area of occupational health and safety.

1.1 Background of vibration and single-shock exposure in the hand arm system

Hand-arm vibration research, spanning the better part of a century, initially concentrated on identifying and characterizing the phenomenon, often within specific occupational settings. Early investigations, such as those conducted in the 1930s and 1940s, documented "vibration white finger" in miners and workers utilizing pneumatic tools [11]. This issue remains prevalent in many modern workplaces, particularly in industries like manufacturing, forestry, and agriculture, where workers regularly use machinery that generates hand-arm vibrations [12-15].

The specific characteristics of the machinery used, including the frequency, range, and amplitude of the vibrations produced, can contribute to a range of adverse health effects. For instance, some studies suggest a link between high-frequency vibration exposure and circulatory disorders, while others indicate an association between low-frequency vibrations and joint damage [16, 17]. However, it's important to note that the precise relationship between vibration characteristics and specific health outcomes remains an area of ongoing research, and further investigation is needed to fully elucidate these complex interactions.

Further health implications include neurological effects, such as tingling, numbness, and loss of sensation in the fingers [18], as well as musculoskeletal effects, such as fatigue and weakness in the muscles of hands, wrists, and arms [19-21]. While these effects are well-documented in the literature, it is crucial to emphasize that individual susceptibility and the precise manifestation of symptoms can vary significantly depending on a multitude of factors, including the intensity, duration, and frequency of vibration exposure, as well as individual predispositions and other contributing factors.

In addition to random vibration, occupational exposure can also involve repeated single-shocks to the hand-arm system. These shocks are characterized as sudden, transient forces transmitted to the hands and arms [22], often originating from the use of impact tools such as jackhammers, chipping hammers, and riveting guns, or from repetitive impacts like those experienced when using a hammer or mallet. The effects of these shocks are theorized to vary depending on factors such as the magnitude, direction, and duration of the impact, as well as individual susceptibility.

Focused research on the effects of repeated single-shocks or impacts on the hand-arm system gained prominence in the 1970s and 1980s [9, 23, 24]. This increased attention stemmed from a growing recognition of the potential hazards associated with impact-tools and processes in various industries. Increased attention was driven by a growing awareness of the potential hazards associated with impact tools and processes across various industries, given their implications for health effects such as neurological symptoms (e.g., altered sensitivity), musculoskeletal disorders, and symptoms of vibration white finger [25-27].

1.1.1 Measurement of vibration and shocks on the hand-arm system

Assessing hand-arm vibration exposure is crucial for preventing occupational health risks. This assessment involves calculating the vibration dose to which workers are exposed. To determine this dose, the frequency-weighted acceleration signal of the hand-arm vibration is considered alongside the duration of exposure. The daily exposure value, A(8), normalized to an 8-hour reference period, serves as the dose value. It is calculated as the product of the weighted total acceleration, ahv, and the square root of the exposure time, T = 8 hours.

To protect workers from the adverse health effects of hand-arm vibration, the EU Directive 2002/44/EC has established a daily exposure action value of 2.5 m/s² and a daily exposure limit value of 5.0 m/s² for A(8) [Art. 3 para. 1]. These limits have been adopted into German law through the Ordinance on the Protection of Workers against the Risks arising from Noise and Vibration (LärmVibrationsArbSchV) since 2007.

To ensure consistency and accuracy in these assessments, the International Organization for Standardization (ISO) has developed ISO 5349-1:2014, "Mechanical vibration -- Measurement and evaluation of human exposure to hand-transmitted vibration -- Part 1: General requirements" [28]. This standard provides a standardized methodology for measuring and evaluating vibration transmitted to the hand-arm system.

ISO 5349-1 mandates the use of accelerometers to measure vibration. These accelerometers are affixed to the hand-arm system at specific locations, such as the hand or the wrist, to capture the vibration transmitted to the operator. The accelerometer signal is then processed, undergoing filtering and analysis to determine key vibration parameters, including magnitude, frequency, and duration.

Critically, the standard also specifies the application of a frequency weighting function. This function accounts for the varying sensitivity of the human hand-arm system to different vibration frequencies. By applying this weighting, the measured vibration data is adjusted to better reflect the potential for harm, providing a more accurate assessment of the risk to the worker.

While standardized methods exist for measuring continuous hand-arm vibration, the measurement of shock-type vibration transmitted to the hand-arm system remains an evolving field. Providing some guidance in this area is the ISO/TS 15694 technical specification, which outlines procedures for measuring discrete vibration shocks affecting the hand-arm system at repetition frequencies below 5 Hz [29]. This technical specification complements ISO 5349, which focuses on periodic and random/non-periodic vibration, thereby extending the scope of measurement to include shock-type events [22].

It is important to note that while ISO/TS 15694 provides valuable guidance on measurement techniques, it stops short of defining methods for assessing the health risks associated with shock exposure [22].

Vibration analysis software plays a crucial role in the assessment of hand-arm vibration exposure. This software processes the raw data acquired from accelerometers and hand-arm vibration meters, providing valuable insights into the characteristics of the vibration. By analyzing the accelerometer signals, the software can accurately determine the magnitude, frequency, and duration of the vibration, enabling a comprehensive evaluation of the exposure. In the case of shock-type vibration, the software can identify and analyze individual shock events, characterizing their peak amplitude and duration [30].

1.1.2 Hand-arm vibration and shock, influence on the hand-arm system

Hand-arm vibration (HAV) refers to the mechanical vibration transmitted from a vibrating tool or machine into a worker's hands and arms [31]. This can occur through the operation of hand-held power tools, hand-guided equipment, or by handling materials being processed by machines.

Single shock/impact vibration refers to a sudden, transient, and non-periodic force transmitted to the hand-arm system. It is characterized by a rapid rise to a peak acceleration followed by a rapid decay, typically lasting for only a few milliseconds [22]. This type of vibration is often associated with the use of impact tools, sudden jolts, or handling of heavy objects.

The influence of hand-arm vibration (HAV) and shocks on the hand-arm system is well-established. International Standard ISO 5349-1:2001 provides a framework for evaluating the effects of hand-transmitted vibration, including both HAV and shocks, and acknowledges their potential to cause damage to tissues, nerves, and blood vessels. This understanding is further supported by Griffin's comprehensive Handbook of human vibration (1990), which details how these forces are transmitted through the hand and arm, leading to specific effects on nerves, muscles, and blood vessels [32].

These health effects on the hand arm system are known as Hand-arm vibration syndrome (HAVS) and are a prevalent occupational disease affecting workers in multiple industries in which hand-held tools are used. The UK's Health and Safety Executive provides extensive guidance on HAVS, clearly outlining the damage to nerves, blood vessels, and musculoskeletal structures caused by HAV. Together, these sources paint a clear picture of the mechanical influence of HAV and shocks on the hand-arm system, leading to a range of adverse effects.

The severity of the mechanical influence on the hand-arm system depends on several factors, including the magnitude, frequency, and duration of the vibration or shock, the type of tool or machine being used, the individual's hand-arm posture and grip force, and the individual's overall health and fitness [33-35].

Exposure to HAV can lead to various health issues, primarily affecting the vascular, neurological, and musculoskeletal systems [34]. HAV can cause vasospasm, a narrowing of the blood vessels in the fingers, leading to vibration white finger (VWF) [36-38]. VWF is characterized by tingling, numbness, and blanching of the fingers, and can potentially progress to tissue necrosis.

In addition to vascular effects, HAV can also damage the peripheral nerves in the hand and arm, causing sensory and motor impairment [18, 39, 40]. Finally, both HAV and shock can damage the muscles, tendons, and ligaments in the hand and arm. This can result in pain, stiffness, and weakness [41-43].

1.1.3 Impacts / Single shocks as form of exposure and its health effects on the hand-arm system

Research using animal models, while few, provides evidence for the detrimental effects of shock-type vibration on the hand-arm system. For example, a study on rats exposed to high-magnitude shocks for a short duration of a single 12-min exposure showed immediate damage to nerve endings in the skin [44], highlighting the potential for acute injury. Another animal base study has found that impact/shock type vibration may affect the nerves but not the blood vessels [45].

The studies found in the literature that focus on the medical outcomes of impacts/single shocks as a form of exposure show a complex picture. The effects of these shocks depend on a number of factors, including the magnitude, frequency, and duration of the shock; the type of tissue exposed; and the individual's overall health and fitness [10, 35].

While the existing literature on the medical outcomes of impacts/single shocks paints a complex picture, most studies on the health effects of shocks to the hand-arm system focus on acute effects [10, 46-48], although long-term studies have been made [49]. Studies investigating peripheral vascular responses to single or repetitive mechanical shocks showed acute reductions in finger blood flow [50, 51]. Proximal extensor muscle edema was observed in studies that looked at muscular response [47]. Our pilot study showed a temporary increase in vibration perception thresholds, especially at high test frequencies, a slight decrease in skin temperature, and increased effort in two forearm muscles during shock transmission. [48].

While these studies shed light on the immediate consequences of single shocks, further research is needed to understand the cumulative effects of repeated exposure. This is a critical area of inquiry because, as mentioned, many occupational settings involve repeated shocks to the hand-arm system. This understanding will be vital in developing effective prevention strategies.

To better understand the potential long-term impact of repeated shocks, it's important to consider the occupational diseases already recognized by the German government. These include damage to the joints (No. 2103), circulatory disorders in the fingers (No. 2104), carpal tunnel syndrome (No. 2113) and hypothenar hammer syndrome (No. 2114), all of which can be caused by vibration exposure. These recognized conditions highlight the potential for serious health consequences and emphasize the need for further research into the effects of repeated shocks and effective prevention strategies [52].

This need is further underscored by the fact that approximately 1.8 million employees in Germany work in sectors involving hand-arm vibrations [53]. Each year, roughly 1,600 occupational diseases are reported in connection with such exposure, of these, around 350 are officially recognized [54]. This stark reality emphasizes the urgent need for effective prevention strategies in this area.

However, despite the recognized risks, a truly effective prevention concept remains elusive. For 20 years, there has been a lacked of comprehensive approach to prevention with proven efficacy. This is a crucial area of focus for occupational disease development in Germany, as it highlights the need for continued research and development of preventative strategies to protect workers exposed to not only to hand-arm vibration but to single-shock / impact vibration as well.

The existing preventive measurements presented by the BAuA outlines the legal obligations of employers in Germany to prevent and minimize health risks associated with hand-arm vibrations in the workplace, according to the LärmVibrationsArbSchV (Noise and Vibration Occupational Safety and Health Ordinance) [55]. This proactive approach prioritizes worker safety through several key actions. First, employers must assess vibration exposure levels and inform employees about the associated risks. If necessary, a vibration reduction program should be implemented, focusing on the use of low-vibration tools, proper tool maintenance, and work organization strategies to minimize exposure. Additionally, providing protective equipment and health surveillance is crucial to monitor and address potential health issues [56].

To further support these efforts, the BMAS (Bundesministerium für Arbeit und Soziales) has created a handbook specifically to address the complexities of assessing and managing hand-arm vibration risks. This non-legally-binding guide offers practical support in evaluating vibration risks, identifying controls to eliminate or reduce exposure, and implementing systems to prevent the onset and progression of related disorders. The handbook focuses on three key areas: risk assessment, avoidance or reduction of exposure, health monitoring and occupational health care [57].

It is important to acknowledge, however, that these existing frameworks predominantly focus on continuous or intermittent random vibrations, with limited guidance on mitigating the effects of shock and impact vibration. While some general principles may overlap, the distinct characteristics of shock and impact events, such as their sudden onset and high peak acceleration and forces, necessitate targeted research and the development of tailored preventive strategies. This dissertation aims to contribute to this critical area by investigating the biomechanical and subjective responses to repeated shocks, with the ultimate goal of informing the future development of effective preventive measures to protect workers in shock-prone occupations.

1.1.4 Questions and Hypothesis

Existing research indicates that repeated single-shock exposure to the hand-arm system may adversely affect the hand-arm system. However, crucial knowledge gaps persist regarding the influence of repetition rate on the severity of these effects and the potential for distinct injury mechanisms compared to random vibration exposure.

This dissertation seeks to address these gaps, with the aim of providing an in-depth exploration for increasing the understanding of the risks associated with single-shock exposure. Such knowledge is essential for the development of informed safety measures within occupational settings where this type of exposure occurs.

This dissertation seeks to address three overarching questions related to single-shock exposure and the hand-arm system:

Does single-shock exposure cause acute responses in the hand-arm system, and if so, what types of responses (neurological, vascular, muscular) occur?

Is there a positive correlation between the frequency of single-shock exposure and the severity of acute responses in the hand-arm system? This hypothesis suggests that the intensity of effects on the hand-arm system will increase with the frequency of single shocks, even when the total number of exposures remains constant.

Do the acute effects of single-shock exposure on the hand-arm system differ in nature and/or severity from the acute effects of random vibration exposure, regardless of the repetition rate? This hypothesis proposes that the mechanisms by which single-shock exposure impacts the hand-arm system may be distinct from those involved in random vibration exposure.

These hypotheses build upon existing research, which suggests potential links between single-shock exposure and adverse effects on the hand-arm system [48]. A more comprehensive investigation addressing the questions and hypotheses outlined above will advance our understanding of the specific risks associated with single-shock exposure and contribute to the development of evidence-based safety practices in occupational settings.

Chapter 2: Material and Methods

2.1 Study design

This study employed a single-center, prospective, parallel-group, vibration-controlled, simple randomized design to investigate the acute health effects of three different repeated single-shock exposure frequencies on the hand-arm system of healthy male participants. A control group exposed to random vibration was used for comparison with these effects. The study was conducted between April 2020 and April 2021 at the Institute for Occupational Safety and Health (IFA) of the German Social Accident Insurance in Sankt Augustin, Germany.

This study focused on the acute physiological responses of healthy males following exposure to shock vibrations, using a Shaker V726 electrodynamic shaker controlled by Premier Shock software [Chapter 2.4.4]. Participants were randomly assigned to one of three single-shock exposure frequencies (1 s^{-1}, 4 s^{-1}, or 20 s^{-1}) for a duration of 4 x 5 minutes. All participants concluded the session with a 5-minute exposure to random vibration, resulting in a total of 25 minutes of vibration exposure. A fourth group of participants exposed to random vibration signal served as a control. Physiological measurements were recorded before and after each exposure, with approximately 12-minute intervals between exposures. The experimental schedule is outlined in [Figure 2.4.1].

2.2 Ethics

This study adhered to strict ethical guidelines, receiving approval from the University of Lübeck ethics committee (approval number: 20-099) and following the principles of the Declaration of Helsinki. All participants provided written informed consent, which included provisions for the use of anonymized data in publications. Participants were also informed of their right to withdraw without consequence. The study prioritized ethical data collection and protection, ensuring confidentiality and compliance with the European Data Protection Regulation [Art. 32, Art. 89 DSGVO]. All collected data was pseudonymized.

2.3 Participants

Given the higher prevalence of vibration-related injuries in male-dominated industries and the study's focus on this at-risk population, only male participants were included. While including both sexes would have been ideal, resource constraints necessitated a focused approach to maximizing the statistical power within the available resources.

2.3.1 Eligibility criteria

This study included healthy male participants aged 18-65 who were capable of moderate-intensity exercise (defined as any activity elevating the heart rate and breathing without causing excessive fatigue or discomfort). Individuals were excluded if they were active smokers, regularly used hand-arm vibration tools (at least weekly for over two hours), had hypertension, a cardiac pacemaker, any musculoskeletal disorders affecting the hand-arm system, hand-arm complaints of the dominant limb, upper back or hip disorders, any illness limiting participation, or a history of neuropathy or musculoskeletal disorders of the upper limb. Individuals who refused to provide informed consent were also excluded.

The study also excluded potential participants who had a history of chronic or acute peripheral or central neuropathy, any musculoskeletal disorders of the upper limb, or any current or past-experience of pain, even if that pain was limited to post-exercise discomfort.

2.3.2 Recruitment and enrollment

To recruit participants of working age living near the IFA in Sankt Augustin, Germany, recruitment was conducted primarily through Facebook. This strategy allowed for cost-effective access to a convenience sample during the COVID-19 pandemic. The recruitment process involved two phases: initial screening and follow-up. Potential participants responded to invitations on Facebook and completed an initial screening via email to determine eligibility based on health status, chronic diseases, smoking habits, hand-arm complaints, and exposure to vibrating tools.

Eligible individuals received the informed consent form, a description of the study, and a detailed health questionnaire (Appx. Chapters 8.4 and 8.5). They were given at least 48 hours to review the materials and ask questions, and participation was confirmed by phone 24 hours before their scheduled visit. Initially, 48 participants were recruited, followed by a second recruitment phase to mitigate potential dropouts, resulting in a total of 56 participants after exclusions.

2.3.3 Sample size

To determine the necessary sample size for this study, a power analysis was conducted. This analysis was based on the findings of Schäfer and Dupuis (1986) [23] and FP-0376 [58], which provided parameters for estimating the effect size. Due to the limited availability of comparable data, these sources were deemed the most appropriate for this study.

To supplement this initial estimation, various online calculators were also consulted (e.g., Kohn et al. 2017) [59]. This multi-faceted approach led to an estimated sample size of 12 subjects per frequency exposure. With four different exposure frequencies being tested, this resulted in a total sample size of 48 subjects. This sample size ensures sufficient statistical power (80%) to detect significant differences between subjects and exposure conditions, with a significance level of $\alpha=0.05$ (two-sided test).

The sample size was subject to a standardized exposure protocol [Chapter 2.4.1]. This involved using a developed method set under controlled conditions (on a shaker) simulating four distinct exposure frequencies. The frequencies were selected to represent the vibration profiles of four common types of tools/machines encountered in real-world occupational settings. All tests were conducted under expert supervision in the IFA's exposure laboratory, allowing for direct comparison between subjects and across the varying exposure levels.

2.3.4 Randomization and blinding

This open-label study used a two-stage randomization process to ensure balanced group sizes. Initially, a computer-generated allocation sequence was used for the first 48 participants, assigning them to one of four groups in a 1:1:1:1 ratio. Following a second recruitment phase, which increased the participant pool to 56, manual randomization was used to allocate additional participants. After exclusions, the final sample size for each group was 13. This resulted in four distinct exposure conditions: three groups exposed to repeated single-shock vibrations at different frequencies (G1: 1 s^{-1}, G4: 4 s^{-1}, and G20: 20 s^{-1}) and a control group exposed to random vibration (GR). This allowed for comparison between the effects of repeated single-shock vibrations at specific frequencies and random vibration.

2.4 Procedures

Participants first acclimatized to the room temperature for 30–35 minutes. During this time, they underwent a structured interview and reviewed the health questionnaire with the researcher to confirm eligibility and current health status. They were also informed of the study's purpose, procedure, and potential risks. To prepare for the examinations, participants were asked to refrain from alcohol for 12 hours, avoid vibration or impact exposure to the hands and fingers for 5 hours, and avoid caffeine and strenuous physical activity for 3 hours. This included avoiding vibrating tools, repetitive work, heavy lifting, sports, and bike commuting. Participants were offered €70 compensation for their time, with the total study duration lasting approximately 4 hours. Due to the SARS-CoV-2 pandemic, acute infections were excluded using rapid tests.

2.4.1 Experimental setup

To systematically evaluate the impact of various vibration exposures, a block-wise study procedure was adopted for each participant. This approach, adapted from the pilot study, involved a series of experimental blocks. Each block employed a pre-test–post-test design to assess three key physiological responses: skin temperature, finger sensitivity, and muscle fatigue. Muscle activity was measured using surface electromyography (sEMG) to assess muscle fatigue and potential changes in activation patterns. Simultaneously, infrared (IR) thermography monitored skin temperature changes in the hand and fingers to provide insights into the vascular response to vibration. Lastly, the VibroSense Meter evaluated tactile sensitivity in the fingertips to detect potential sensory nerve dysfunction.

This structured design, with its multi-faceted assessment within each block, allowed for a controlled comparison of responses across different exposure conditions while minimizing the influence of individual differences.

2.4.2 Impact exposure simulation

Simulation of shock exposure and evaluation of health effects, under standardized conditions in the laboratory, offered advantages in terms of comparability of exposure conditions and did not require practice or safety instruction of the subjects.

A pre-test (hereafter referred to as baseline), post-test design was established. The post-test consisted of measurements taken after each of the exposures (altogether five post-tests with varying frequency intensity). The experimental protocol involved five (5) x 5-minute exposures,

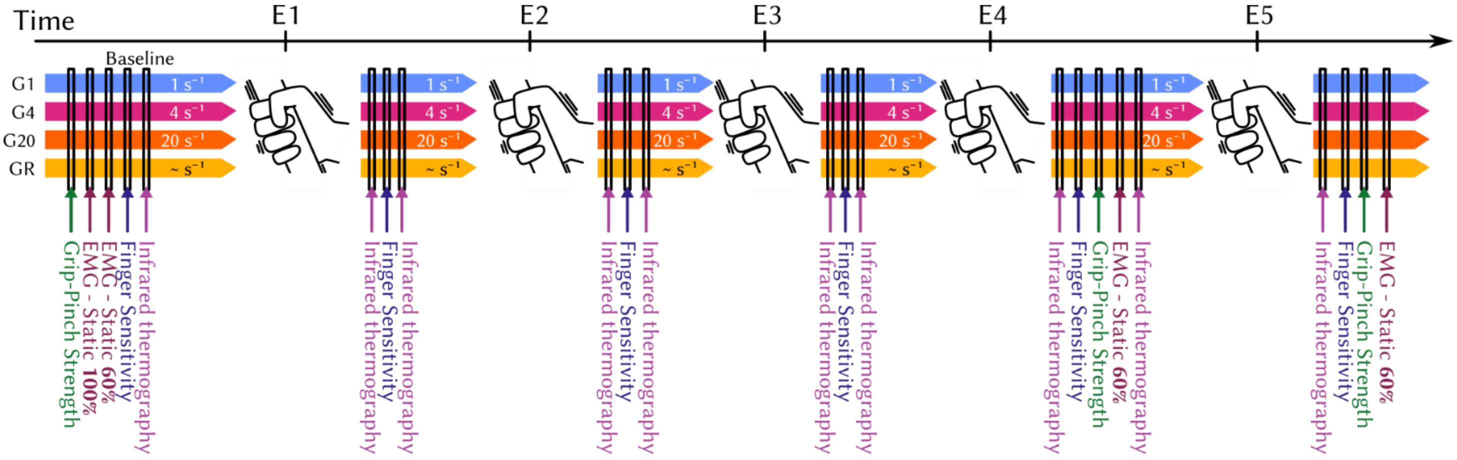


Figure 2.4.1 Systematic representation of the experimental protocol for each exposure group (G1: 1s^{-1}; G4: 4s^{-1}; G20: 20s^{-1}; GR:[~ s^{-1}] random vibration). Each exposure was followed by a 12-minute period for physiological measurements. This allowed for the assessment of the immediate effects of vibration on physiological parameters.

totaling 25 minutes. Each exposure was followed by a 12 to 15-minute recovery period. Physiological measurements (post-test) were recorded during these recovery periods.

2.4.3 Experimental procedure and instrumentation

Exposures and physiological measurements were performed in two adjacent laboratory rooms controlled for temperature and humidity. The rooms maintained a mean temperature of 21.8 °C (SD 0.9 ºC), and a mean humidity of 43.7% (SD 6.9%).

Instruments for physiological measurements were placed near the shaker to optimize the time taken for post-test measurements.

2.4.4 Shaker setup

Impact simulations were performed using a V726 electrodynamic shaker (Ling Dynamic Systems, Royston, United Kingdom), subsequently referred to as the "shaker." This shaker can deliver a rated force of 6,672N, operates within a frequency range up to 4,500Hz, and can achieve a maximum acceleration of 920m/s². The shaker was coupled to an aluminum handle, 155 mm high and 40 mm in diameter, which could be fully gripped by an adult hand. The handle was equipped with a strain gauge bar, allowing the gripping force to be monitored on a continuous basis. The platform of the shaker was connected to 'ground' by a strain gauge load ring, allowing the measurement and monitoring of the pushing force. A monitor at eye level provided constant visual feedback of the grip and push force being maintained on the handle.

The Premier Shock control software (Spectral Dynamics, San José, USA) generated uniform and approximately triangular shocks of repetition rates 1 s^{-1}, 4 s^{-1}, and 20 s^{-1} which acted unidirectionally in the z-direction only, so that the collection of acceleration components in the x- and y-directions could be omitted (ahv = ahw). All three single-shock exposures (1 s^{-1} repetition rate, 4 s^{-1} repetition rate, (20 s^{-1} repetition) had a shock duration of 3 ms and a rise time of 1.5 ms. In the following, the single-shock exposures are simplified based on the repetition rate of the shocks as "1 s^{-1} ", "4 s^{-1} ", and "20 s^{-1} ".

For the control group and as the last comparative exposure form, of shock exposed groups, random signal, the vibration spectrum S_M of ISO standard 10819 for the testing of vibration protective gloves [DIN EN ISO 10819:2013] (undirected vibration, spectrum vibration) in a vibration frequency range of 20–200 Hz was used, also with a duration of 5 minutes. This is referred to as the random signal or random vibration in the further course. Although gloves were not used in this study, the vibration exposures were designed in accordance with DIN EN ISO 10819:2013. This standard provides a well-defined framework for characterizing vibration transmissibility, ensuring that the vibration stimuli delivered to participants was consistent and controlled across the experimental conditions.

Following our previous pilot study setup [48], the signal was controlled in such a way that the ahw value was kept constant at 10 m/s^2 for each 5-min exposure. Thus, an approximately uniform dose delivery was achieved for the subjects in the experiment regardless of the repetition rates.

2.4.5 Measurement procedures

The standardized posture of the test subjects largely corresponded to ISO standard 10819 [2013] for the testing of vibration protective gloves [33]. Subjects were standing in an upright posture, with the forearm aligned along the z-axis, flexed by about 100° and slightly abducted. To maintain the standardized posture between subjects, the handle and platform were marked as a visual reminder for subjects for correct hand and feet placement [Figure 2.4.2].

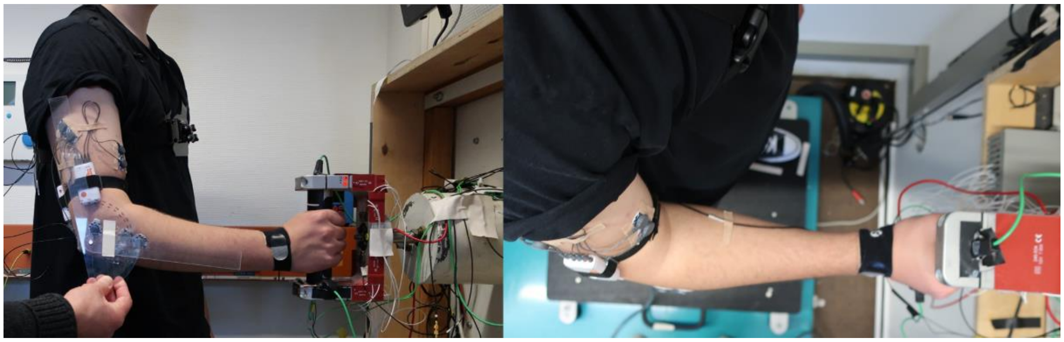


Figure 2.4.2 Experimental setup on Shaker. (A) Subject positioning with visual reminders for optimal posture and hand placement on handle. (B) Platform markings ensuring consistent foot placement across trials (top view).

To measure acceleration, unidirectional sensors were attached to the skin at three anatomical locations: the foveola radialis in contact with the distal radius of the wrist, the lateral humeral condyle of the elbow, and the acromion of the shoulder blade [Figure 2.4.3], These locations were selected to capture acceleration data and calculate the transfer factor. The measurement direction (z-axis) corresponded to the expected deflection of the hand-arm system for each shock or vibration transmitted through the handle.

Weighted acceleration values ahw obtained from the sensors were then related to the acceleration generated by the shaker and measured at the handle to determine the localized transmission factor. This factor represents the proportion of vibration transmitted from the handle to each measurement location. The parameters chosen for exposure assessment, namely horizontal acceleration ahw and peak acceleration values for each signal type or frequency, were based on the recommendations provided in the IFA report[46].

For the evaluation of the transmission of mechanical loads into the hand-arm system, the coupling forces were also recorded according to ISO standard 15230 [ISO 15230:2007 Mechanical vibration and shock - Coupling forces at the man-machine interface for hand-transmitted vibration]. This was, on the one hand, the pressure force of the test person acting almost exclusively in the z-direction against the handle and, on the other hand, the gripping force that was provided when the handle was grasped [60]. Pressure and grip force were recorded continuously within the measurement intervals, and the pressure force was also kept

Figure 2.4.3 Unidirectional accelerometer placement. (A) Sensors placed on the lateral humeral condyle (elbow) and acromion (shoulder). (B) Sensor placed on the distal radius (wrist).

largely constant at 50 N by the test subjects via visual feedback. From practical experience, it was not expected that the test subjects would be able to simultaneously control gripping and pressure force over five minutes, so the gripping force, while being measured continuously, fluctuated individually.

2.4.6 Baseline measurements

Baseline physiological measurements were conducted at the end of the acclimatization period and included: anthropometric data of hand and arm system (lengths, circumferences, and widths); hand (grip) strength, finger (pinch) strength and static maximum voluntary isometric contraction (MVIC) of the triceps, biceps, and forearm muscles. Followed by finger sensitivity and hand temperature just before the start of the first exposure.

2.5 Vibration perception threshold

2.5.1 Setup

The VibroSense Meter II model (VibroSense Dynamics, Malmö, Sweden) was used to measure the vibration perception threshold (VPT) of the 2nd and 5th fingers of the exposed hand. To maintain a constant time schedule between exposure and measurement, the VibroSense was placed in a room adjacent to the exposure room. Finger sensitivity on the exposed hand was measured before and approximately 1 minute after exposure, following the measurement of hand temperature. Approximately 9-10 min was required for the complete set of finger sensitivity measurements.

Participants were positioned in a standardized posture as recommended by the manufacturer. They were instructed to sit upright in a relaxed position with their exposed right arm loosely extended and their elbow slightly flexed. Subjects either placed the fingertip of their 2nd or 5th finger on the 4 mm thick metal probe [Figure 2.5.1]. Participants held a response button in their other hand and pressed it according to the researcher's instructions. For noise reduction during high-frequency measurements, participants were provided with ear protection. To enhance concentration, they were encouraged to close their eyes.

The VibroSense examination procedure was fully automated, ensuring adherence to ISO 13091-2 standards. This included the instrument's continuous monitoring and display of ramp speed, static finger pressure, and finger temperature for the operator. This design feature allowed for immediate correction of any significant deviations from the testing protocol. The VibroSense frequencies, referred to as Finger Sensitivity Frequencies (FSF), were selected based on the pilot study's recommendations and included 32Hz, 125Hz, 250Hz, and 500Hz, representing both low and high-frequency ranges [48].

2.5.2 Measurement procedure

Baseline finger sensitivity measurements were initiated following acclimatization [2.4 Procedures] and after each exposure. Before baseline measurements, all subjects underwent a brief 16 Hz trial on the VibroSense, lasting approximately 10 seconds, followed by a rest period of approximately 4–5 minutes. This allowed the subjects to gain practical experience and helped to minimize the potential learning curve between subjects [Figure 2.5.1].

Figure 2.5.1 Finger sensitivity measurement with the VibroSense Meter II. The subject is positioned with their arm loosely extended, elbow slightly flexed, and fingertip placed on the 4 mm thick metal probe.

Before and following each exposure, finger sensitivity was measured [Figure 2.5.2]. VPT were examined on the pulp of the 2nd (index) and 5th (little fingers) fingers of the exposed hand. The examination with the VibroSense Meter II is fully automated, with frequencies running from low to high. Vibrations were applied through the probe according to a von Bekesy up-and-down psychophysical algorithm, and the acceleration of the probe is expressed in decibels (dB; relative 10-6 m/s^2) [61].

Each examination frequency (32 Hz, 125 Hz, 250 Hz, and 500 Hz) was automatically ramped up fivefold to above threshold intensity and then ramped down to below threshold intensity while varying the ramp rates. The acceleration began at 100 dB and increased with an amplitude ramp rate of 3 dB/s until the subject perceived the vibration and pressed down a response button. Upon the subject's pressing of the button, the intensity decreased at a corresponding speed of 3 dB/s until the subject no longer perceived vibration, at which point the subject was instructed to release the button.

Finger pulps were examined in accordance with ISO 13091-1, Method A, with a contact force of 0.15 ± 0.09 N between the finger pulp and the probe (***reference ISO 1390). This equates to a static skin indent of approximately 1.5 mm. Throughout the test, the researcher was able to monitor the finger pressure on the probe to ensure that the force remained within the required limits. The fingertip temperature was also monitored by the VibroSense. If the temperature of the fingers was ≤ 21 °C, the subjects were asked to warm their hands before the examination.

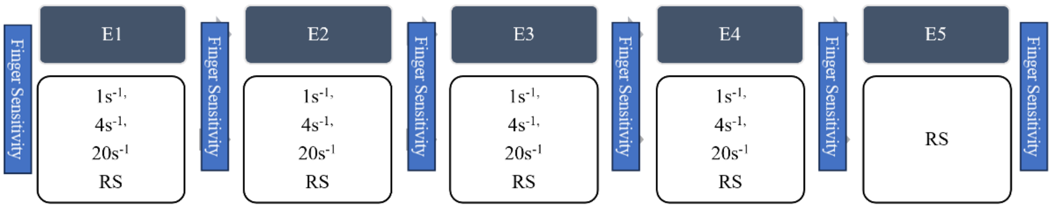


Figure 2.5.2 Finger sensitivity measurement protocol. Vibrotactile thresholds were measured at baseline and after each of five exposures (E1-E5) at four test frequencies (32, 125, 250, and 500 Hz) using the VibroSense Meter II.

For each examination frequency, a "vibrogram" could be generated, from which the mean vibration sensitivity threshold of the measured finger could be determined.

2.6 Temperature reaction

The skin temperature was examined using an infrared thermal camera (IR). Infrared technology has been utilized for non-invasive surface temperature measurement of fingers and hands for several decades and has been employed in numerous studies on HAVS, particularly with cold provocation tests [62-64]. This approach is based on the premise that skin temperature serves as an indicator of vascular changes, both in normal pulsatile arterial blood flow and in provoked vascular reactions [65, 66].

2.6.1 Setup

The infrared thermal camera (IR) used for all tests, was a compact FLIR ONE® Pro (FLIR Systems, Wilsonville, USA) attached to an iPhone 6 smartphone (Apple, Cupertino, USA) and the corresponding manufacturer's app FLIR ONE®. According to the manufacturer, the IR had a measurement accuracy of ± 3 °C or ± 5% of the difference to the ambient temperature. The resolution of the infrared images was 160 × 120 pixels, a native photo taken in parallel of the same image section had a resolution of 1440 × 1080 pixels [67].

Temperature was measured before and immediately after each exposure [Figure 2.6.1]. The IR was mounted on a metallic structure that maintained a fixed distance from the hands of 46 cm. The hands were supported by a nylon mesh, which minimized the contact area and allowed for air circulation around the hands. Markings with contrasting colors were placed on the mesh to facilitate the correct repositioning of the hands. Once the hands' position and temperature range

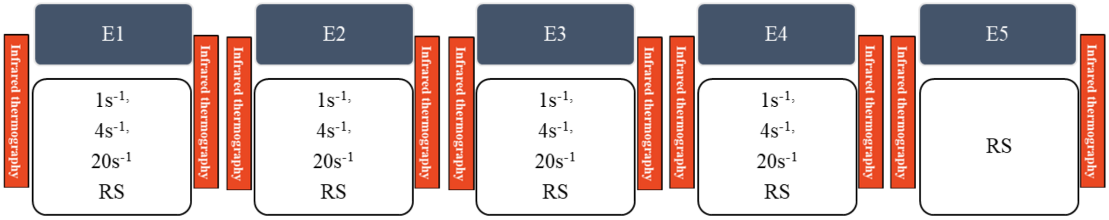


Figure 2.6.1 Temperature measurement protocol. Temperature was measured at baseline and after exposures (E1-E5).

were visually confirmed to be within acceptable limits, the images were immediately saved on the phone [Figure 2.6.2].

2.6.2 Measurement procedure and data analysis

Participants arranged their hands on the grid, keeping their upper arms along their trunk, forearms flexed, and both hands side-by-side directly beneath the camera lens. Fingers were held slightly apart. The dorsal and palmar sides of the hand were photographed immediately (with a maximum of 30 seconds elapsing between the taking of each image) before and after each exposure [Figure 2.6.2].

The images were analyzed using the FLIR Tools app, version 6.4 [Figure 2.6.1]. The software provided the maximum, minimum, and mean temperatures of the regions of interest (ROIs). A total of 24 ROIs were analyzed for each subject, including the distal phalanx of digit I (thumb) and the middle phalanx of digits II through V of the palms, as well as the dorsal side of both hands.

Regions of interest (ROIs) were evaluated using manually created 12x12 pixel (144-pixel total) squared boxes for each finger. Each square was manually placed in the middle phalanx of the digits II-IV and distal phalanx of digit I. For the palmar and dorsal side of the hands, a circle was created to encompass the most amount of area. All values were subsequently averaged, and


[redacted] [redacted]

Figure 2.6.2 Infrared thermography (IRT) setup for measuring temperature reaction. The target area is displayed on the monitor for visual confirmation.

the Mean of each measurement was included for evaluation. Previous research has demonstrated that during dynamic exposures, the point of contact between the hand and the handle experiences the highest pressure distribution [68]. As a result, this area, captured by the finger ROIs, is expected to exhibit the most pronounced effects in terms of both shock transmission and vascular response.

2.7 Gripping strength and pinch strength

In recent decades, measuring fist closure strength has become a well-established orthopedic practice for evaluating injuries and diseases of the upper extremity, as well as monitoring therapeutic progress [69]. This measurement provides an overall assessment of handgrip force, which encompasses multiple intricate components. It's essential to distinguish this fist closure measurement from continuous grip force recordings, such as those obtained when encircling a shaker's handgrip.

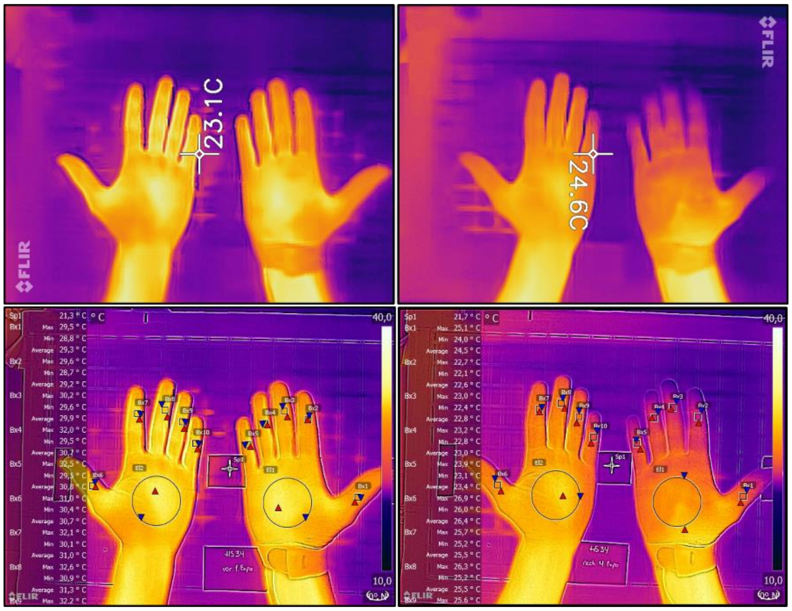


Figure 2.6.1 Infrared thermographic assessment of hand temperature reaction. (A) Baseline palmar temperatures of the exposed and non-exposed hand (left). (B) Palmar temperatures of the exposed and non-exposed hands following the fourth exposure (right). ROIs the regions of interest on the palm.

2.7.1 Setup and measurement procedure

Hand grip and pinch strength were measured before and after the fourth exposure to assess changes in muscle strength [Figure 2.7.2]. A standardized posture was used for both hands to ensure consistent measurements [Figure 2.7.1]. Participants sat upright with their arm at their side, elbow bent to 90 degrees, and wrist slightly extended (up to 15 degrees) [69].

Participants squeezed the dynamometer as hard as possible three times, with three-second rests between attempts. The average of these attempts was used as the final result for its high reliability [70]. A Deyar EH101 electronic hand dynamometer (Camry, Guangdong, China) was used with the grip set at the third level (4.6 cm) for all participants.

The maximum isometric pinch force was measured with a Saehan Professional SH5005 finger-dynamometer (Saehan, Masan, South Korea). Two different types of maneuvers were used while the forearm was held in a neutral position. Maneuver 1 (3-finger grip / three-jaw chuck pinch) was performed by pressing the thumb against the index and middle fingers. In maneuver 2 (key grip / key pinch), the thumb was pressed against the remaining flexed fingers [Figure 2.7.1].

Subjects were instructed to press the metal button of a hydraulic dynamometer as hard as possible and hold for 3 seconds, in accordance with the current recommendations of the American Society of Hand Therapists for measuring pinch strength [71].

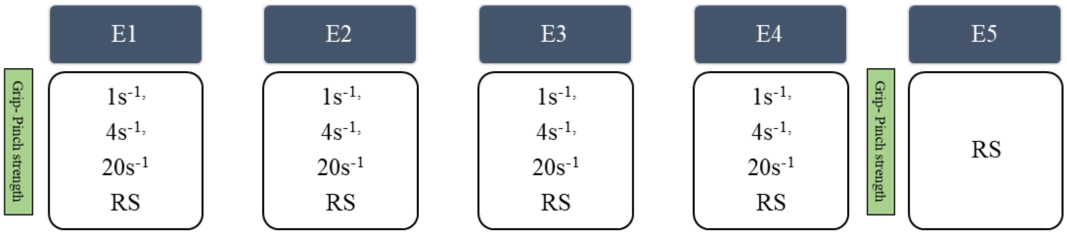


Figure 2.7.2 Hand-grip and pinch strength protocol. Hand-grip and pinch strength was measured at baseline and after the fourth exposures (E4).

2.8 Muscle activation / Muscle fatigue

Surface electromyography (sEMG) is a non-invasive technique that focuses on the electrical activity generated by skeletal muscles during activation [72]. Electrodes are placed on the skin overlying the muscle of interest, and these electrodes detect the collective electrical signals produced as muscle fibers contract. sEMG analysis provides insights into muscle activation patterns, including timing, intensity, and potential signs of fatigue [73]. It has applications in fields like sports science, rehabilitation, and ergonomics to study muscle function and optimize movement patterns.

2.8.1 Setup

Muscle activity was monitored using a Shimmer3 Consensys EMG system (Shimmer Sensing, Dublin, Ireland) consisting of EMG electrodes (Kendall^{TM}, H124SG) and Consensys software. The Shimmer3 EMG enabled non-invasive, two-channel muscle activity recording. Signals were displayed in real-time on the researcher's computer and simultaneously logged to an SD card. The system's digital differential amplification improved the signal-to-noise ratio (SNR). Data was transferred to the main research computer following each participant's session.

To minimize interfacial potentials between the electrode gel and the epidermis [74], the corresponding skin area was disinfected with alcoholic solution. After palpation of the muscle bellies, the electrodes were placed in a bipolar configuration approximately 25 mm apart along the longitudinal direction of the muscle fibers of the four muscles under study: the triceps brachii

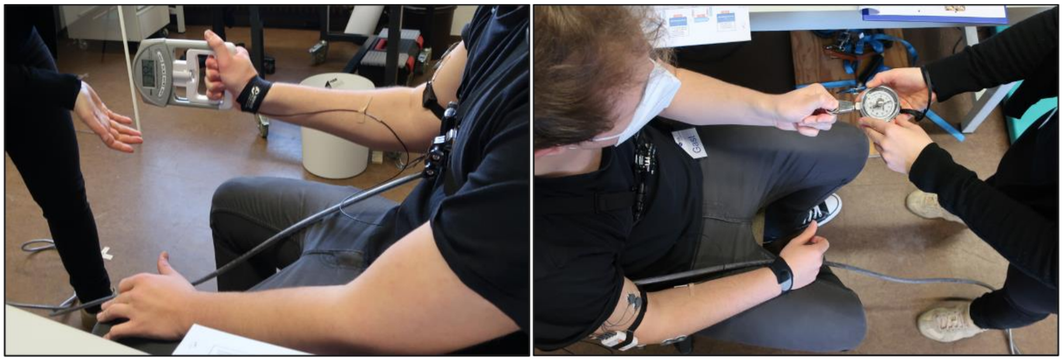


Figure 2.7.1 Hand strength measurements. (A) Grip strength measurement of the exposed (right) hand using a standardized position. (B) Key pinch strength measurement (Maneuver 2) performed on the non-exposed (left) hand.

muscle, lateral head; biceps brachii muscle; extensor digitorum muscle; and flexor carpi ulnaris muscle [75]. Sensor wires were secured to avoid movement-induced artifact [Figure 2.8.2].

Electrodes were placed on the triceps and biceps muscles according to SENIAM recommendations [76]. To accurately place electrodes on the forearm muscles, participants briefly contracted those muscles: extending their middle finger to identify the extensor digitorum muscle and bending their wrist towards their pinky to identify the flexor carpi ulnaris muscle [48]. After attaching the electrodes and sensors, participants contracted each target muscle individually while keeping their arm relaxed and supported. This allowed researchers to visually assess the signal quality using computer software and adjust electrode placement for optimal signal clarity [77].

2.8.2 Measurement procedure

The upper arm's primary muscles for elbow movement are the biceps (front) for bending and the triceps (back) for straightening. The forearm muscles studied were the extensor carpi ulnaris (ECU) which extends the wrist towards the pinky finger, and the extensor digitorum (ED) which extends the fingers.

Muscle activity was measured using a 24 mm, pre-gelled, self-adhesive, Ag/AgCI disposable EMG electrodes (Kendall^{TM}, H124SG Electrodes, Dublin, Ireland).

Figure 2.8.2 EMG electrode placement on the exposed arm. (A) Biceps brachii. (B) Triceps brachii. (C) Extensor digitorum (top) and flexor carpi ulnaris (bottom).

Each participant completed nine electromyographies (EMG) sessions: four static and five dynamic. Static measurements involved first measuring the maximum voluntary isometric contractions (MVIC) where participants maximally contracted each muscle group. Then, participants held a 60% MVIC contraction for 3 seconds, with 5-second rests, using visual feedback from a digital gauge to maintain the target force. These submaximal contractions were taken after the fourth and fifth exposures [Figure 2.8.3].

Static measurements involved specific postures on an adjustable platform with a digital force gauge to help participants achieve MVIC in different muscle groups. The examiner guided participants to achieve MVIC for their biceps (standing with arm at their side and elbow bent to 90 degrees with palm facing up), triceps (kneeling with arm straight up and elbow fully bent), and ECU and ED (standing with arm at their side, elbow bent to 90 degrees with palm facing down). Dynamic measurements were conducted with participants in a standardized position) on the shaker. Five exposure sessions, totaling 25 minutes, were conducted, with EMG data continuously recorded for all four muscles. The system's high temporal resolution (512 Hz) ensured high-quality data collection for 285 seconds of each 300-second exposure session.

2.9 Statistical analysis

Due to the limited sample size and potential deviations from normality, non-parametric statistical tests were employed throughout this study. This deliberate methodological choice enhances the robustness and reliability of analyses when dealing with datasets that may not fully adhere to the assumptions of parametric methods. Specifically, the Friedman test was utilized

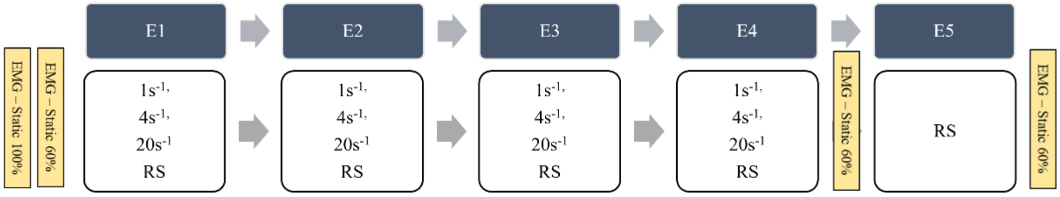


Figure 2.8.3 Static muscle activation (EMG) measurement protocol. EMG activity was recorded at baseline and after the fourth and fifth exposures (E4-E5) to exposure frequencies on Shaker of 1s^{-1}, 4s^{-1}, 20s^{-1}, and a random signal (RS).

to assess within-group changes over time, while the Wilcoxon signed-rank test was employed for pairwise comparisons of related samples, such as pre- and post-exposure measurements. For comparisons among three or more independent groups, the Kruskal-Wallis test was applied. Comparisons between two independent groups were conducted using the Mann-Whitney U test.

Whenever feasible, exact significance calculations were performed. However, when sample size constraints precluded the use of exact methods, Monte Carlo significance testing was employed to provide unbiased p-value estimations without the limitations of asymptotic approaches [Mehta & Patel, 1996]. To control the family-wise error rate in multiple pairwise comparisons, the Holm-Bonferroni correction was implemented. Statistical analyses were conducted using SPSS Statistics, version 28 (IBM Corp., Armonk, NY, USA).

Due to limitations in access to SPSS for the final stage of the analysis focused on muscle fatigue evaluation and group comparison, the data were imported into NumPy [78] and processed using SciPy [79] within the Python programming language [80]. SciPy provided the necessary functionality to perform the Kruskal-Wallis's test and post-hoc pairwise comparisons using the Dunn test.

Muscle fatigue

Muscle activation data, derived from EMG recordings, were analyzed separately using RStudio 2020 software. [81]. This dedicated analysis was conducted to accommodate the unique characteristics of the EMG data and to ensure the most appropriate statistical approach was employed. Customs scripts were developed for this experimental setup, facilitating separate analysis of static and dynamic measurements. However, due to constraints, only the static measurement script was completed.

The script for static measurement retained muscle activation analysis features from the pilot study, excluding acceleration assessment. It was used to evaluate four of the nine EMG sessions:

Session 1 (MVIC), Session 2 (60% MVIC), Session 7 (60% MVIC after all shock exposures), and Session 9 (60% MVIC after random vibration exposure).

EMG data underwent a multistep analysis process. First, MVIC recordings were visually inspected to manually correct any aberrant data spikes. Bandpass filtering (lower-cut frequency = 10Hz, upper-cut frequency = 250Hz) was applied to remove motion artifacts in the low-frequency range and unrelated high-frequency noise. Signals were then rectified and integrated to assess the magnitude of amplitude. MVIC was determined by analyzing the maximum integral value of the filtered, rectified EMG signal for each of the four target muscles over a 1-second window.

Established fatigue indices were calculated during static measurements over 300-second sessions, using 1-second windows. These indices included EMG integral, slope of EMG, mean frequency (MNF) and median frequency (MDF) of the power density spectrum, fractal dimension (box count = HBox), and fractal dimension (wavelet method = HWv). Mean values across all windows, as well as intercept and slope values from a linear regression over the 300 seconds, were output to a .csv file. EMG curve smoothing and Fast Fourier Transform spectral analysis were used to derive fatigue indices [82]. Maximum, median, and mean frequencies were determined from the spectrum. Linear regression and quotient formation (last value of the line divided by the first) were employed to assess the progression of these parameters, providing insights into central and peripheral muscle fatigue.

Chapter 3: Results

3.1 Participants

3.1.1 Characteristics

A total of 56 participants were assessed for eligibility, 54 participants were enrolled and randomized to four different groups with a 1:1:1:1 allocation ratio. Participants were randomly assigned to receive different single-shot exposures. During the measurement phase, two participants were excluded due to health concerns. After completing all measurements, 52 participants (96.4%) were included in the final analysis [Figure 3.1.1]

The study sample consisted of 52 male participants with an age range of 18 to 61 years (mean age ± SD = 29.4 ± 9.8 years). Participants were randomly assigned to one of four exposure groups: Single-Shock $1s^{-1}$ (G1), Single-Shock $4s^{-1}$ (G4), Single-Shock $20s^{-1}$ (G20), and Random Signal (GR). G1 had an age range of 18 to 41 years, with a mean age of 27.0 years (SD = 7.9). G4 participants ranged in age from 20 to 53 years, with a mean age of 31.2 years (SD = 10.1). The G20 group included participants with ages between 18 and 61 years and had a mean age of

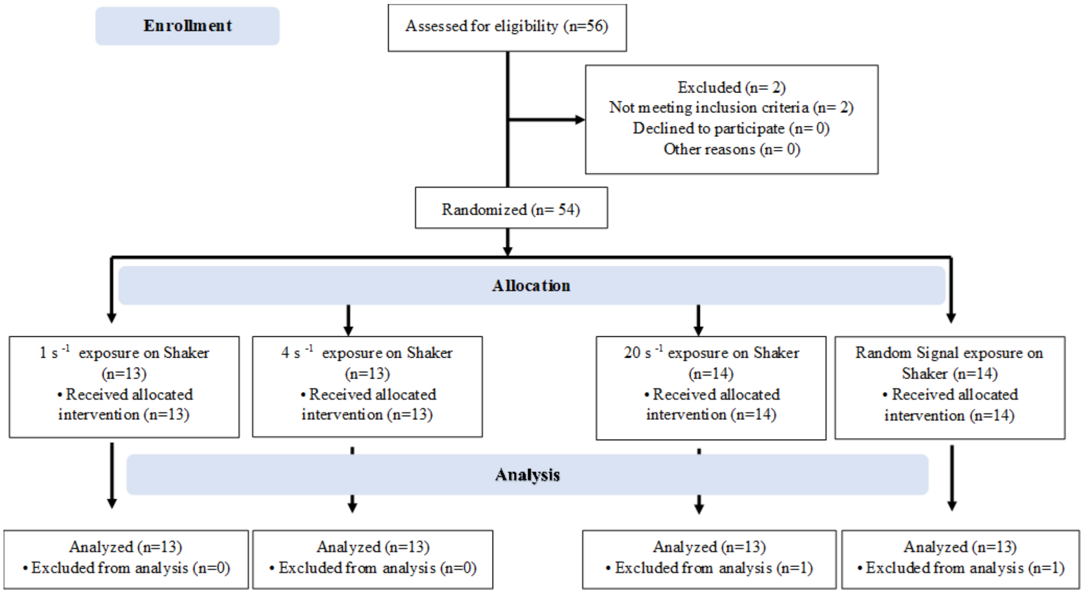


Figure 3.1.1 CONSORT flow diagram of participant progression through the study. The diagram illustrates participant assessment, randomization to exposure groups, exclusions, and those included in the final analysis.

29.9 years (SD = 13.3). Finally, the GR group had an age range of 19 to 51 years, with a mean age of 29.5 years (SD = 8.0). A Kruskal-Wallis's test was conducted to assess whether there were any significant differences in age distribution among the four exposure groups. The results of the test indicated no significant differences in age distribution among the groups (p = 0.61).

3.1.2 Anthropometry

The mean height of the participants was 180 cm (SD = 7.4), they weighed 81.5 kg (SD = 14.4) and had a BMI of 24.6 kg/m^2 (SD = 4.2). The mean of wrist circumference was on average 18 cm (SD +1.0), forearm circumference 26.8 cm (SD = 2.4) and biceps circumference of 33 cm (SD = 4.4). To assess potential differences among the four exposure groups, a Kruskal-Wallis's test was performed. This test examined height, weight, BMI, and circumferences of the wrist, forearm, and biceps. The analysis revealed no significant differences in any of these measurements across the groups (p > 0.05 for all) [Appx Table 8.3.1]

3.1.3 Complaints - post exposures

After each exposure, participants reported any hand-related complaints. These complaints were most frequent in the exposed hand, the primary entry point for vibration into the hand-arm system. Sensory disturbances, especially numbness and tingling (paresthesia), were the most

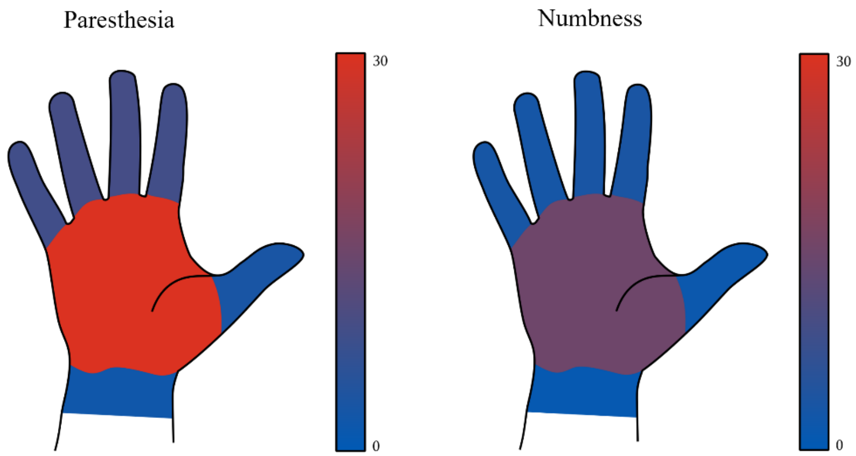


Figure 3.1.2 Heatmap illustrating the distribution and intensity of numbness and paresthesia symptoms in the exposed hand, based on aggregated data of all exposures (E1-E5) and all subjects (52). Red areas indicate more frequent complaints, while blue areas show fewer.

common subject complaint after exposure. These symptoms were mainly described in the palm, followed by the index and middle fingers.

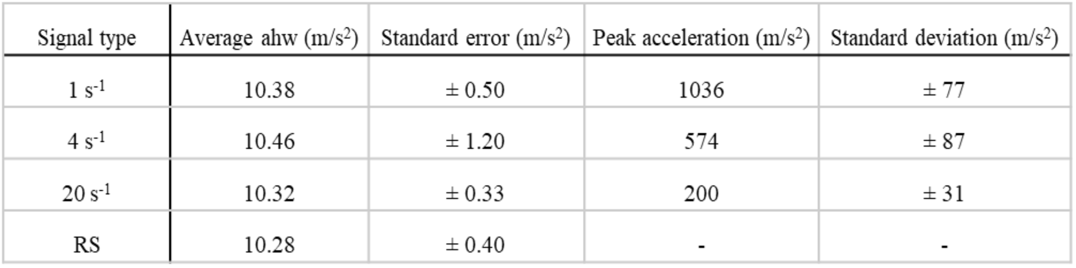
3.2 Impact exposure simulation

Data on average horizontal acceleration (ahw) and peak acceleration values are provided in Table 3.2.1. These values were measured at the shaker handle and correspond to signal types designed to replicate real-world shock conditions.

The biomechanical transmission behavior of the hand-arm system was investigated, with a focus on the transmission of single shocks and undirected vibrations evaluated using accelerometers. Acceleration data, collected at the wrist, elbow, and shoulder, was used to calculate transmission factors [Table 3.2.2]. These factors provided reference information for understanding the mechanical properties of the hand-arm system, particularly its damping and resonance characteristics observed during the experiment.

The results demonstrate a clear attenuation of vibrations as they travel through the hand-arm system. Transfer factors measured at the wrist consistently remained above 0.7 across all tested frequencies (1 s^{-1}, 4 s^{-1}, and 20 s^{-1}) and the random signal, indicating a transmission of vibrations. In contrast, transfer factors at the elbow (olecranon) were generally lower than those at the wrist and further decreased at the shoulder (acromion) [Table 3.2.2]. This progressive reduction in transfer factors highlights the vibration damping characteristics of the hand-arm system, showing a more pronounced attenuation effect with increasing distance from the vibration source.

Table 3.2.1 Shaker handle acceleration. Average horizontal (ahw) and peak acceleration values (the maximum acceleration recorded) are presented for each exposure group (G1: 1s^{-1}; G4: 4s^{-1}; G20: 20s^{-1}; RS: random signal).



Signal type	Average ahw (m/s^2)	Standard error (m/s^2)	Peak acceleration (m/s^2)	Standard deviation (m/s^2)
1 s^{-1}	10.38	± 0.50	1036	± 77
4 s^{-1}	10.46	± 1.20	574	± 87
20 s^{-1}	10.32	± 0.33	200	± 31
RS	10.28	± 0.40	-	-

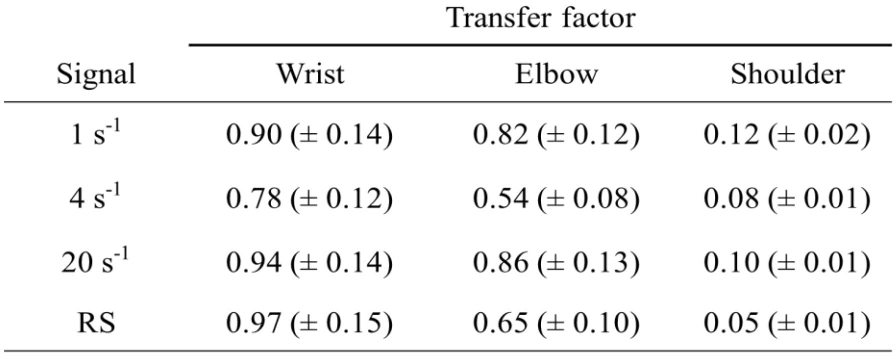
A total calculated dose of A (8) = 2,28 m/s² was achieved in this setup by the cumulative 25-minute exposure. The cumulative dose of the 4x5-min single shock / impact exposure had dose emissions of A(8) = 2,04 m/s². When including the fifth exposure to random vibration A(8) = 2,28 m/s², the values were below the EU action value of 2.5 m / s² and far below the exposure limit value of 5.0 m /s² [Art. 3 Para. 1 Directive 2002/44/EC] specified therein so that it did not have to be assumed that the subjects were endangered by participation in this study.

3.3 Vibration perception threshold

This study explored how hand-arm vibration exposure, both repeated single-shock and random vibration, affects vibration perception thresholds (VPTs) in the index (DII) and little fingers (DV). Finger sensitivity was measured at various frequencies (32, 125, 250, and 500 Hz) before exposure, after the initial exposure, and after each subsequent exposure, up to five total. This allowed the tracking of changes in VPTs over time and across different vibration frequencies.

In general, analysis of the overall VPT data, combining all participant groups and measurements from both fingers, revealed a progressive worsening in sensitivity to vibration following each exposure. This trend, illustrated by a rising median VPT over time, suggests a potential cumulative effect of the vibration stimuli on perceptual thresholds [Figure 3.3.1].

Table 3.2.2 Transfer factors into the hand-arm system at the wrist (distal radius), elbow (lateral humeral condyle), and shoulder (acromion) measured with accelerometers. Values represent the ratio between the response at each location and the shaker excitation (dimensionless). Standard error is shown in parentheses (±). RS denotes random signal.



	Transfer factor		
Signal	Wrist	Elbow	Shoulder
$1\ s^{-1}$	0.90 (± 0.14)	0.82 (± 0.12)	0.12 (± 0.02)
$4\ s^{-1}$	0.78 (± 0.12)	0.54 (± 0.08)	0.08 (± 0.01)
$20\ s^{-1}$	0.94 (± 0.14)	0.86 (± 0.13)	0.10 (± 0.01)
RS	0.97 (± 0.15)	0.65 (± 0.10)	0.05 (± 0.01)

Specifically, measurements taken after the fourth or fifth exposure showed increased VPT at all test frequencies, for both fingers. This trend was observed across the entire participant sample.

3.3.1 Baseline vibration perception threshold

Baseline vibrotactile sensitivity was assessed in digits 2 and 5 at four frequencies (32, 125, 250, and 500 Hz) for each group (G1, G4, G20, and GR) [Figure 3.3.2]. Vibration perception thresholds (VPTs) were similar across frequencies and fingers in all groups. However, VPTs did vary with frequency, with the highest thresholds (lowest sensitivity) observed at 500 Hz and the lowest thresholds (highest sensitivity) predominantly found at 125 Hz. Thresholds at 32 Hz and 250 Hz consistently fell between these two extremes.

A Kruskal-Wallis's test was used to observe whether the baseline VPT of the test frequencies showed any difference between the groups for each finger. There was no significant variance of the baseline VPT in any of the test frequencies before exposure to DII and DV between the groups [Appx. Table 8.3.2].

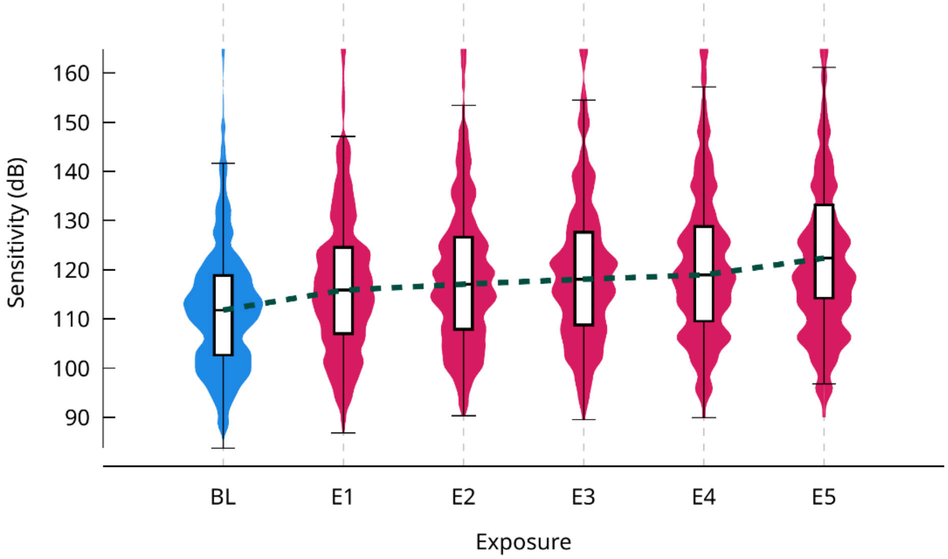


Figure 3.3.1 Global distribution of finger sensitivity (dB). Data points represent all subjects, exposure groups (G1, G4, G20, GR), both fingers (DII and DV), and test frequencies (32, 125, 250, 500 Hz) at baseline (BL, blue) and after each exposure (E1-E5, red). The dotted line indicates the median sensitivity.

3.3.2 Increase / worsening vibration perception threshold

Vibration perception thresholds (VPTs) generally increased during the study, often immediately after the first exposure [Figure 3.3.3]. This upward trend continued after each subsequent exposure across both fingers, most groups, and test frequencies. The largest increases were seen in groups G1 and G4 after the fifth exposure. This may suggest a dose-dependent and nearly continuous increase in VPTs [Appx. Table Chapter 8.3.2].

While G1 showed minimal VPT changes at lower frequencies (32 and 125 Hz), higher frequencies (250 and 500 Hz) revealed a progressive increase, indicating decreased sensitivity. G4 and G20 exhibited continuous VPT increases across all frequencies [Figure 3.3.3]. GR differed with an initial sharp increase after the first exposure, followed by slower increases or even slight recovery. However, the highest VPTs across all frequencies were still observed after the fourth exposure. Friedman tests revealed significant changes in vibration perception thresholds (VPTs) over time ($p < 0.001$) across both fingers, all groups, and all test frequencies. This may indicate that VPTs were affected by exposure to the different vibration frequencies. To pinpoint the specific differences, post-hoc pairwise comparisons were performed using Wilcoxon signed rank tests with Benjamin-Hochberg correction.

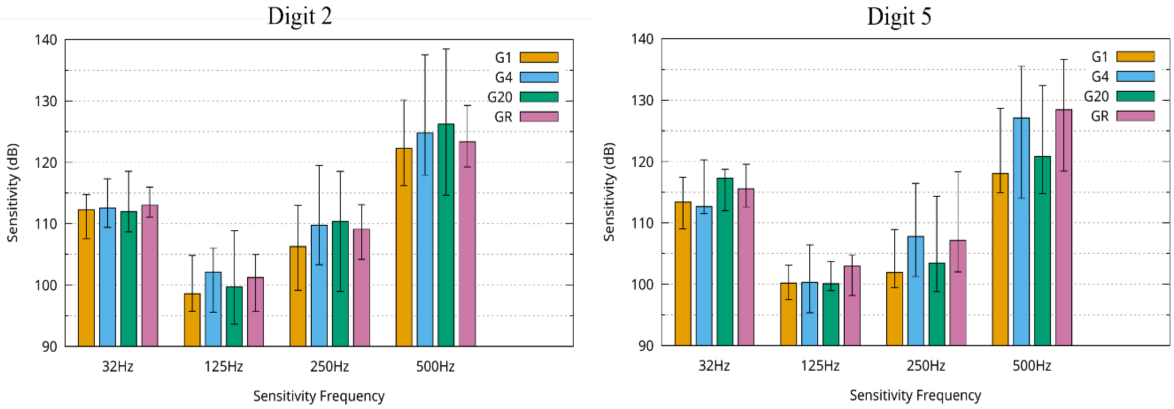


Figure 3.3.2 Baseline vibrotactile perception thresholds (VPTs) in decibels (dB) for digit 2 (DII) and digit 5 (DV) for each group (G1, G4, G20, GR) at test frequencies of 32Hz, 125Hz, 250Hz and 500 Hz

Change in Vibration Perception Threshold (ΔVPT) Following Exposure

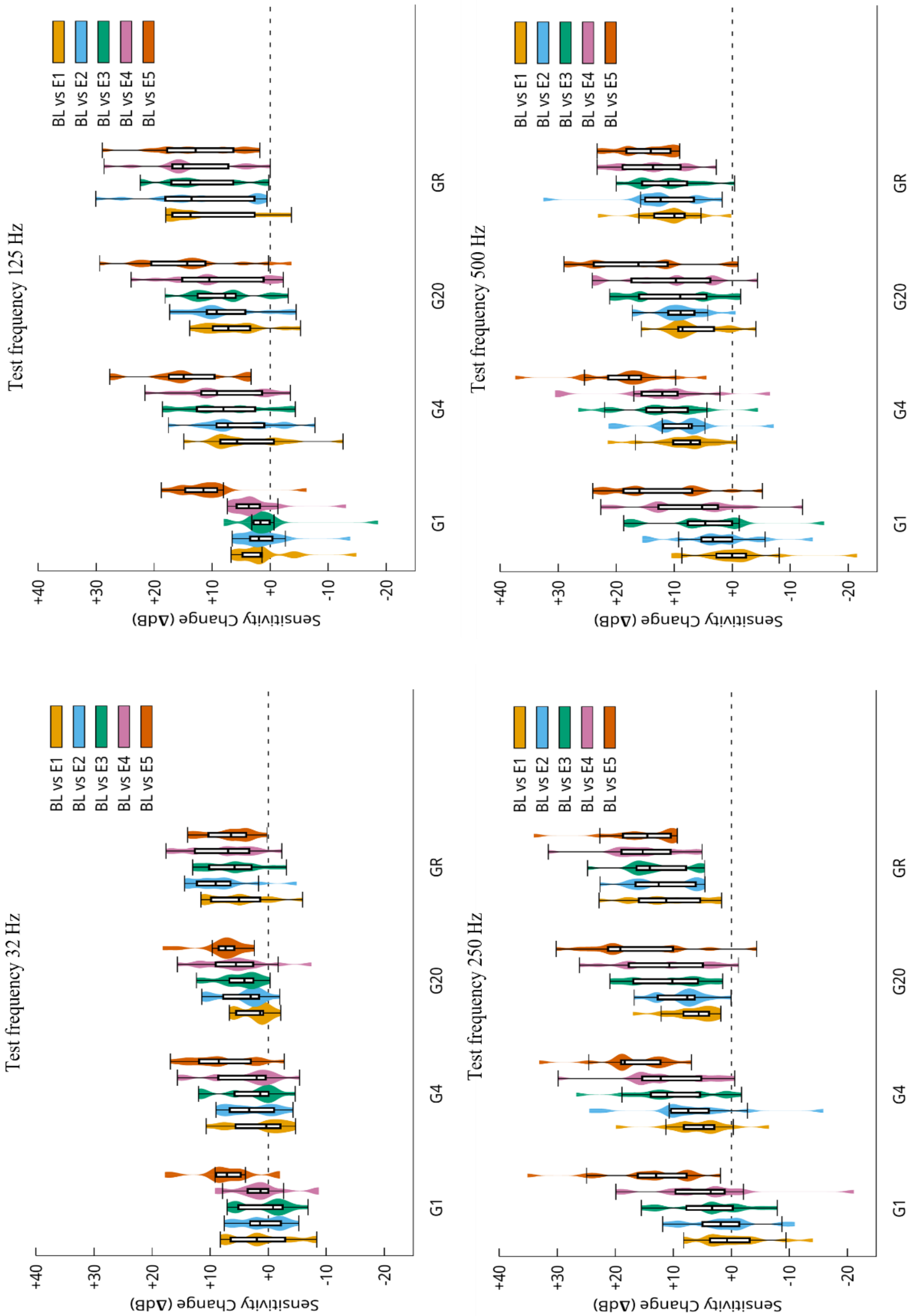


Figure 3.3.3 Change in vibration perception threshold (ΔVPT) at four test frequencies (32, 125, 250, and 500 Hz). ΔVPT is calculated as the difference between the baseline VPT and the VPT measured after each exposure condition, for each group (G1, G4, G20, GR).

Digit 2 (DII)

Analysis of the second digit revealed a significant increase in VPTs after exposure in most groups and frequencies. However, G1 only showed a significant difference compared to baseline at the fifth exposure (E5), while G20 showed significant increases across all post-exposure measurements (E1-E5).

Comparing VPTs between exposures revealed a different pattern. Significant increases were mainly seen in the single-shock groups (G1, G4, G20) when comparing earlier exposures (E1-E4) to the final exposure (E5). This trend wasn't present in the random vibration group (GR), which had less consistent results. [Appx. Table Chapter 8.3.2].

Digit 5 (DV)

Analysis of the fifth digit showed a significant increase in VPTs after exposure in most groups and frequencies, but with different patterns than those seen in the second digit.

G1 showed significant VPT differences across all frequencies at both the fourth (E4) and fifth (E5) exposures, except for 125Hz at E4. In contrast, GR consistently showed significant increases across all frequencies and post-exposure measurements (E1-E5). G4 and G20 primarily showed significant differences at 250 and 500Hz across all post-exposure measurements [Appx. Table Chapter 8.3.2].

3.3.3 Intergroup comparisons of vibration perception threshold

Kruskal-Wallis tests revealed significant differences in VPTs across the four exposure groups for both digits and at various frequencies. Digit 2 showed the most significant differences, especially at 125 Hz, with significant findings in exposure sessions E2 ($H(3) = 14.19$, $p = .003$), E3 ($H(3) = 12.84$, $p = .005$), and E4 ($H(3) = 11.38$, $p = .010$). Post-hoc comparisons showed that G1 consistently had lower VPTs (better finger sensitivity) than the other groups across these sessions. For example, significant differences were found between G1 vs. G4, G1 vs. G20, and G1 vs. GR in sessions E2, E3, and E4 ($p < .05$ for all comparisons). Significant differences were also found in digit 2 at 32 Hz, and to a lesser extent, at 250 and 500 Hz. Digit 5 showed significant differences mainly at 32 and 125 Hz in sessions E2, E3, and E4. Post-hoc comparisons revealed distinct patterns: for digit 2, significant differences were consistently found between G1 and GR across all significant sessions and frequencies, as well as between G1 and G20, and to a lesser extent, between G1 and G4. For digit 5, significant differences were found exclusively between G1 and GR.

3.4 Temperature reaction

The temperature of specific areas on both the exposed (right) and non-exposed (left) hands was measured. These areas included the middle phalanges (bony segments) of the dorsal (back) and palmar (front) surfaces of the fingers, as well as the dorsum and palm.

The global temperature distribution across 52 subjects, four groups (G1, G4, G20, GR), both hands, five fingers (digits 1-5), both hand regions (palmar and dorsal), and all tested frequencies $1s^{-1}$, $4s^{-1}$, $20s^{-1}$, and RS (random signal) are illustrated in Figure 3.4.1. Overall, the data suggests

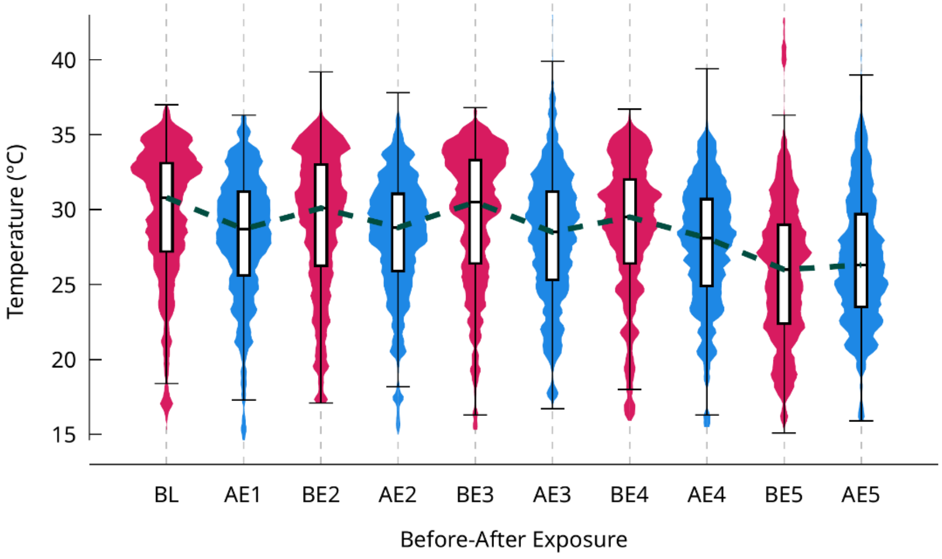
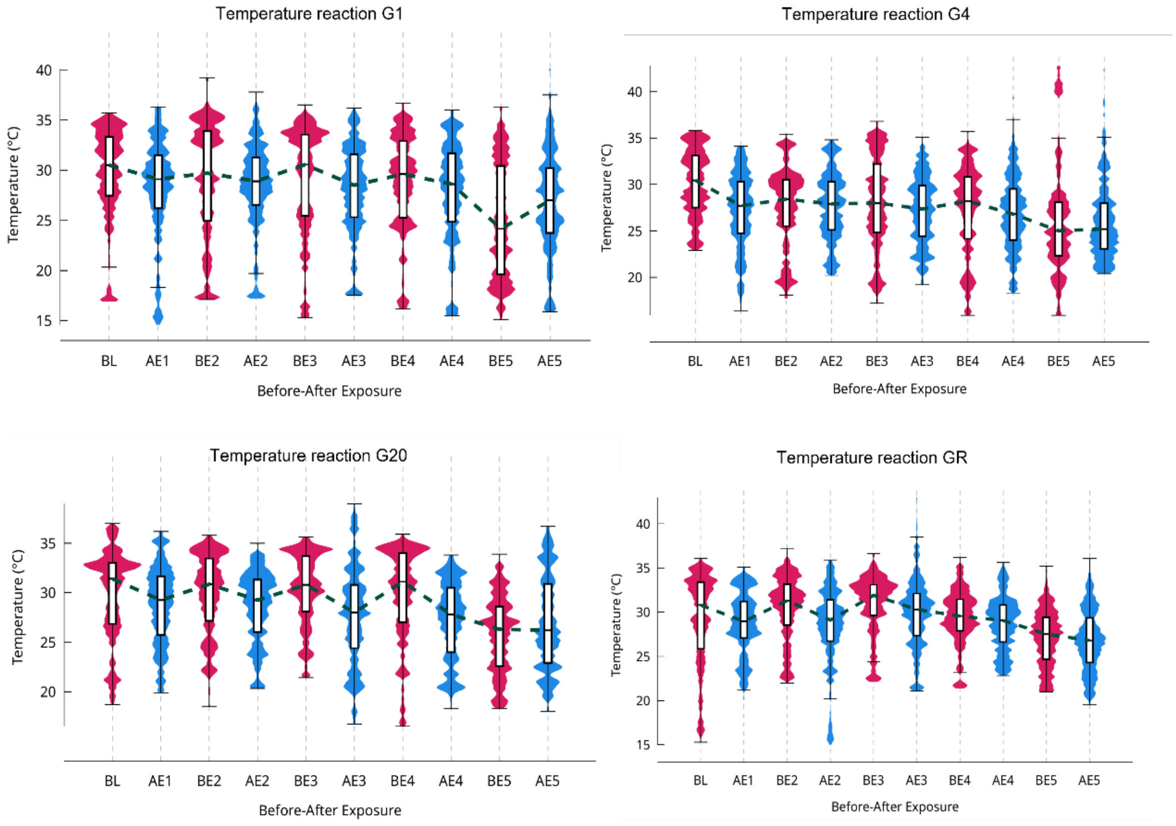


Figure 3.4.1 Global distribution of hand temperature reaction (°C). Data points represent all subjects, groups, hands, regions, fingers, and frequencies at baseline (BL) and before (BE, red) and after (AE, blue) each exposure (E1-E5). The dotted line indicates the median temperature.

a trend of decreasing temperature after each exposure. Additionally, pre-exposure temperature measurements also appear to decrease cumulatively throughout the experiment.

Group-level analysis of the aggregated data reveals a cyclical pattern in temperature distribution. Each exposure elicits a minor temperature decrease, followed by partial recovery before the subsequent exposure. Furthermore, a cumulative temperature decline emerges, becoming more pronounced after the fourth exposure. This trend is consistent across the single-shock exposure groups (G1, G4, and G20). However, a divergence is observed during the fifth exposure (random vibration), where G1 exhibits a temperature increase, while G4 and G20 maintain relatively stable temperatures. In contrast, the GR group initially follows a pattern similar to the single-shock groups, but then demonstrates a consistent temperature decline from the third exposure onwards, without any indication of recovery [Figure 3.4.2].


Temperature reaction G1

Temperature reaction G4

Temperature reaction G20

Temperature reaction GR

Figure 3.4.2 Temperature reaction to exposure across groups. Data points represent hand temperature (°C) for all regions and areas at baseline (BL) and before (BE, red) and after (AE, blue) each exposure (E1-E5). The dotted line indicates the median temperature.

Analysis of aggregated data for each hand reveals distinct temperature profiles. The exposed hand demonstrates a cyclical decrease with each exposure, followed by partial recovery. A cumulative decline becomes evident after the fourth exposure, with no subsequent recovery. The non-exposed hand exhibits a less pronounced decrease, becoming noticeable after the fourth exposure, with slight recovery observed after the fifth [Figure 3.4.3].

Temperature differences (delta)

To ensure our observations were not influenced by the camera's measurement accuracy (± 3 °C or ± 5 %), we focused our statistical analysis on temperature differences (deltas) between pre-exposure and post-exposure measurements. This approach helped eliminate potential systematic bias introduced by the camera's limitations.

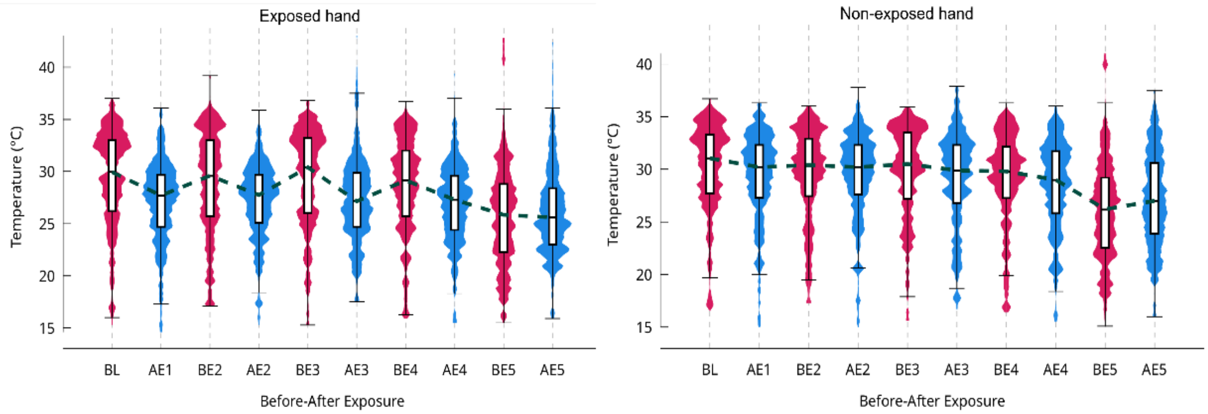


Figure 3.4.3 Temperature reaction to exposure for exposed and non-exposed hands. Data points represent hand temperature (°C) for all subjects, groups, regions, areas, and frequencies at baseline (BL) and before (BE, red) and after (AE, blue) each exposure (E1-E5). The dotted line indicates the median temperature.

Analysis of global, aggregated delta-temperature reaction (°C) revealed a general trend of temperature decrease for both hands, hand regions, and exposure frequencies ($1s^{-1}$, $4s^{-1}$, $20s^{-1}$, and random signal) [Figure 3.4.4]. A decrease in temperature was observed after the first exposure (E1) across all groups, with the magnitude of the decrease varying by frequency: G4 ($4\ s^{-1}$) exhibited the steepest drop, followed by G1 ($1\ s^{-1}$), then G20 ($20\ s^{-1}$) and GR (random vibration).

G1 and G4 demonstrated a slight recovery after E1, but this was followed by a further temperature decrease after the third exposure (E3). Conversely, GR showed a gradual warming trend from E2 onwards, though remaining below zero. G20 displayed a unique pattern of consistent temperature decrease after each exposure. Following exposure to random vibration signal, a marked increase in temperature was observed in all groups previously exposed to shock (G1, G4, G20), with the temperature revering above zero. This rebound effect was particularly prominent in G20. This might suggest a complex interaction between the effects of single shocks and random vibration on hand temperature.

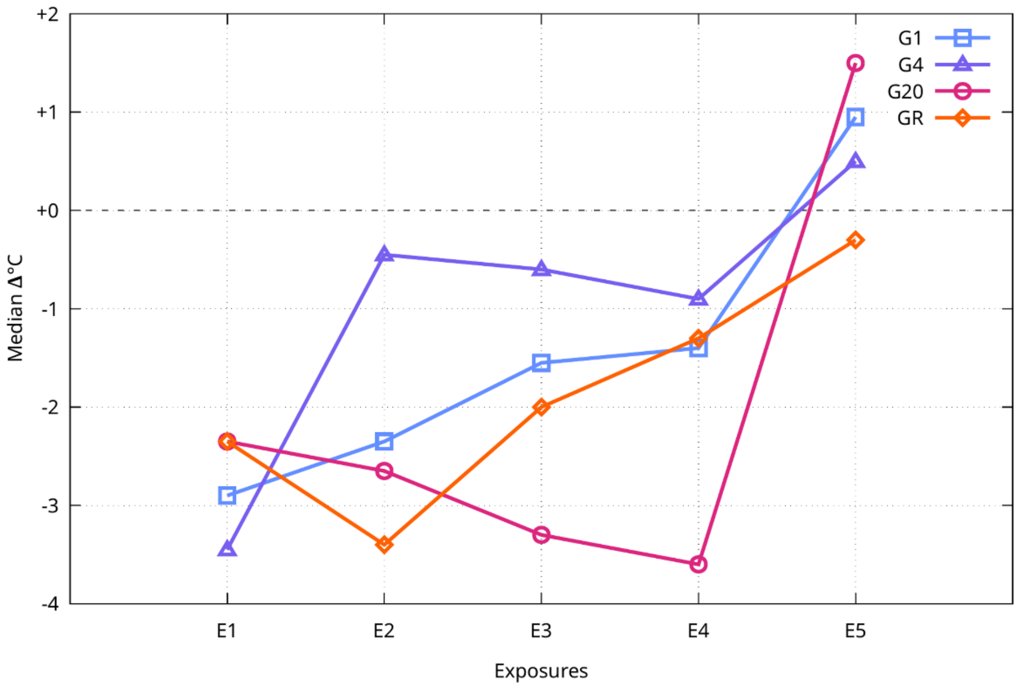


Figure 3.4.4 Median of all individual pre/post-exposure deltas in °C, broken down by groups. Negative numbers indicate a drop in temperature during the exposure for the subject (E1-E5). G1 ($1\ s^{-1}$), G4 ($4\ s^{-1}$), G20 ($20\ s^{-1}$), and GR (random vibration).

For the exposed hand, Figure 3.4.5 illustrates the global delta-temperature distribution across all subjects. The majority of data points lie below zero, indicative of a general temperature decrease. Occasional data points above zero suggest sporadic warming, likely attributable to random noise rather than a specific group or finger. The median delta-temperature shows minor fluctuations across the initial four exposures, with a possible increase during the fifth. Highlighting all GR measurements (random signal exposure) further confirms the absence of correlation with this group. Comparing the delta of exposed and non-exposed hand showed on dorsal and palmar region of hand, a steeper drop of temperature was mostly observed on exposed hand on all groups and on all areas of the hand.

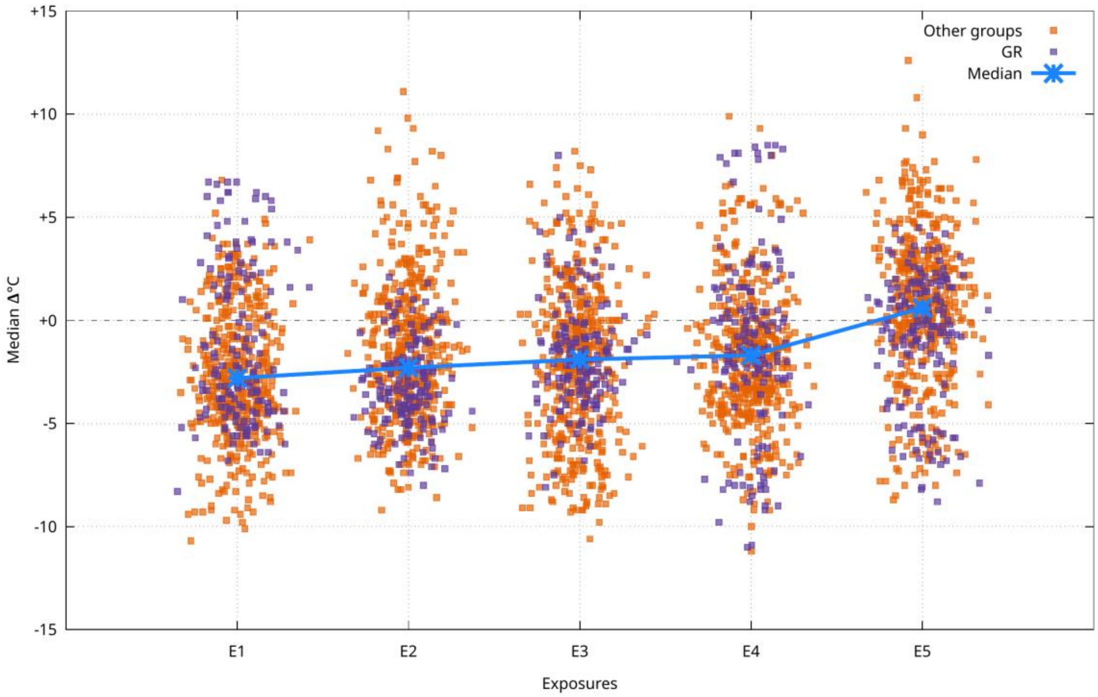


Figure 3.4.5 Global distribution of delta temperature (°C) in the exposed hand across all subjects, groups, fingers, hand regions, and frequencies. Delta temperature is calculated as the difference between the temperature after and before each exposure (E1-E5). Groups were exposed to different vibration frequencies: G1 ($1s^{-1}$), G4 ($4s^{-1}$), G20 ($20s^{-1}$), and GR (random signal, purple). The blue line represents the median delta temperature across all groups, hand areas, and frequencies.

3.4.1 Delta-Temperature Reaction of Exposed and Non-Exposed Hand: Dorsal and Palmar Region

A series of Friedman non-parametric repeated measures ANOVAs were conducted to assess potential differences in temperature differentials (delta) on both exposed and non-exposed hand, across the five exposure periods within each vibration frequency group. Separate analyses were performed for each hand area (digits 1 -5, back and front of the hand) and hand region (palm, dorsum).

Exposed Hand

Exposure to both 20 s^{-1} (G20) and 4 s^{-1} (G4) led to temperature decreases in the dorsal and palmar regions. G20 showed the most widespread effect, with significant decreases ($p < 0.05$) across most exposed areas. For example, on the dorsum, significant changes were seen in D1 ($\chi2(4) = 15.5$, $p = 0.002$), D2 ($\chi2(4) = 13.5$, $p = 0.006$), and the overall dorsum ($\chi2(4) = 9.7$, $p = 0.037$). Similarly, the palmar region showed significant decreases in areas like D1 ($\chi2(4) = 10.1$, $p = 0.033$) and the overall palm ($\chi2(4) =17$, $p = 0.001$). G4 also exhibited significant decreases, though less widespread, with notable examples including D1 ($\chi2(4) = 10.9$, $p = 0.023$) on the dorsum and the overall palm ($\chi2(4) = 12.1$, $p = 0.012$). Neither G1 nor GR experienced any significant temperature changes [Appx table Chapter 8.3.3].

Non-Exposed Hand

Both G20 and G4 exposures caused temperature decreases, but with different patterns. In the dorsal region, G20 showed significant decreases ($p < 0.05$) in D4 ($\chi2(4) = 9.5$, $p = 0.045$), D5 ($\chi2(4) = 11.5$, $p = 0.018$), and the overall dorsum ($\chi2(4) = 9.5$, $p = 0.047$). G4 had significant decreases in D1 ($\chi2(4) = 10.2$, $p = 0.032$), D2 ($\chi2(4) = 11.4$, $p = 0.018$), and D5 ($\chi2(4) = 9.3$, $p = 0.046$).

Only G20 impacted the palmar region, with significant decreases in multiple areas, including D1 ($\chi 2(4) = 12.6$, $p = 0.008$), D2 ($\chi 2(4) = 10$, $p = 0.037$), and the overall palm ($\chi 2(4) = 10$, $p = 0.044$). Notably, G1 and GR did not show any significant temperature changes in either region. These findings suggest that the vibration frequency influences temperature decreases in specific areas, with G20 and G4 demonstrating consistent changes [Appx. table. Chapter 8.3.3].

3.4.2 Comparing Dorsum of Exposed vs. Dorsum of Non-Exposed Hand and Palm of Exposed vs. Palm of Non-Exposed Hand, Delta-Temperature reaction.

Comparing the exposed and non-exposed hands revealed significant temperature decreases ($p < 0.05$) in both dorsal and palmar regions, with varying effects across exposure groups (G1; $1s^{-1}$, G4; $4s^{-1}$, G20; $20s^{-1}$, and GR; random vibration) [Figure 3.4.6]. G20 and GR showed the most pronounced effects on the dorsal side. G20 consistently impacted fingers 1, 2, 3, and 5 across the first four exposures. For instance, in the first exposure, significant differences were found in digit 1 ($Z = -2.832b$, $p < 0.002$), digit 2 ($Z = -2.377b$, $p < 0.014$), and others. GR showed a

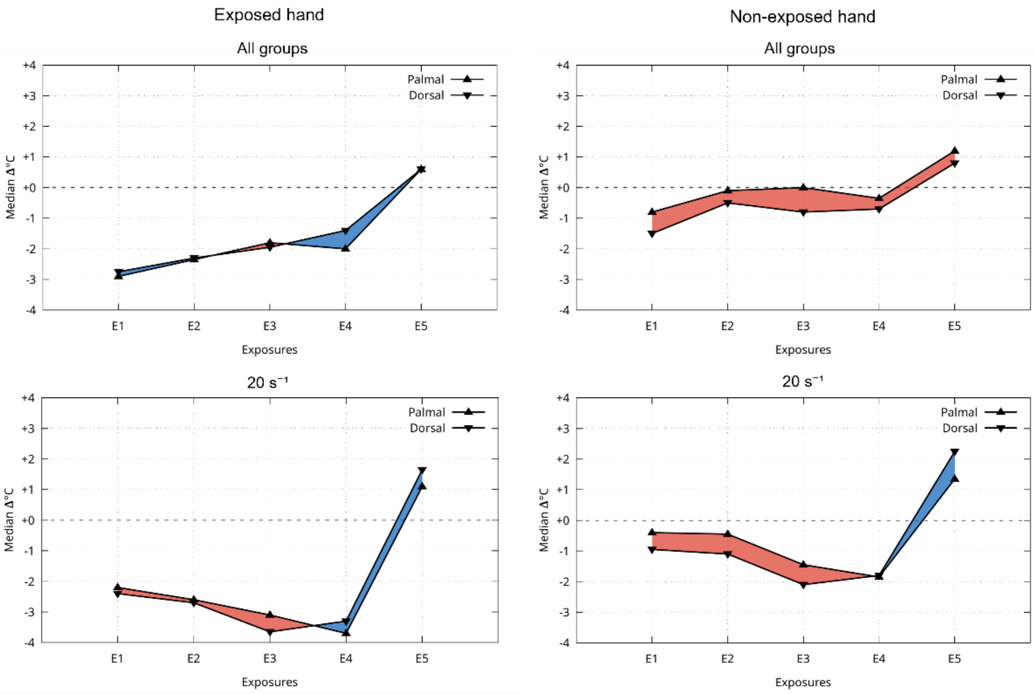


Figure 3.4.6 Delta temperature (°C) in the palmar and dorsal regions of the exposed and non-exposed hands. Data are aggregated across all fingers, hand areas, and frequencies for all groups (G1, G4, G20, and GR) and presented separately for G20 ($20s^{-1}$). Delta temperature is calculated as the difference between the temperature after and before each exposure (E1-E5).

similar pattern. G1 had a milder effect, with sporadic significance in the first three exposures, while G4 primarily affected digit 1 in the first two exposures (Exposure 1: Z = -2.621b, $p < 0.006$). [Appx. Table 8.3.5 (extract)]. Notably, no significant changes were observed on the back of the hand (dorsum) for any group.

Palmar

Delta-Temperature reaction on the palmar side of the hand, the Wilcoxon signed-rank test revealed a statistically significant decrease in temperature of the exposed hand compared to the non-exposed hand ($p < 0.05$, corrected for multiple comparisons). In contrast to the varying patterns observed across individual fingers, all exposure groups exhibited significance on the palm throughout most exposures. Groups G1 (1 s^{-1}), G20 (20 s^{-1}), and GR (random vibration) demonstrated the strongest effects. Within these groups, G20 showed the most consistent significance across all exposures, while G4 displayed significance primarily on digit one, with occasional effects on digits three and four [Appx. Table 8.3.6].

3.4.3 Dorsal vs. Palmar Delta-temperature difference of exposed hand and non-exposed hand

Analysis of temperature changes in the exposed hand revealed some interesting patterns. While finger comparisons showed inconsistent results across groups, the dorsal side of the fingers generally experienced a greater temperature decrease than the palmar side. Interestingly, G1, G20, and GR primarily affected digit 1 (DD1-PD1) [Appx. Table 8.3.7].

In contrast to the fingers, the palm and dorsum (back of hand) showed a more consistent pattern, with the palm often experiencing a greater temperature decrease than the dorsum. This was confirmed by significant differences (Wilcoxon signed-rank test) between these regions across all groups. G4 had the most consistent effect, followed by GR, G20, and G1.

Analysis of the non-exposed hand also revealed some significant differences between the dorsal and palmar regions, though with variable patterns depending on the group and exposure frequency. Generally, the dorsum of the non-exposed hand showed a greater temperature decrease. For example, in GR, the dorsum showed a greater decrease than the palm in the last three exposures (E3-E5).

3.4.4 Intergroup comparisons of temperature reaction

To examine the influence of exposure frequencies on changes in finger temperature, a Kruskal-Wallis's test was conducted to compare delta-temperature (i.e., the change in temperature from baseline to post-exposure) across the four exposure groups. The analysis revealed no statistically significant differences in delta-temperature between the groups.

3.5 Grip strength and pinch strength.

3.5.1 Grip (hand) strength.

At baseline, subjects exhibited a median grip strength of 45.2 kg (interquartile range [IQR]: 10.6 kg) in the exposed hand and 40.6 kg (IQR: 12.5 kg) in the non-exposed hand. Following the 4th exposure, the median grip strength in the exposed hand was 45.7 kg (IQR: 13.1 kg) after the fourth exposure. The non-exposed hand showed a median grip strength of 42.7 kg (IQR: 11.9 kg) at the same time point. Preliminary analysis suggests a slight decrease in handgrip strength in the exposed hand, most notably in groups G1 and G4. Conversely, the non-exposed hand may demonstrate a potential increase in strength within groups G20 and GR. [Figure 3.5.1].

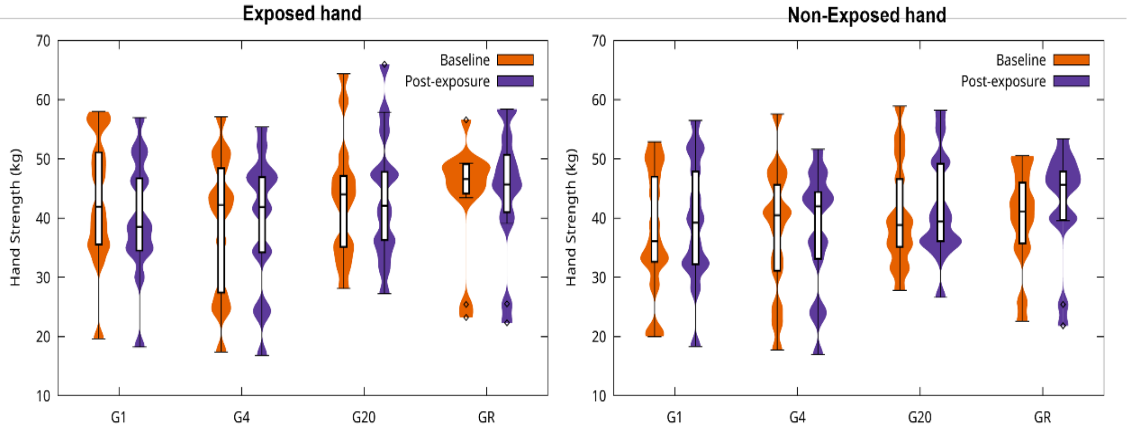


Figure 3.5.1 Grip strength (kg) of the exposed (right) and non-exposed (left) hands before (orange) and after (purple) the fourth exposure (E4) to vibration. Groups were exposed to different vibration frequencies: G1 ($1s^{-1}$), G4 ($4s^{-1}$), G20 ($20s^{-1}$), and GR (random vibration).

A Wilcoxon signed-ranks test only revealed a significant decrease in grip strength for the exposed hand in group G1 following exposure (baseline Mdn = 41.9, post-exposure Mdn = 38.5, Z = -2.981, p: 0.003). Conversely, the non-exposed hand only demonstrated a significant increase in grip strength in GR (baseline Mdn = 41.1; post-exposure Mdn = 45.6; Z = -2.342, p: 0.017 [Table 8.3.8]. A Kruskal-Wallis's test revealed no significant differences in baseline or post-exposure grip strength across the four exposure groups for either the exposed or non-exposed hand [Appx. Table 8.3.9].

3.5.2 Pinch strength

Changes in pinch strength (kg) following vibration exposure were visualized using delta (change) violin plots, with separate plots for exposed and non-exposed hands. Each violin's body depicts the distribution of changes in pinch strength, with positive values indicating an increase and negative values indicating a decrease (below zero).

The graph of the exposed hand reveals a slight decrease in pinch strength, most notably in groups G4 and G20 during maneuver 1 (lateral pinch). Conversely, maneuver 2 (chuck pinch) demonstrates increased pinch strength in the exposed hand for all groups. The non-exposed hand shows an increase in strength across most of the groups, particularly during maneuver 2 (chuck pinch) [Figure 3.5.2]. A Wilcoxon signed-ranks test revealed a significant decrease in pinch strength only for the exposed hand during maneuver 1 in group G20 following exposure

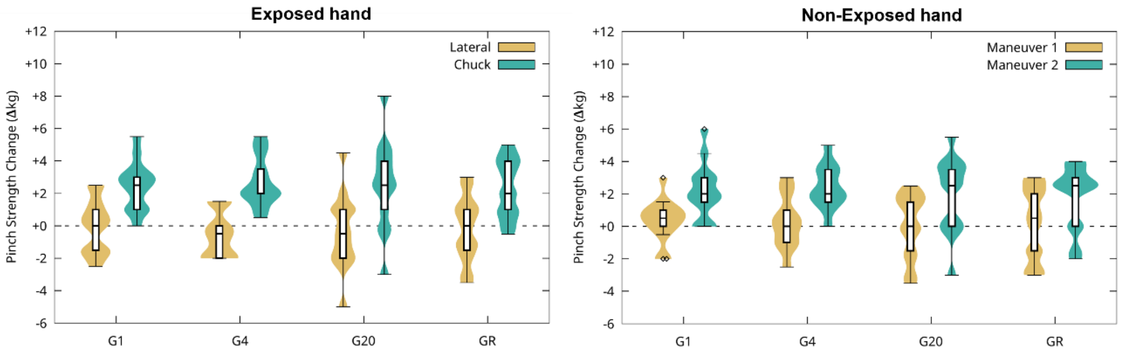


Figure 3.5.2 Change in pinch strength (Δkg) for the exposed and non-exposed hands after vibration exposure. Data are shown for two pinch maneuvers: key/lateral pinch (yellow) and palmar/chuck pinch (blue) for each exposure group (G1: $1s^{-1}$; G4: $4s^{-1}$; G20: $20s^{-1}$; GR: random vibration).

(baseline Mdn = 10.5, post-exposure Mdn = 9.5, Z = -2.365, p: 0.018) [Table 8.3.10]. A slight trend of strength decrease can be seen in both hands and both maneuvers. Wilcoxon signed-ranks test for maneuver 2 is provided in [Appx. Table 8.3.11]. A Kruskal-Wallis's test revealed no significant differences in baseline or post-exposure pinch strength across the four exposure groups for either the exposed or non-exposed hand or the maneuvers [Appx. Table 8.3.12].

3.6 Muscle activation / Muscle fatigue

3.6.1 Static measurements

The CSV files obtained from the recordings were evaluated using a custom script designed to analyze the static measurements. This analysis yielded the following output parameters for each muscle evaluated (biceps, carpi ulnaris, extensor digitorum, and triceps): signal-to-noise ratio (SNR), mean frequency (MNF), median frequency (MDF), HBox and HWv.

To assess muscle fatigue, changes in MNF, MDF, HBox, and HWv were analyzed. Specifically, the Wilcoxon signed-rank test was used to compare these parameters at 60% maximum voluntary contraction (MVC) at baseline and after the fourth exposure (E4). This analysis was performed for each muscle and exposure condition (repeated single-shock and random signal exposure). No significant differences were found in any of the frequency parameters between the 60% MVC condition at baseline and after E4, indicating no evidence of muscle fatigue in the selected muscle groups. This result was consistent across all groups exposed to repeated single-shock exposure and random signal exposure conditions. Kruskal-Wallis test was performed, the analysis revealed no statistically significant differences in any of the EMG parameters (MNF, MDF, HBox, HWv) across the four groups ($p > 0.05$). This finding indicates that the different exposure conditions did not have distinct effects on the EMG frequency characteristics of the selected muscles.

Chapter 4: Discussion

This study employed a prospective, parallel-group, vibration-controlled, simple randomized design to investigate the acute health effects of shock exposure on the hand-arm system. This design built upon insights gained from our institute's pilot study [48], and was informed by several key considerations.

Potential challenges in subject retention were identified based on the pilot study's quasi-experimental pretest-posttest design. This was attributed to the substantial time commitment required of participants (4 hours) and limitations in the recruitment timeline. To mitigate this, processes were streamlined in the current study, while maintaining a focus on investigating the direct effects of single impacts on the hand-arm system. Neurological, vascular, and musculoskeletal outcomes were prioritized, informed by the pilot study and relevant literature. Emphasis was placed on the selection of non-invasive methods suitable for operational settings, ensuring practicality, cost-effectiveness, and ease of use.

The prospective design facilitated the collection of baseline data, enabling an assessment of changes specifically induced by shock exposure. The parallel-group design minimized carryover effects that could potentially bias results in a crossover study. Furthermore, the inclusion of a vibration-controlled condition allowed us to isolate the unique effects of shock exposure, distinct from general vibration. Finally, simple randomization ensured an unbiased allocation of participants across groups.

4.1 Participants

This study adopted a targeted approach, focusing on healthy males aged 18-65 without a history of occupational vibration exposure. This choice reflects the demographics most frequently associated with hand-held device use and aims to maximize the real-world relevance of our findings within the context of occupational health risks [83, 84]. However, it's important to recognize that this specific sample may limit the generalizability of results to females or individuals with pre-existing conditions, whose responses to shock exposure could differ.

4.1.1 Complaints – post exposure

The exposed hand showed a higher frequency of sensory complaints. Numbness and tingling were the most prevalent, concentrated in the palm and then the index and middle fingers, as previously described [85-88]. This pattern may be linked to grip and force distribution during tool use, warranting further investigation into the role of hand posture in repeated single shock and vibration-induced injuries [88].

Considering these symptoms arose in a cohort of healthy individuals with no prior experience with vibrating tools and after a short exposure period, the long-term consequences of these sensory changes warrant further investigation to develop effective preventative measures, particularly for those exposed to repeated single-shock vibration.

4.2 Impact exposure simulation

This study evaluated the biomechanical transmission behavior of the hand-arm system, focusing on how repeated single shocks and random vibrations are transmitted. Accelerometers were used to measure vibration transmission, with acceleration data collected at the wrist, elbow, and shoulder.

Participants were randomly assigned to different frequencies of repeated single-shock exposures, with a random signal serving as a control exposure. This randomization scheme allowed for the examination of frequency-specific transmission behavior while maintaining a constant calculated vibration dose across all groups, with a total calculated dose of A(8) = 2,28 m/s^2 and a constant ahw value of 10 m/s^2. The total dose was below currently legally binding limits.

In our study, wrist accelerometry measurements revealed similar transmission values across most groups, except for G4 (4 s^{-1}), which exhibited slightly decreased values compared to the others (Table 3.2.2, Chapter 3.2). However, transmission values at the elbow were higher for groups G1 (1 s^{-1}) and G20 (20 s^{-1}). These findings suggest a potential increase in shock transmission with these specific exposure conditions compared to non-directional vibration.

Burström et al. [89] demonstrated that shock and impulse exposures, characterized by abrupt bursts of vibrational energy, result in greater energy absorption and muscle activation in the hand-arm system compared to continuous harmonic vibrations. The differences observed between shock and harmonic vibrations likely stem from how the body's tissues respond to the rate of energy delivery. Shock vibrations involve rapid transfer of high-energy levels, potentially overwhelming the musculoskeletal system's capacity to dampen the impact [90]. Conversely, harmonic vibrations over extended durations may allow for greater energy dissipation and less abrupt strain on the tissues. For a comprehensive assessment of the physiological effects induced by hand-arm vibration, it is crucial to consider the dynamics of energy transmission and absorption within the tissues.

The intricate biomechanical properties of the hand-arm system pose significant challenges for human experimentation. To address this complexity and incorporate both the active components, muscles, and the viscoelastic properties of tissues which are important for passive energy absorption, researchers have developed biomechanical models that simulate the transmission and resonance behavior of the human hand-arm system [91, 92]. These models can serve as valuable complements to occupational health research on single impacts.

4.3 Vibration perception threshold

The aim of this study was to determine if and to what extent acute single-shock, and random vibration exposures influence vibration perception thresholds (VPTs). VPTs were measured on the index and little fingers of the exposed hand using a VibroSense® device at four different test frequencies: 32, 125, 250, and 500 Hz. Five exposures (BS - E5) were assessed.

Both the mean baseline VPT and its standard deviation for male participants in this study aligned with ranges established in previous reference studies [93, 94]. This finding suggests that our sample population exhibited typical vibration sensitivity at the outset of the study [Figure 3.3.2, Chapter 3.3.1].

A significant increase in the VPT was observed for both the index finger (D2) and the little finger (D5) generally between the baseline measurement and the values obtained after the fourth and fifth exposures. These changes indicate a temporary decrease in vibration sensitivity following repeated exposures. Similar results have been observed in other studies, although experimental settings differed regarding acceleration amplitudes and exposure durations [10, 88].

The analysis revealed that the VPT exhibited changes following repeated single-shock exposures, with the magnitude of change influenced by the frequency of the exposure, similar to the findings by Malchaire et al. [88]. These results provide preliminary evidence that single-shock exposures may acutely alter vibration perception in the hand-arm system. A dose-response relationship, potentially mediated by cutaneous mechanoreceptor inhibition, could be involved [95]. Further analysis indicated that the relationship between VPT change, and exposure frequency is complex and may not be linear.

This study findings demonstrate a complex interplay between exposure frequency, exposure type (repeated single-shock or random), and the hand-arm system's sensitivity as measured by the VPT. The minimal VPT changes observed after the 1 s^{-1} exposure at 32 Hz and 125 Hz frequencies suggest a possible threshold effect, where the hand-arm system may exhibit greater tolerance to lower frequency vibrations at this specific exposure rate. This aligns with findings from some studies [88], but contrasts with those reported by Thonnard, J. [96] who used a power tool for vibration exposure instead of a controlled shaker setup. This methodological difference, which allowed us to control for push force and subject positioning, may account for the observed discrepancies in results.

Conversely, the results in this study demonstrate a marked and consistent increase in VPT at higher test frequencies (250 Hz and 500 Hz) for all exposure groups. This finding underscores the importance of considering test frequency when evaluating the risks associated with vibration exposure. Similar increases in VPT at higher test frequencies have been reported in previous research [18, 97, 98].

While this study findings suggest a potential for cumulative effects from acute repeated single-shock and random vibration exposures, particularly at higher frequencies, further research is needed to confirm this observation and explore its implications for occupational health. The distinct VPT increase patterns observed in the single-shock groups (G4 and G20) and randomized signal group highlight the need for more detailed investigations into the effects of complex vibration profiles, such as those encountered in real-world workplaces.

Comparison of the four exposure groups revealed a pattern indicating that higher exposure frequency leads to a greater impact on finger sensitivity. This was evident in both digits 2 and 5, but digit 2 exhibited a higher number of statistically significant differences. This finding of inter-digit differences contrasts with previous research, where no difference in mean VPT values was observed between the index and little finger [99, 100]. However, it is important to note that their study differed from the present study, as they were a cross-sectional analysis of shipyard workers and office without a prior history of vibration tool use, unlike the experimental setup used in the present study.

The most pronounced effects observed at a test frequency of 125 Hz. This finding suggests that 125 Hz may be a particularly sensitive frequency for detecting changes in VPT following exposure, at least for digit 2, as found by other studies, but contrasts with research indicating that a 31.5 Hz test frequency yielded a higher percentage of positive mean reference threshold shift compared to 125 Hz [100]. Furthermore, the significant differences detected in multiple exposure sessions (E2, E3, E4) indicate a consistent pattern of reduced sensitivity in the higher exposure groups (G4, G20, GR) compared to G1. The significant differences observed between

G1 and GR, followed by G1 and G20, suggest a dose-dependent effect, with higher exposure frequencies leading to greater reductions in sensitivity, as previously suspected [88].

The pattern observed for digit 5, with significant differences exclusively between G1 and GR, suggests that this digit may be less sensitive to the effects of exposure when comparing between the groups. It is also possible the grip employed during testing may result in differing levels of contact between the digits and the handle, potentially influencing the observed results. Further research investigating the contact forces and pressure distribution on each digit during vibration exposure would be needed to confirm this.

These results on acute repeated single-shock compared to random vibration exposure highlight the need for a more nuanced approach to modeling repeated single-shock and vibration-induced injuries, as also showed by Maeda, S. [7]. Future research should investigate the physiological mechanisms underlying these frequency-dependent adaptations and explore how different exposure frequencies interact to influence long-term hand-arm health [101].

4.4 Temperature reaction

This study maintained the methodology established in the pilot study [48] for the skin temperature reaction measurements. Absolute temperature readings may have varied between participants, attributed to the internal calibration of the IR camera as per the manufacturer [67], therefor the use of the temperature difference ΔT was used to normalize the data, allowing for meaningful comparisons.

Analysis of global temperature distribution across the four exposure groups with variant exposure frequency (G1: $1s^{-1}$, G4: $4s^{-1}$, G20: $20s^{-1}$, and GR: random signal), encompassing both hands, and palmar and dorsal hand regions, reveals two notable trends.

Firstly, a consistent decrease in temperature is observed for both exposed and non-exposed hands, at post-exposure, across all groups, suggesting a potential correlation between exposure and thermoregulatory mechanisms. Further supporting this notion, our analysis of global delta-temperature consistently demonstrated a cooling trend across both hands, regardless of group, hand region, or exposure frequency. This effect was particularly pronounced in the exposed hand, with most data points falling below zero.

This aligns with existing literature on the acute effects of hand-arm vibration, where similar trends of decreasing skin temperature have been interpreted as indicators of reduced blood flow [5, 102, 103]. This finding highlights the robustness of the overall cooling trend, suggesting a consistent physiological response to the experimental conditions regardless of specific exposure parameters.

Secondly, a slight progressive decline in pre-exposure temperature measurements is observed throughout the experiment [Figure 3.4.2] This suggests a potential cumulative effect of repeated exposures, influencing baseline thermoregulation during acute exposure. This observation aligns with findings from some studies investigating the effects of hand-arm vibration, where cumulative exposure has been associated with alterations in vascular reactivity and thermoregulatory responses [104, 105]. Further investigation is warranted to clarify the specific physiological mechanisms responsible for these temperature fluctuations.

When analyzing temperature data across exposure groups, a pattern of cyclical fluctuations emerges. After each exposure, there's a slight temperature decrease followed by a partial recovery before the next exposure. This pattern is particularly evident in the single-shock exposure groups (G1, G4, and G20), with G20 showing the most pronounced response. This suggests a stronger physiological reaction to the experimental condition in G20, potentially due to higher exposure frequency of repeated single-shocks. Additionally, a cumulative temperature decline becomes more pronounced after the fourth exposure, suggesting that repeated exposures might have a compounding effect on temperature regulation [Chapter 3.4; Figure 3.4.2].

Interestingly, during the fifth exposure of random vibration, the responses of the shock-exposed groups diverged. The G1 group exhibited an increase in hand temperature, while the G4 and G20 groups showed a slight increase [Chapter 3.4; Figure 3.4.2]. This divergence highlights the potential influence of prior exposure type (single shock vs. random vibration) on subsequent thermoregulatory responses. In contrast, the GR group demonstrated a unique pattern, initial cyclical temperature fluctuations followed by a steady decline from the third exposure onwards, without recovery. This observation underscores the potential for prolonged vibration exposure to disrupt normal thermoregulatory mechanisms, as suggested by Bovenzi et al. [106].

The non-exposed hand exhibited a less pronounced temperature decrease, with subtle changes until a more noticeable drop after the fourth exposure. Differences in the functional temperature decrease between the exposed and non-exposed hands were observed across all four groups. This aligns with the explanation in the literature that a central mechanism is responsible for vasoconstriction in cases of uniform hand-arm vibration [107-110]. These findings underscore the differential impact of exposure and warrant further investigation into the direct and indirect mechanisms governing temperature regulation.

Analyzing temperature changes in the dorsal and palmar hand regions revealed distinct responses. Dorsal finger temperature decreased significantly after shock exposure, but this effect was localized to the fingers, potentially due to increased vasoconstriction sensitivity. In contrast, the palm showed significant cooling across all groups and exposures, particularly in the G20 group. These findings suggest that the exposed hand region and vibration frequency interact to influence temperature responses. The consistent cooling in the palm may be related to its contact with the metal handle.

This difference in dorsal and palmar responses could be attributed to variations in blood vessel distribution and thermoregulatory mechanisms between these regions. The palmar surface has a higher density of blood vessels and sweat glands, which play a crucial role in heat dissipation [111]. Therefore, the palmar region might be more responsive to changes in blood flow triggered by shock exposure. Essentially, these findings suggest that shock exposure can induce distinct localized cooling patterns in the hand, where the fingers and palm may be exhibiting different sensitivities and thermoregulatory responses [103, 112].

These findings in our study offer partial support for our initial hypotheses. The observed temperature decreases in G20 and G4 align with the hypothesis that increasing the frequency of single shocks intensifies the effects on the hand-arm system. Furthermore, the distinct temperature responses across the groups suggest that, when controlling acceleration and exposure time, single shock exposures indeed affect the hand-arm system differently than random vibration, as hypothesized.

Moreover, while this study doesn't definitively establish a cumulative effect of vibration exposure, the data reveals some suggestive patterns. Often, increasing exposure frequency led to progressively larger temperature decreases across exposures E1 to E4. This hints at a potential dose-response relationship, where greater exposure frequency results in more significant temperature changes.

The analysis of delta-temperature revealed no significant differences between the four exposure groups. While all groups exhibited a decrease in finger temperature following vibration exposure, the magnitude of this decrease was statistically similar across the different exposure conditions. This finding suggests that the degree of vibration exposure, at least within the parameters of this study, did not differentially impact the rate or magnitude of temperature change in the fingers. This contrasts with Bovenzi et al. [113] who investigated finger blood flow (FBF) rather than temperature and reported that higher vibration frequencies were associated with a greater decrease in FBF in both fingers during the recovery period. While the present study focused on temperature, the findings of Bovenzi et al. [113] suggest a potential link between vibration frequency, blood flow, and temperature regulation in the fingers, warranting further investigation.

The absence of significant between-group differences in temperature change may be attributable to several factors. The exposure durations may have been insufficient to induce significant temperature changes across the groups. Alternatively, individual differences in physiological responses, such as vascular reactivity, skin thickness, and baseline hand temperature, may have masked any potential effects of exposure when comparing the groups. Finally, the small group sizes in this study may have limited the power to detect between-group differences.

While the results offer a relationship between frequency-exposure and temperature changes, the underlying physiological mechanism leading to this effect warrants further investigation. Potential mechanisms could include alterations in blood flow patterns (such as vasoconstriction), or changes in cellular metabolic activity within the exposed tissue [106, 108, 114]. Understanding these mechanisms would be crucial for exploring the potential long-term implications of such temperature changes and possible applications.

4.5 Gripping strength and pinching strength

This study demonstrated a statistically significant difference in grip strength in two of the groups. The group G20 ($20s^{-1}$) on the exposed hand experienced a decrease in hand strength, while the group exposed to random vibration on the non-exposed hand showed an unexpected increase in grip strength. While these were the only two statistically significant results, it is important to note that this acute exposure appears to show a slight trend towards decreased strength in exposed hands and a trend towards increased strength in non-exposed hands [Chapter 3: Table 3.5.1].

The decrease in grip strength observed in G20 and the trends observed in the other groups is consistent with previous research, highlighting the detrimental effects of hand-arm vibration on neuromuscular function [115-117]. It is interesting to note that so far studies have described hand strength reduction effects mostly on chronically exposed subjects to vibration [118, 119], but not in young, healthy men after only acute exposure.

The increase in grip strength in the random vibration group may warrant further discussion. One possible explanation for this strength increase could be training or exercise effect, while the random vibration exposure was not intended as a strength-training intervention, it may have inadvertently stimulated contralateral strength adaptation [120].

Pinch strength tests, specifically the key grip maneuver, revealed a significant difference in maneuver 1 of the exposed hand between pre- and post-exposure measurements exclusively within the G20 group [Table 8.3.10, Chapter: 8.3]. This observation suggests a potential impact of experimental condition on pinch strength.

Caution should be exercised in interpreting these findings, as the clinical relevance of dynamometric force measurements in diagnosing musculoskeletal impairments related to hand-arm vibration syndrome (HAVS) remains unclear, due to the lack of evidence in favor of the application of grip strength and pinch strength tests for diagnosing musculoskeletal injuries in HAVS [121]. Also in the literature, statistical effects regarding a reduction in hand strength can only be found in manifest HAVS sufferers or those who have been chronically exposed to vibration for many years [15, 118], but not in young, healthy men. Therefore, further research is warranted to establish the diagnostic utility of grip and pinch strength assessment in the context of HAVS and determine the implications of the observed changes in our study.

4.6 Muscle activation

This study showed no significant differences in any of the EMG fatigue parameters between the 60% MVC condition at baseline and after E4, suggesting that no muscle fatigue occurred in the selected muscle groups. This finding appears to contradict the results reported by Schäfer et al. (1985) [122], who observed increased muscle activity under vibration exposure. However, several key differences between their study and the present investigation should be considered.

Firstly, unlike Schäfer et al. (1985), the current study did not require participants to maintain a constant grip force on the shaker. This decision was made due to the extended exposure duration, which would have made maintaining a constant grip force impractical and potentially confounded the fatigue assessment. Secondly, Schäfer et al. (1985) focused solely on changes in muscle activity, whereas this study specifically examined the development of muscle fatigue. The type of exposure and its short duration in their study likely did not induce fatigue, making a direct comparison challenging.

Our findings demonstrated no significant muscle fatigue, despite the experimental protocol involving repeated exposures, which was expected to induce fatigue detectable through EMG. This unexpected outcome may be attributed to the necessary 12-minute delay between the final exposure and the 60% MVC retest. This delay, prioritized to accommodate the collection of other physiological measures, could have allowed for some muscle recovery.

Although no evidence of muscle fatigue in the trapezius muscle was discovered by Astrom, C. [123] following a 3-minute exposure to vibration, it is important to note that this study differs from ours in terms of both the targeted muscle group and the exposure duration. Conversely, it has been demonstrated by several studies that muscle fatigue in the hand-arm system can be exacerbated by vibration exposure [124], These studies, however, employed different levels of muscle activation and postures [125, 126] than those used in the present study, potentially explaining the discrepancy in findings.

It has been described, that muscular strain in the hand-arm system, when coupled with the biomechanical strain of impacts/single-shocks and random vibration, pose a risk for musculoskeletal health [20]. This combination may increase the likelihood of developing conditions such as repetitive strain injury syndrome, tendinitis, and compression syndromes [127, 128]. This risk may be further heightened in the smaller forearm muscles, which may be more susceptible to reaching maximum recruitment due to their role in compensatory and stabilizing movements. This phenomenon of increased strain in smaller forearm muscles has been observed in workplace settings, particularly during tasks involving drilling activities [129].

While fatigue was likely present immediately after the fourth exposure, the 12-minute interval might have provided sufficient time for partial physiological restoration, potentially masking any fatigue effects in the subsequent EMG recording. This concern is supported by studies suggesting that complete muscle recovery can occur with rest periods of 5 to 15 minutes [130, 131]. Therefore, the absence of clear evidence of fatigue in the EMG data should be interpreted cautiously, acknowledging the potential influence of this delay. Future studies could consider modifying the protocol to minimize the interval between exposures and EMG retesting to obtain a more precise assessment of muscle fatigue.

4.7 Limitations of the Study

This study offers valuable insights into the acute effects of repeated single-shocks on the hand-arm system, establishing a foundation for future research in this area.

While the single-center design and focus on male participants, reflecting the prevalence in the targeted occupation, may influence the generalizability of findings, this study provides crucial data on a specific population. Future research can expand on these findings by including female participants and investigating the impact of diverse settings and individual factors, such as baseline health conditions and environmental influences, on the effects of repeated single-shocks.

The study's emphasis on short-term effects allows for a detailed examination of immediate physiological responses. This focus lays the groundwork for future investigations into the potential long-term and cumulative effects of repeated single-shock exposure. Additionally, while the controlled environment ensures precise measurement of acute effects, future studies could explore the impact of real-life distractions and usage patterns on the perception and consequences of repeated single-shocks.

Though time constraints limited the scope of data collection, the study successfully captured key physiological responses to repeated single-shock exposure. Future research with an extended study period could delve deeper into these responses, including the recovery time of physiological systems.

Despite these considerations, this study makes a significant contribution to understanding the immediate impact of repeated single-shocks on the hand-arm system. By acknowledging these aspects, this research paves the way for future studies to build upon these findings and expand the knowledge base in this important area.

Chapter 5: Conclusion

This study investigated the acute physiological effects of repeated single shocks on the hand-arm system in healthy men. Specifically, it examined how different shock frequencies impacted these physiological responses and compared these effects to those induced by random vibration exposure. This research provides a foundation for future investigations into the acute effects of single shocks on the hand-arm system and their potential long-term health consequences.

To investigate the acute effects of repeated single-shock on the hand-arm system, this study employed a comprehensive approach incorporating neurological, vascular, and muscular measurement techniques. These techniques demonstrated a high degree of sensitivity in detecting immediate physiological responses while maintaining practical feasibility within the study design. This technique's ability to detect immediate physiological changes is critical because it helps to establish the link between repeated single-shocks and the potential onset of secondary pathologies, informing preventative measures in occupational health.

This study hypothesized that repeated single shocks would elicit an acute physiological response in the hand-arm system (neurological, vascular, and muscular). The results partially supported this hypothesis. An increase in vibration perception thresholds was observed in all groups exposed to single shocks, particularly at higher test frequencies. A decrease in hand temperature was also observed in all groups, affecting both the exposed and non-exposed hands, although the decrease was more pronounced in the exposed hand and most pronounced in the G20 group. Muscle fatigue was not observed after the fourth exposure, likely due to the recovery period before measurement. Changes in grip strength (both hand grip and pinch grip) were less clear, with both increases and decreases observed.

The hypothesis, suggesting that the intensity of effects on the hand-arm system would increase with the frequency of single shocks, even when the total number of exposures remained constant, was largely supported. The findings demonstrated a clear trend of increasing physiological effects as the frequency of shocks increased. Vibration perception thresholds showed a greater increase in the G20 group (20 Hz) compared to the G4 group (4 Hz) and G1 group. Similarly, the reduction in hand temperature was more pronounced at higher shock frequencies. While all groups experienced a decrease in hand temperature in response to the shocks, the magnitude of this effect was significantly greater in the G20 group. This group displayed a strong and consistent temperature drop after each shock, highlighting a relationship between shock frequency and temperature response. This frequency-dependent response highlights the importance of considering shock frequency in the assessment and prevention of hand-arm vibration syndrome, as even seemingly minor increases in frequency can significantly impact physiological responses.

The final hypothesis proposed that the acute effects of repeated single-shock exposure on the hand-arm system would differ in nature and/or severity from the acute effects of random vibration exposure, regardless of the repetition rate. While sensitivity was observed to be worse in the group exposed to random vibration, this difference should be interpreted cautiously as it was almost exclusively observed when comparing this group to G1 ($1s^{-1}$). This may suggest that repeated single-shock exposure from G4 ($4s^{-1}$) and G20 ($20s^{-1}$) onward may be as detrimental to sensitivity as random vibration. However, no significant differences were found between the groups regarding other physiological responses. Specifically, temperature reaction, muscle fatigue, and strength were similar across all groups, regardless of the exposure type or repetition rate, but this should be interpreted with caution as observed in the temperature reaction results of this study [Chapter 3.4.1]. While previous research on the comparative effects of vibration and shock exposure on the hand-arm system has been limited, this study adds to existing. This new information contributes to a growing understanding of single-shock exposures in the hand arm system.

This study provides a foundation to understand the short-term and long-term health effects of repeated shock exposure and to develop effective interventions. This includes exploring biomechanical responses to shock, identifying vulnerable individuals and occupations, and evaluating the efficacy of potential preventative measures such as specialized gloves, tool dampeners, and modified work practices.

With these results, despite the distinct mechanical impact profile and high maximum acceleration values for single shocks, the immediate medical consequences in the domains investigated appear to be fundamentally comparable to those of hand-arm vibration. At the same time, the results show in detail that a differentiated assessment of human vibration is necessary regarding occupational exposure to repeated single-shocks. This includes the possible dependence on the repetition rate and the potentially local damage mechanism in the occurrence of functional circulatory disturbances or the observed prolonged regeneration phases in vibration perception (cf. Chapter 4.2.2.).

While research on the effects of repeated single-shock exposure and the comparative effects of single-shock and random vibration on the hand-arm system is still emerging, this study represents a significant step forward. Further investigation is crucial to better understand the distinct effects of these exposures and to develop effective strategies for minimizing the risk of injury. By expanding the scope of prevention to encompass shock and impact vibration, the health and well-being of workers across a wider range of occupations can be better protected.

To provide more targeted prevention recommendations, future studies should directly compare the effects of impacts and vibration on both healthy individuals and exposed workers. This will help to conclusively determine whether separate risk assessments are necessary for single-impact tools like nailers, riveting hammers, and rammers, which are currently often assessed under general vibration guidelines. This research may lead to the adaptation of existing occupational health and safety concepts to better address the unique risks associated with impact tools.

Chapter 6: Abstract

Exposure to repeated single-shocks to the hand-arm system remains prevalent in numerous occupations (e.g. pneumatic riveting, nailing, hammering, and bolt setting). Given the established health risks associated with hand-arm vibration, repeated single-shocks are also suspected of detrimental effects on the physiology of the hand-arm system, potentially causing permanent damage in a dose-dependent manner. A comprehensive risk assessment framework specifically for repeated single-shock vibrations is currently lacking. Current occupational health and safety directives in the European Union tend to treat shock emissions similarly to continuous vibrations, which may lead to an underestimation of the true health risks posed by occupational exposure to single-shocks.

This dissertation aims to address this knowledge gap by systematically investigating the acute effects of single-shock vibrations on various physiological parameters in the hand-arm system. An experimental, controlled laboratory study was conducted, employing a block-wise experimental design with repeated exposures to repeated single-shock vibrations at different frequencies and exposure to random vibration as a control.

The study revealed significant effects of single-shock vibrations on skin temperature reaction, with observed decreases in temperature following exposure, particularly at higher frequencies. Finger sensitivity was significantly reduced, indicating potential impairment of sensory nerve function. These findings suggest a potential for both vascular and neurological impairment due to acute repeated single-shock vibration exposure. This highlights the potential for acute physiological changes even after short-term exposure to single-shock vibrations, raising concerns about the long-term health consequences for workers exposed to such vibrations in occupational settings.

Chapter 7: References

[1] UK. (2023, July 4). *IIAC position paper 49, Limitations of epidemiology when investigating occupations with a potential for significant vibration exposure and PD A11, HAVS*. [Online] Available: https://www.gov.uk/government/publications/limitations-of-epidemiology-when-investigating-occupations-with-a-potential-for-significant-vibration-exposure-iiac-position-paper-49/limitations-of-epidemiology-when-investigating-occupations-with-a-potential-for-significant-vibration-exposure-and-pd-a11-havs

[2] C. M. Nelson and P. F. Brereton, "The European vibration directive," (in eng), *Ind Health,* vol. 43, no. 3, pp. 472-9, Jul 2005, doi: 10.2486/indhealth.43.472.

[3] M. Farkkila, "Grip force in vibration disease," (in eng), *Scand J Work Environ Health,* vol. 4, no. 2, pp. 159-66, Jun 1978. [Online]. Available: https://www.ncbi.nlm.nih.gov/pubmed/684389.

[4] M. Bovenzi, L. Petronio, and F. DiMarino, "Epidemiological survey of shipyard workers exposed to hand-arm vibration," (in eng), *Int Arch Occup Environ Health,* vol. 46, no. 3, pp. 251-66, 1980. [Online]. Available: https://www.ncbi.nlm.nih.gov/pubmed/7450890.

[5] H. Dupuis and G. Jansen, "Immediate effects of vibration transmitted to the hand," *Studies in Environmental Science,* Conference Paper vol. 13, no. C, pp. 76-86, 1981, doi: 10.1016/S0166-1116(09)70140-2.

[6] K. Nishiyama and S. Watanabe, "Temporary threshold shift of vibratory sensation after clasping a vibrating handle," *Int Arch Occup Environ Health,* Article vol. 49, no. 1, pp. 21-33, 1981, doi: 10.1007/BF00380805.

[7] S. Maeda, "Temporary threshold shifts in fingertip vibratory sensation from hand-transmitted vibration and repetitive shock," (in eng), *Nagoya J Med Sci,* vol. 57 Suppl, pp. 185-93, May 1994. [Online]. Available: https://www.ncbi.nlm.nih.gov/pubmed/7708100.

[8] S. Maeda and M. J. Griffin, "The growth and recovery of vibrotactile TTs caused by hand-transmitted repetitive shocks of various waveforms," (in eng), *Cent Eur J Public Health,* vol. 3 Suppl, pp. 57-61, 1995. [Online]. Available: https://www.ncbi.nlm.nih.gov/pubmed/9150972.

[9] N. Schafer, H. Dupuis, and E. Hartung, "Acute effects of shock-type vibration transmitted to the hand-arm system," (in eng), *Int Arch Occup Environ Health,* vol. 55, no. 1, pp. 49-59, 1985. [Online]. Available: https://www.ncbi.nlm.nih.gov/pubmed/6526500.

[10] S. Kihlberg, M. Attebrant, G. Gemne, and A. Kjellberg, "Acute effects of vibration from a chipping hammer and a grinder on the hand-arm system," (in eng), *Occup Environ Med,* vol. 52, no. 11, pp. 731-7, Nov 1995, doi: 10.1136/oem.52.11.731: 10.1136/oem.52.11.731.

[11] I. I. A. C. (IIAC), "Hand-arm vibration syndrome CM 6098," Department for Work and Pensions, 2004. [Online]. Available: https://assets.publishing.service.gov.uk/media/5a7c2894ed915d0b036b5670/6098.pdf

[12] M. Bovenzi, A. Franzinelli, and F. Strambi, "Prevalence of vibration-induced white finger and assessment of vibration exposure among travertine workers in Italy," *International Archives of Occupational and Environmental Health,* Article vol. 61, no. 1-2, pp. 25-34, 1988, doi: 10.1007/bf00381604.

[13] M. Farkkila, I. Pyykko, V. Jantti, S. Aatola, J. Starck, and O. Korhonen, "Forestry workers exposed to vibration: a neurological study," (in eng), *Br J Ind Med,* vol. 45, no. 3, pp. 188-92, Mar 1988, doi: 10.1136/oem.45.3.188: 10.1136/oem.45.3.188.

[14] N. Kurumatani *et al.*, "Cross-sectional study of blood pressure and electrocardiograms of forestry workers exposed to both noise and local vibration," *Ind Health,* Article vol. 26, no. 1, pp. 43-54, 1988, doi: 10.2486/indhealth.26.43: 10.2486/indhealth.26.43.

[15] L. Gerhardsson and M. Hagberg, "Vibration induced injuries in hands in longterm vibration exposed workers," *Occupational and environmental medicine,* Journal: Conference Abstract vol. 75, pp. A515-, 2018, doi: 10.1136/oemed-2018-ICOHabstracts.1459.

[16] M. Furuta, H. Sakakibara, M. Miyao, T. Kondo, and S. Yamada, "Effect of vibration frequency on finger blood flow," *Int Arch Occup Environ Health,* Clinical Trial; Journal Article; Randomized Controlled Trial vol. 63, no. 3, pp. 221-4, 1991. [Online]. Available: https://www.ncbi.nlm.nih.gov/pubmed/1917073.

[17] M. Bovenzi, A. Franzinelli, L. Scattoni, and L. Vannuccini, "Hand-arm vibration syndrome among travertine workers: a follow up study," *Occup Environ Med,* Article vol. 51, no. 6, pp. 361-5, Jun 1994, doi: 10.1136/oem.51.6.361: 10.1136/oem.51.6.361.

[18] H. Virokannas, "Vibration perception thresholds in workers exposed to vibration," (in eng), *Int Arch Occup Environ Health,* vol. 64, no. 5, pp. 377-82, 1992. [Online]. Available: https://www.ncbi.nlm.nih.gov/pubmed/1336767.

[19] D. E. Adamo, B. J. Martin, and P. W. Johnson, "Vibration-induced muscle fatigue, a possible contribution to musculoskeletal injury," *Eur J Appl Physiol,* Article vol. 88, no. 1-2, pp. 134-40, Nov 2002, doi: 10.1007/s00421-002-0660-y: 10.1007/s00421-002-0660-y. Epub 2002 Aug 27.

[20] A. O. Chourasia, M. E. Sesto, W. F. Block, and R. G. Radwin, "Prolonged mechanical and physiological changes in the upper extremity following short-term simulated power hand tool use," (in eng), *Ergonomics,* vol. 52, no. 1, pp. 15-24, Jan 2009, doi: 10.1080/00140130802480877.

[21] A. Burdorf and A. Monster, "Exposure to vibration and self-reported health complaints of riveters in the aircraft industry," *Ann Occup Hyg,* Article vol. 35, no. 3, pp. 287-98, Jun 1991, doi: 10.1093/annhyg/35.3.287: 10.1093/annhyg/35.3.287.

[22] U. Kaulbars, "Measurement of isolated shocks in accordance with ISO/TS 15694," presented at the 25th Japan Conference on Human Response to Vibration (JCHRV2017), Nagoya University Daiko Campus, Nagoya, Japan, 2017. [Online]. Available: https://www.dguv.de/medien/ifa/de/pub/grl/pdf/proceedings-jchrv2017_kaulbars-(new2).pdf.

[23] H. Dupuis and N. Schafer, "Effects of impulse vibration on the hand-arm system," *Scandinavian Journal of Work, Environment and Health,* Article vol. 12, no. 4, pp. 320-322, 1986. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-0022892330&partnerID=40&md5=60f91e61dec3b0b6bfeff75d6ae713d8.

[24] L. Jorulf, "Vibration-induced effects caused by impact wrenches used in truck assembly," *Scandinavian Journal of Work, Environment and Health,* Article vol. 12,

no. 4, pp. 269-271, 1986. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-0022879182&partnerID=40&md5=e7324293c4cbea5c20ef095106631ff5.

[25] M. Bovenzi, P. Apostoli, G. Alessandro, and O. Vanoni, "Changes over a workshift in aesthesiometric and vibrotactile perception thresholds of workers exposed to intermittent hand transmitted vibration from impact wrenches," (in eng), *Occup Environ Med,* vol. 54, no. 8, pp. 577-87, Aug 1997, doi: 10.1136/oem.54.8.577: 10.1136/oem.54.8.577.

[26] Y. Musson, A. Burdorf, and D. van Drimmelen, "Exposure to shock and vibration and symptoms in workers using impact power tools," *Ann Occup Hyg,* Article vol. 33, no. 1, pp. 85-96, 1989, doi: 10.1093/annhyg/33.1.85: 10.1093/annhyg/33.1.85.

[27] e. Bernard BP, *Musculoskeletal disorders and workplace factors: A critical review of epidemiologic evidence for work-related musculoskeletal disorders of the neck, upper extremity, and low back.* Cincinnati: OH: National Institute for Occupational Safety and Health, U. S. Department of Health and Human Services, 1997.

[28] *ISO 5349:2002: Mechanical vibration – Measurement and evaluation of human exposure to hand-transmitted vibration – Part 1: General requirements, Part 2: Practical guidance for measurement at the workplace*, 2002.

[29] *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*, 2004.

[30] (2012). *NIOSH Method 1500: A comprehensive method for the evaluation of human exposure to hand-transmitted vibration*.

[31] H. a. S. Executive. "Hand-arm vibration at work." https://www.hse.gov.uk/vibration/hav/index.htm (accessed 9 Oct. 2024., 2024).

[32] M. J. Griffin, *Handbook of human vibration*. London: Academic Press, 1990.

[33] *International Organization for Standarditazion, DIN EN ISO 2041: Mechanical vibration, shock and condition monitoring - Vocabulary*, 2018.

[34] (1989). *Occupational exposure to hand-arm vibration*. [Online] Available: https://stacks.cdc.gov/view/cdc/11176

[35] M. J. Griffin, "Frequency-dependence of psychophysical and physiological responses to hand-transmitted vibration," *Industrial health,* vol. 50, no. 5, pp. 354-369, 2012.

[36] A. Thompson and R. House, "Hand-arm vibration syndrome with concomitant arterial thrombosis in the hands," *Occup Med (Lond),* Article vol. 56, no. 5, pp. 317-21, Aug 2006, doi: 10.1093/occmed/kql022 10.1093/occmed/kql022. Epub 2006 May 22.

[37] M. Bovenzi, "A follow up study of vascular disorders in vibration-exposed forestry workers," (in eng), *Int Arch Occup Environ Health,* vol. 81, no. 4, pp. 401-8, Feb 2008, doi: 10.1007/s00420-007-0225-9 10.1007/s00420-007-0225-9. Epub 2007 Jul 21.

[38] M. Bovenzi, F. D'Agostin, F. Rui, and C. Negro, "A longitudinal study of finger systolic blood pressure and exposure to hand-transmitted vibration," (in eng), *Int Arch Occup Environ Health,* vol. 81, no. 5, pp. 613-23, Apr 2008, doi: 10.1007/s00420-007-0255-3 10.1007/s00420-007-0255-3. Epub 2007 Sep 26.

[39] A. J. Brammer, W. Taylor, and J. E. Piercy, "Assessing the severity of the neurological component of the hand-arm vibration syndrome," (in eng), *Scand J Work Environ Health,* vol. 12, no. 4 Spec No, pp. 428-31, Aug 1986. [Online]. Available: https://www.ncbi.nlm.nih.gov/pubmed/3775334.

[40] H. Sakakibara, M. Hirata, T. Hashiguchi, N. Toibana, and H. Koshiyama, "Affected segments of the median nerve detected by fractionated nerve conduction measurement in vibration-induced neuropathy," *Ind Health,* Article vol. 36, no. 2, pp. 155-9, Apr 1998, doi: 10.2486/indhealth.36.155 10.2486/indhealth.36.155.

[41] L. E. Necking, J. Friden, and G. Lundborg, "Reduced muscle strength in abduction of the index finger: an important clinical sign in hand-arm vibration syndrome," (in eng), *Scand J Plast Reconstr Surg Hand Surg,* vol. 37, no. 6, pp. 365-70, 2003. [Online]. Available:https://www.ncbi.nlm.nih.gov/pubmed/15328777https://www.tandfonline.com/doi/pdf/10.1080/02844310310004316?needAccess=true.

[42] M. Bovenzi, A. Della Vedova, P. Nataletti, B. Alessandrini, and T. Poian, "Work-related disorders of the upper limb in female workers using orbital sanders," *Int Arch Occup Environ Health,* Article vol. 78, no. 4, pp. 303-10, May 2005, doi: 10.1007/s00420-004-0574-6 10.1007/s00420-004-0574-6. Epub 2005 Mar 25.

[43] M. Bovenzi, "Criteria for case definitions for upper limb and lower back disorders caused by mechanical vibration," (in eng), *Med Lav,* vol. 98, no. 2, pp. 98-110, Mar-Apr 2007. [Online]. Available: https://www.ncbi.nlm.nih.gov/pubmed/17375603.

[44] S. G. Raju, O. Rogness, M. Persson, J. Bain, and D. Riley, "Vibration from a riveting hammer causes severe nerve damage in the rat tail model," *Muscle Nerve,* Article vol. 44, no. 5, pp. 795-804, Nov 2011, doi: 10.1002/mus.22206 10.1002/mus.22206.

[45] K. M. Krajnak *et al.*, "The effects of impact vibration on peripheral blood vessels and nerves," (in eng), *Ind Health,* vol. 51, no. 6, pp. 572-80, 2013, doi: 10.2486/indhealth.2012-0193 10.2486/indhealth.2012-0193. Epub 2013 Sep 27.

[46] I. R. 2017, "Hand-arm vibration: Exposure to isolated and repeated shock vibrations – Review of the International Expert Workshop 2015 in Beijing," in *Thirteenth International Conference on Hand-Arm Vibration*, China, B. I. f. A. Bia, Ed., 2015.

[47] K. A. Buchanan *et al.*, "Proximal forearm extensor muscle strain is reduced when driving nails using a shock-controlled hammer," (in eng), *Clinical biomechanics (Bristol, Avon),* vol. 38, pp. 22-8, Oct 2016, doi: 10.1016/j.clinbiomech.2016.08.004 10.1016/j.clinbiomech.2016.08.004. Epub 2016 Aug 9.

[48] J. Witte *et al.*, "Acute physiological and functional effects of repetitive shocks on the hand–arm system: a pilot study on healthy subjects," *International Journal of Occupational Safety and Ergonomics,* pp. 1-10, 2022, doi: 10.1080/10803548.2022.2110358.

[49] Y. Aiba *et al.*, "A longitudinal study on Raynaud's phenomenon in workers using an impact wrench," *J Occup Health,* Article vol. 54, no. 2, pp. 96-102, 2012, doi: 10.1539/joh.11-0058-oa 10.1539/joh.11-0058-oa. Epub 2012 Jan 31.

[50] Y. Ye, M. Mauro, M. Bovenzi, and M. J. Griffin, "Acute effects of mechanical shocks on finger blood flow: influence of shock repetition rate and shock magnitude," (in eng), *Int Arch Occup Environ Health,* vol. 85, no. 6, pp. 605-14, Aug 2012, doi: 10.1007/s00420-011-0704-x 10.1007/s00420-011-0704-x. Epub 2011 Oct 2.

[51] M. Bovenzi, "Vibration white finger, digital blood pressure, and some biochemical findings on workers operating vibrating tools in the engine manufacturing industry," (in eng), *Am J Ind Med,* vol. 14, no. 5, pp. 575-84, 1988. [Online]. Available: https://www.ncbi.nlm.nih.gov/pubmed/3228071https://onlinelibrary.wiley.com/doi/abs/10.1002/ajim.4700140508?sid=nlm%3Apubmed.

[52] D. G. U. (DGUV). "Occupational diseases." Institut für Arbeitsschutz der DGUV (IFA). https://www.dguv.de/ifa/fachinfos/vibrationen/index-2.jsp#:~:text=Occupational%20diseases-,Occupational%20diseases,this%20area%20is%20therefore%20important. (accessed October 10, 2024.

[53] E. Christ, Fischer, S., Kaulbars, U., & Sayn, D. , "Vibrationseinwirkung an Arbeitsplätzen – Kennwerte der Hand-Arm- und Ganzkörperbelastung," DGUV, Sankt Augustin, 2006.

[54] D. G. U. (DGUV), "DGUV Statistiken für die Praxis 2019," 2019. [Online]. Available: https://publikationen.dguv.de/zahlen-fakten/ueberblick/3903/dguv-statistiken-fuer-die-praxis-2019

[55] (2007). *Noise and vibrations - Occupational Safety and Health Ordinance*. [Online] Available: https://www.baua.de/DE/Themen/Arbeitsgestaltung/Physikalische-Faktoren/Laerm/pdf/LaermVibrationsArbSchV-englisch.pdf?__blob=publicationFile&v=2

[56] B. f. A. u. A. (BAuA). "Hand-Arm-Vibrationen." BAuA. https://www.baua.de/DE/Themen/Arbeitsgestaltung/Gefaehrdungsbeurteilung/Handbuch-Gefaehrdungsbeurteilung/Expertenwissen/Physikalische-Einwirkungen/Hand-Arm-Vibrationen/Hand-Arm-Vibrationen_dossier?pos=3 (accessed 10 October 2024, 2024).

[57] (2018). *Handbuch "Hand-Arm-Vibrationen" [Handbook "Hand-arm vibrations"]*. [Online]Available: https://www.bmas.de/SharedDocs/Downloads/DE/Publikationen/c219-handbuch-hand-arm-vibration-a220.pdf?__blob=publicationFile&v=2

[58] T. Schenk, Kaulbars, U., & Haas, F., "Investigations on the description and definition of single shocks affecting the human hand-arm system during work as well as on possibilities for their assessment," Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung (IFA), Project No. FF-FP 0376, 2015. [Online]. Available: https://www.dguv.de/ifa/forschung/projektverzeichnis/ff-fp0376-2.jsp

[59] S. J. Kohn MA. "Sample Size Calculators." https://www.sample-size.net/ (accessed.

[60] E. Hartung, H. Dupuis, and M. Scheffer, "Effects of grip and push forces on the acute response of the hand-arm system under vibrating conditions," *International Archives of Occupational and Environmental Health,* vol. 64, no. 6, pp. 463-467, 1993/01/01 1993, doi: 10.1007/BF00517954.

[61] L. B. Dahlin, N. Güner, H. Elding Larsson, and T. Speidel, "Vibrotactile perception in finger pulps and in the sole of the foot in healthy subjects among children or adolescents," *PLoS ONE,* vol. 10, 01/01 2015, doi: 10.1371/journal.pone.0119753.

[62] R. House, L. Holness, I. Taraschuk, and R. Nisenbaum, "Infrared thermography in the hands and feet of hand-arm vibration syndrome (HAVS) cases and controls," *International Journal of Industrial Ergonomics,* Article vol. 62, pp. 70-76, 2017, doi: 10.1016/j.ergon.2017.01.001.

[63] S. Youakim, "Infrared thermometry in the diagnosis of hand-arm vibration syndrome," (in eng), *Occup Med (Lond),* vol. 60, no. 3, pp. 225-30, May 2010, doi: 10.1093/occmed/kqq004. Epub 2010 Feb 18.

[64] S. Voelter-Mahlknecht, S. Letzel, and H. Dupuis, "Diagnostic significance of cold provocation test at 12 degrees C," (in eng), *Environ Health Prev Med,* vol. 10, no. 6, pp. 376-9, Nov 2005, doi: 10.1007/BF02898200 10.1007/BF02898200.

[65] S. Bagavathiappan *et al.*, "Infrared thermal imaging for detection of peripheral vascular disorders," (in eng), *J Med Phys,* vol. 34, no. 1, pp. 43-7, Jan 2009, doi: 10.4103/0971-6203.48720.

[66] C. I. Wright, C. I. Kroner, and R. Draijer, "Non-invasive methods and stimuli for evaluating the skin's microcirculation," *Journal of Pharmacological and Toxicological Methods,* vol. 54, no. 1, pp. 1-25, 2006/07/01/ 2006, doi: https://doi.org/10.1016/j.vascn.2005.09.004.

[67] FLIR-Systems. "FLIR One Pro - Specifications." FLIR System. (accessed last call 19.01.2023.

[68] R. Gurram, S. Rakheja, and G. J. Gouw, "A study of hand grip pressure distribution and EMG of finger flexor muscles under dynamic loads," *Ergonomics,* Article vol. 38, no. 4, pp. 684-99, Apr 1995, doi: 10.1080/00140139508925140: 10.1080/00140139508925140.

[69] H. C. Roberts *et al.*, "A review of the measurement of grip strength in clinical and epidemiological studies: towards a standardised approach," (in eng), *Age Ageing,* vol. 40, no. 4, pp. 423-9, Jul 2011, doi: 10.1093/ageing/afr051.

[70] R. W. Bohannon, "Test-Retest Reliability of Hand-Held Dynamometry During a Single Session of Strength Assessment," *Physical Therapy,* vol. 66, no. 2, pp. 206-209, 1986, doi: 10.1093/ptj/66.2.206.

[71] C. W. Stegink Jansen, V. K. Simper, H. G. Stuart, and H. M. Pinkerton, "Measurement of maximum voluntary pinch strength:: Effects of forearm position and outcome score," *Journal of Hand Therapy,* vol. 16, no. 4, pp. 326-336, 2003/10/01/ 2003, doi: https://doi.org/10.1197/S0894-1130(03)00159-5.

[72] L. McManus, G. De Vito, and M. M. Lowery, "Analysis and Biophysics of Surface EMG for Physiotherapists and Kinesiologists: Toward a Common Language With Rehabilitation Engineers," (in eng), *Front Neurol,* vol. 11, p. 576729, 2020, doi: 10.3389/fneur.2020.576729.

[73] S. Rampichini, T. M. Vieira, P. Castiglioni, and G. Merati, "Complexity Analysis of Surface Electromyography for Assessing the Myoelectric Manifestation of Muscle Fatigue: A Review," (in eng), *Entropy (Basel),* vol. 22, no. 5, May 7 2020, doi: 10.3390/e22050529.

[74] B. Gerdle, S. Karlsson, S. J. Day, and M. Djupsjöbacka, "Acquisition, Processing and Analysis of the Surface Electromyogram," 1999.

[75] H. Hermens, Freriks, B., Dißelhorst-Klug, Catherine, Rau, G., "The recommendations for sensors and sensor placement procedures for surface electromyography," vol. 8: Roessingh Research and Development, 1999, pp. 15-53.

[76] H. J. Hermens, B. Freriks, C. Disselhorst-Klug, and G. Rau, "Development of recommendations for SEMG sensors and sensor placement procedures," (in eng), *Journal of electromyography and kinesiology : official journal of the International Society of Electrophysiological Kinesiology,* vol. 10, no. 5, pp. 361-74, Oct 2000, doi: 10.1016/s1050-6411(00)00027-4.

[77] D. Roman-Liu and P. Bartuzi, "Influence of type of MVC test on electromyography measures of biceps brachii and triceps brachii," (in eng), *Int J Occup Saf Ergon,* vol. 24, no. 2, pp. 200-206, Jun 2018, doi: 10.1080/10803548.2017.1353321.

[78] C. R. Harris *et al.*, "Array programming with NumPy," *Nature,* vol. 585, no. 7825, pp. 357-362, 2020/09/01 2020, doi: 10.1038/s41586-020-2649-2.

[79] P. Virtanen *et al.*, "SciPy 1.0: fundamental algorithms for scientific computing in Python," *Nature Methods*, vol. 17, no. 3, pp. 261-272, 2020/03/01 2020, doi: 10.1038/s41592-019-0686-2.

[80] G. a. D. J. Van Rossum, Fred L, *Python reference manual*. Centrum voor Wiskunde en Informatica Amsterdam, 1995.

[81] *R: A language and environment for statistical computing. R Foundation for Statistical Computing*. (2021). Viena, Austria. [Online]. Available: http://www.R-project.org/

[82] E. F. Shair, S. A. Ahmad, M. H. Marhaban, S. B. Mohd Tamrin, and A. R. Abdullah, "EMG Processing Based Measures of Fatigue Assessment during Manual Lifting," (in eng), *Biomed Res Int*, vol. 2017, p. 3937254, 2017, doi: 10.1155/2017/3937254.

[83] K. T. Palmer, M. J. Griffin, H. Bendall, B. Pannett, and D. Coggon, "Prevalence and Pattern of Occupational Exposure to Hand Transmitted Vibration in Great Britain: Findings from a National Survey," *Occupational and Environmental Medicine*, vol. 57, no. 4, pp. 218-228, 2000. [Online]. Available: http://www.jstor.org/stable/27731292.

[84] P. Vihlborg *et al.*, "Carpal Tunnel Syndrome and Hand-Arm Vibration: A Swedish National Registry Case-Control Study," (in eng), *J Occup Environ Med*, vol. 64, no. 3, pp. 197-201, Mar 1 2022, doi: 10.1097/jom.0000000000002451.

[85] M. Edlund *et al.*, "A prospective cohort study investigating an exposure-response relationship among vibration-exposed male workers with numbness of the hands," *Scand J Work Environ Health*, Article vol. 40, no. 2, pp. 203-9, Mar 2014, doi: 10.5271/sjweh.3386 10.5271/sjweh.3386. Epub 2013 Sep 25.

[86] L. Gerhardsson, L. Burstrom, M. Hagberg, R. Lundstrom, and T. Nilsson, "Quantitative neurosensory findings, symptoms and signs in young vibration exposed workers," (in eng), *J Occup Med Toxicol*, vol. 8, no. 1, p. 8, Mar 27 2013, doi: 10.1186/1745-6673-8-8: 10.1186/1745-6673-8-8.

[87] A. T. Su *et al.*, "A cross sectional study on hand-arm vibration syndrome among a group of tree fellers in a tropical environment," (in eng), *Ind Health*, vol. 52, no. 4, pp. 367-76, 2014, doi: 10.2486/indhealth.2013-0137: 10.2486/indhealth.2013-0137. Epub 2014 Apr 17.

[88] J. Malchaire, L. S. Rodriguez Diaz, A. Piette, F. Goncalves Amaral, and D. de Schaetzen, "Neurological and functional effects of short-term exposure to hand-arm vibration," (in eng), *Int Arch Occup Environ Health*, vol. 71, no. 4, pp. 270-6, Jun 1998. [Online]. Available: https://www.ncbi.nlm.nih.gov/pubmed/9638484.

[89] T. Nilsson, J. Wahlström, and L. Burström, "Hand-arm vibration and the risk of vascular and neurological diseases-A systematic review and meta-analysis," (in eng), *PLoS One*, vol. 12, no. 7, p. e0180795, 2017, doi: 10.1371/journal.pone.0180795.

[90] H. Gierke and A. Brammer, "Effects of shock and vibration on humans," 01/01 2002.

[91] S. Adewusi, S. Rakheja, and P. Marcotte, "Biomechanical models of the human hand-arm to simulate distributed biodynamic responses for different postures," *International Journal of Industrial Ergonomics*, vol. 42, no. 2, pp. 249-260, 2012/03/01/ 2012, doi: https://doi.org/10.1016/j.ergon.2012.01.005.

[92] M. Fritz, "An improved biomechanical model for simulating the strain of the hand-arm system under vibration stress," (in eng), *J Biomech*, vol. 24, no. 12, pp. 1165-71, 1991, doi: 10.1016/0021-9290(91)90008-b.

[93] L. Ekman, E. Lindholm, E. Brogren, and L. B. Dahlin, "Normative values of the vibration perception thresholds at finger pulps and metatarsal heads in healthy adults," *PLoS One,* vol. 16, no. 4, p. e0249461, 2021.

[94] L. Ekman, J. Persson Löfgren, and L. B. Dahlin, "Examining practice effects in repeated measurements of vibration perception thresholds on finger pulps of healthy individuals–Is it possible to improve your results over a clinically relevant test interval?," *PLoS One,* vol. 14, no. 12, p. e0226371, 2019.

[95] J. Z. Wu, K. Krajnak, D. E. Welcome, and R. G. Dong, "Analysis of the dynamic strains in a fingertip exposed to vibrations: Correlation to the mechanical stimuli on mechanoreceptors," (in eng), *J Biomech,* vol. 39, no. 13, pp. 2445-56, 2006, doi: 10.1016/j.jbiomech.2005.07.027.

[96] J. L. Thonnard, D. Masset, M. Penta, A. Piette, and J. Malchaire, "Short-term effect of hand-arm vibration exposure on tactile sensitivity and manual skill," (in eng), *Scand J Work Environ Health,* vol. 23, no. 3, pp. 193-8, Jun 1997. [Online]. Available: https://www.ncbi.nlm.nih.gov/pubmed/9243729.

[97] H. Virokannas, "Dose-response relation between exposure to two types of hand-arm vibration and sensorineural perception of vibration," (in eng), *Occup Environ Med,* vol. 52, no. 5, pp. 332-6, May 1995, doi: 10.1136/oem.52.5.332 10.1136/oem.52.5.332.

[98] H. Virokannas and A. Virokannas, "Temperature and vibration perception thresholds in workers exposed to hand-arm vibration," (in eng), *Cent Eur J Public Health,* vol. 3 Suppl, pp. 66-9, 1995. [Online]. Available: https://www.ncbi.nlm.nih.gov/pubmed/9150974.

[99] R. Ahn *et al.*, "Normative data for neuromuscular assessment of the hand-arm vibration syndrome and its retrospective applications in Korean male workers," (in eng), *Int Arch Occup Environ Health,* vol. 86, no. 7, pp. 837-44, Oct 2013, doi: 10.1007/s00420-013-0904-7 10.1007/s00420-013-0904-7. Epub 2013 Aug 24.

[100] S. B. Tamrin, M. N. Jamalohdin, Y. G. Ng, S. Maeda, and N. A. Ali, "The characteristics of vibrotactile perception threshold among shipyard workers in a tropical environment," *Ind Health,* Article vol. 50, no. 2, pp. 156-63, 2012, doi: 10.2486/indhealth.ms1221: 10.2486/indhealth.ms1221. Epub 2012 Feb 1.

[101] L. Gerhardsson and M. Hagberg, "Work ability in vibration-exposed workers," (in eng), *Occup Med (Lond),* vol. 64, no. 8, pp. 629-34, Dec 2014, doi: 10.1093/occmed/kqu121.

[102] H. Pettersson, S. Rissanen, J. Wahlstrom, and H. Rintamaki, "Skin temperature responses to hand-arm vibration in cold and thermoneutral ambient temperatures," (in eng), *Ind Health,* vol. 56, no. 6, pp. 545-552, Nov 21 2018, doi: 10.2486/indhealth.2018-0013: 10.2486/indhealth.2018-0013. Epub 2018 Jul 3.

[103] M. H. Mahbub and N. Harada, "Digital blood flow and temperature responses in palmar and dorsal skin induced by short-term vibration exposure while grasping a vibratory handle," (in eng), *Int Arch Occup Environ Health,* vol. 81, no. 7, pp. 889-97, Jul 2008, doi: 10.1007/s00420-007-0283-z: 10.1007/s00420-007-0283-z. Epub 2007 Dec 5.

[104] R. Sauni *et al.*, "Vibration-induced white finger syndrome and carpal tunnel syndrome among Finnish metal workers," (in eng), *Int Arch Occup Environ Health,* vol. 82, no. 4, pp. 445-53, Mar 2009, doi: 10.1007/s00420-008-0357-6: 10.1007/s00420-008-0357-6. Epub 2008 Sep 10.

[105] H. Pettersson, S. Rissanen, J. Wahlström, and H. Rintamäki, "Skin temperature responses to hand-arm vibration in cold and thermoneutral ambient temperatures," (in

eng), *Ind Health,* vol. 56, no. 6, pp. 545-552, Nov 21 2018, doi: 10.2486/indhealth.2018-0013.

[106] M. Bovenzi, M. J. Griffin, and C. M. Ruffell, "Acute effects of vibration on digital circulatory function in healthy men," *Occupational and Environmental Medicine,* vol. 52, no. 12, pp. 834-841, 1995, doi: 10.1136/oem.52.12.834.

[107] J. Luo, H. Sakakibara, S. K. Zhu, T. Kondo, and H. Toyoshima, "Effect of vibration magnitude and repetitive exposure on finger blood flow in healthy subjects," (in eng), *Int Arch Occup Environ Health,* vol. 73, no. 4, pp. 281-4, May 2000, doi: 10.1007/s004200050429.

[108] M. Bovenzi, C. J. Lindsell, and M. J. Griffin, "Magnitude of acute exposures to vibration and finger circulation," (in eng), *Scand J Work Environ Health,* vol. 25, no. 3, pp. 278-84, Jun 1999, doi: 10.5271/sjweh.435.

[109] N. Olsen, "Vibration aftereffects on vasoconstrictor response to cold in the normal finger," (in eng), *European journal of applied physiology and occupational physiology,* vol. 66, no. 3, pp. 246-8, 1993. [Online]. Available: https://www.ncbi.nlm.nih.gov/pubmed/8477681.

[110] Y. Ye and M. J. Griffin, "Reductions in finger blood flow induced by 125-Hz vibration: effect of location of contact with vibration," (in eng), *Int Arch Occup Environ Health,* vol. 89, no. 3, pp. 425-33, Apr 2016, doi: 10.1007/s00420-015-1081-7: 10.1007/s00420-015-1081-7. Epub 2015 Aug 5.

[111] K. Wilke, A. Martin, L. Terstegen, and S. S. Biel, "A short history of sweat gland biology," (in eng), *Int J Cosmet Sci,* vol. 29, no. 3, pp. 169-79, Jun 2007, doi: 10.1111/j.1467-2494.2007.00387.x.

[112] K. Leijon-Sundqvist, Y. Tegner, F. Olsson, K. Karp, and N. Lehto, "Relation between dorsal and palmar hand skin temperatures during a cold stress test," *Journal of Thermal Biology,* vol. 66, pp. 87-92, 2017/05/01/ 2017, doi: https://doi.org/10.1016/j.jtherbio.2017.04.003.

[113] M. Bovenzi, C. J. Lindsell, and M. J. Griffin, "Acute vascular responses to the frequency of vibration transmitted to the hand," *Occupational and environmental medicine,* vol. 57, no. 6, pp. 422-430, 2000.

[114] M. Bovenzi, C. J. Lindsell, and M. J. Griffin, "Response of finger circulation to energy equivalent combinations of magnitude and duration of vibration," (in eng), *Occup Environ Med,* vol. 58, no. 3, pp. 185-93, Mar 2001, doi: 10.1136/oem.58.3.185: 10.1136/oem.58.3.185.

[115] M. Widia and S. Z. M. Dawal, "The effect of hand-held vibrating tools on muscle activity and grip strength," *Australian Journal of Basic and Applied Sciences,* vol. 5, no. 11, pp. 198-211, 2011.

[116] M. Bovenzi, "Health effects of mechanical vibration," *G Ital Med Lav Ergon,* vol. 27, no. 1, pp. 58-64, 2005.

[117] M. Bovenzi, A. Zadini, A. Franzinelli, and F. Borgogni, "Occupational musculoskeletal disorders in the neck and upper limbs of forestry workers exposed to hand-arm vibration," *Ergonomics,* vol. 34, no. 5, pp. 547-562, 1991/05/01 1991, doi: 10.1080/00140139108967336.

[118] L. E. Necking, G. Lundborg, and J. Friden, "Hand muscle weakness in long-term vibration exposure," (in eng), *J Hand Surg Br,* vol. 27, no. 6, pp. 520-5, Dec 2002, doi: 10.1054/jhsb.2002.0810.

[119] M. Bovenzi, A. Prodi, and M. Mauro, "Relationships of neurosensory disorders and reduced work ability to alternative frequency weightings of hand-transmitted vibration," *Scand J Work Environ Health,* Article vol. 41, no. 3, pp. 247-58, May 1 2015, doi: 10.5271/sjweh.3490: 10.5271/sjweh.3490. Epub 2015 Mar 16.

[120] J. Munn, R. D. Herbert, M. J. Hancock, and S. C. Gandevia, "Training with unilateral resistance exercise increases contralateral strength," *Journal of Applied Physiology,* vol. 99, no. 5, pp. 1880-1884, 2005, doi: 10.1152/japplphysiol.00559.2005.

[121] M. H. Mahbub *et al.*, "A systematic review of diagnostic performance of quantitative tests to assess musculoskeletal disorders in hand-arm vibration syndrome," (in eng), *Ind Health,* vol. 53, no. 5, pp. 391-7, 2015, doi: 10.2486/indhealth.2014-0221.

[122] N. Schäfer, "Akute Wirkungen stoßhaltiger Schwingungen auf das Hand-Arm-System," in "Humanisierung des Arbeitslebens," Karlsruhe, 1985.

[123] C. Astrom, M. Lindkvist, L. Burstrom, G. Sundelin, and J. S. Karlsson, "Changes in EMG activity in the upper trapezius muscle due to local vibration exposure," (in eng), *Journal of electromyography and kinesiology : official journal of the International Society of Electrophysiological Kinesiology,* vol. 19, no. 3, pp. 407-15, Jun 2009, doi: 10.1016/j.jelekin.2007.11.003: 10.1016/j.jelekin.2007.11.003. Epub 2007 Dec 21.

[124] D. E. Adamo, B. J. Martin, and P. W. Johnson, "Vibration-induced muscle fatigue, a possible contribution to musculoskeletal injury," *European journal of applied physiology,* vol. 88, pp. 134-140, 2002.

[125] L. Fattorini, A. Tirabasso, A. Lunghi, R. Di Giovanni, F. Sacco, and E. Marchetti, "Muscular synchronization and hand-arm fatigue," *International Journal of Industrial Ergonomics,* vol. 62, pp. 13-16, 2017.

[126] W. Rohmert, H. Wos, S. Norlander, and R. Helbig, "Effects of vibration on arm and shoulder muscles in three body postures," *European journal of applied physiology and occupational physiology,* vol. 59, pp. 243-248, 1989.

[127] J. M. Muggleton, R. Allen, and P. H. Chappell, "Hand and arm injuries associated with repetitive manual work in industry: a review of disorders, risk factors and preventive measures," (in eng), *Ergonomics,* vol. 42, no. 5, pp. 714-39, May 1999, doi: 10.1080/001401399185405.

[128] D. Ranney, R. Wells, and A. Moore, "Upper limb musculoskeletal disorders in highly repetitive industries: precise anatomical physical findings," (in eng), *Ergonomics,* vol. 38, no. 7, pp. 1408-23, Jul 1995, doi: 10.1080/00140139508925198.

[129] T. Armstrong, C. Bir, J. Foulke, B. Martin, L. Finsen, and G. Sjøgaard, "Muscle responses to simulated torque reactions of hand-held power tools," (in eng), *Ergonomics,* vol. 42, no. 1, pp. 146-59, Jan 1999, doi: 10.1080/001401399185856.

[130] C. Larivière, D. Gravel, A. B. Arsenault, D. Gagnon, and P. Loisel, "Muscle recovery from a short fatigue test and consequence on the reliability of EMG indices of fatigue," *European journal of applied physiology,* vol. 89, pp. 171-176, 2003.

[131] H.-J. Shin and J.-Y. Kim, "Measurement of trunk muscle fatigue during dynamic lifting and lowering as recovery time changes," *International journal of industrial ergonomics,* vol. 37, no. 6, pp. 545-551, 2007.

Chapter 8: Appendix

8.1 Research Collaboration and Acknowledgements

This project is part of a collaborative research effort on the impact of individual shocks on the hand-arm system. Partners include the Institute for Occupational Safety and Health of the German Social Accident Insurance (Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung e. V.) in Sankt Augustin, which provided the exposure register, hand-arm laboratory, and operational measurements; Research Institutes of Sweden AB in Mölndal, Sweden, which conducted simulations on a newly developed hand-arm model; and the Institute of Occupational Medicine, Prevention and Health Management at the University of Lübeck.

The Lübeck subproject, led by Elke Ochsmann, focuses on identifying the medical effects of repeated single-shocks on the hand-arm system and developing preventive strategies. This work represents a systematic exploration of relevant outcomes and measurement instruments for recording potential physiological effects on the hand-arm system.

We gratefully acknowledge the following individuals for their contributions: Uwe Kaulbars and Benjamin Ernst (Institute for Occupational Safety and Health of the DGUV) for supervising the setup and control of the electrodynamic shaker; Robert Wendlandt (Clinic for Orthopedics and Trauma Surgery, University Hospital Schleswig-Holstein, Lübeck Campus) for developing the script for automated EMG data evaluation; and Nicole Heßler (Institute for Medical Biometry and Statistics, University of Lübeck) for providing statistical advice.

8.2 Vote of ethics committee

UNIVERSITÄT ZU LÜBECK

Universität zu Lübeck · Ratzeburger Allee 160 · 23538 Lübeck

Frau
Prof. Dr. med. Ochsmann
Direktorin des Institutes für Arbeitsmedizin

im Hause

Elke.Ochsmann@uni-luebeck.de

Ethik-Kommission
Vorsitzender:
Herr Prof. Dr. med. Alexander Katalinic
Universität zu Lübeck
Stellv. Vorsitzender:
Herr Prof. Dr. med. Frank Gieseler
Ratzeburger Allee 160
23538 Lübeck

Sachbearbeitung: Frau Janine Erdmann
Tel.: +49 451 3101 1008
Fax: +49 451 3101 1024

ethikkommission@uni-luebeck.de

Aktenzeichen: 20-099
Datum: 08. April 2020

Sitzung der Ethik-Kommission am 02. April 2020
Antragsteller: Frau Prof. Dr. Ochsmann
Titel: Einzelstöße auf das Hand-Arm-System durch Maschinen und Werkzeuge: Expositionen, Übertragung und gesundheitliche Effekte (SSHE)

Sehr geehrte Frau Prof. Ochsmann,

der Antrag wurde unter berufsethischen, medizinisch-wissenschaftlichen und berufsrechtlichen Gesichtspunkten geprüft.

Die Kommission hat **nach der Berücksichtigung der folgenden Hinweise** keine Bedenken: Die Kommission fragt sich, warum nicht Ergebnisse aus der Pilotstudie für statistische Berechnungen (Fallzahl) verwendet wurden. Die Ethik-Kommission empfiehlt bei Weiterführung des Studienvorhabens auch die Untersuchung von Frauen.

Die allfälligen Einschränkungen des öffentlichen Lebens haben auch Auswirkungen auf eine Protokoll–konforme Durchführung von Studienvorhaben. Die Kommission erwartet von den Antragstellern, dass bei anstehenden Entscheidungen zuallererst die Sicherheit und das Wohlergehen der Studienteilnehmenden sichergestellt werden. Dies kann u.a. eine Verschiebung des Studienstarts verlangen.

Bei Änderung des Studiendesigns sollte der Antrag erneut vorgelegt werden. Über alle schwerwiegenden oder unerwarteten und unerwünschten Ereignisse, die während der Studie auftreten, ist die Kommission umgehend zu benachrichtigen.
Die Deklaration von Helsinki in der aktuellen Fassung fordert in § 35 dazu auf, jedes medizinische Forschungsvorhaben mit Menschen zu registrieren. Daher empfiehlt die Kommission grundsätzlich die Studienregistrierung in einem öffentlichen Register (z.B. unter www.drks.de).
Die ärztliche und juristische Verantwortung des Studienleiters und der an der Studie teilnehmenden Ärzte bleibt entsprechend der Beratungsfunktion der Ethikkommission durch unsere Stellungnahme unberührt.
Datenschutzrechtliche Aspekte von Forschungsvorhaben werden durch die Ethikkommission grundsätzlich nur kursorisch geprüft. Dieses Votum / diese Bewertung ersetzt mithin nicht die Konsultation des zuständigen Datenschutzbeauftragten.

Mit freundlichen Grüßen

Prof. Dr. med. Alexander Katalinic
Vorsitzender

☒ Herr Prof. Dr. Katalinic (Sozialmedizin, Vorsitzender)
☒ Hr. Prof. Dr. Gieseler (Onkologie, Stellv. Vorsitzender))
Hr. Prof. Dr. Borck (Medizingeschichte)
☒ Hr. Prof. Dr. Dr. Habermann (Humangenetik)
☒ Fr. Hendelkes (Richterin)
☒ Herr PD Dr. Hummel (Chirurgie)
☒ Frau Prof. Dr. Krämer (Neurologie)
☒ Hr. Prof. Dr. Lauten (Pädiatrie)
Frau Martini (Laiin)
Hr. Prof. Dr. Moser (Neurologie)
Hr. Petit (Richter)
☒ Hr. Prof. Dr. Raasch (Pharmakologie)
☒ Hr. Prof. Dr. Rehmann-Sutter (Medizinethik)
☒ Fr. Prof. em. Dr. Schrader (Plastische Chirurgie)
☒ Hr. PD Dr. Vonthein (Biometrie)

8.3 Tables and graphics

8.3.1 Participant Characteristics

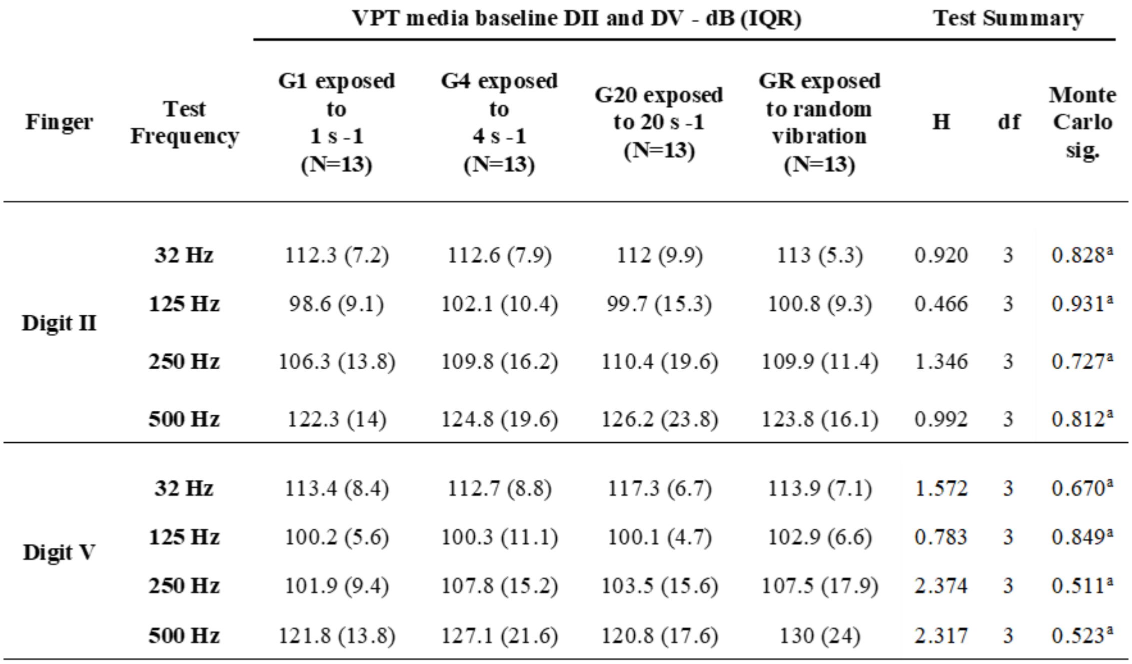
Table 8.3.1Kruskal-Wallis's test results for anthropometric measures, an body composition indices across all four exposure groups

	Groups	Median	Mean	Std Dev.	Mean Rank	H	df	p
Age	G1	24	27.0	7.6	23.1	1.83	3	0.61
	G4	32	31.2	9.7	30.2			
	G20	26	29.9	12.8	24.5			
	GR	28	29.5	7.7	28.2			
	All groups	27	29.4	9.8				
Weight (kg)	G1	81	81.4	14.7	23.9	1.78	3	0.62
	G4	85	85.9	12.0	28.2			
	G20	91	89.4	17.3	30.2			
	GR	81	82.2	11.2	23.7			
	All groups	81.5	84.7	14.4				
Height (cm)	G1	180	179.7	5.3	23.9	1.5	3	0.68
	G4	183	183.2	9.0	30.0			
	G20	180	182.5	7.9	27.9			
	GR	180	179.5	6.1	24.2			
	All groups	180	181.2	7.4				
BMI (kg/m2)	G1	24.8	25.2	4.2	25.3	0.94	3	0.81
	G4	24.3	25.8	4.9	24.9			
	G20	28.0	26.8	4.5	30.0			
	GR	24.4	25.5	2.9	25.8			
	All groups	24.6	25.8	4.2				
Wrist Circum. (cm)	G1	18	18.0	0.8	22.0	1.86	3	0.60
	G4	18	18.5	1.1	29.7			
	G20	18	18.4	1.0	27.4			
	GR	18.5	18.4	1.1	26.9			
	All groups	18	18.3	1.0				
Forearm Circum. (cm)	G1	26.0	26.2	2.8	23.8	1.94	3	0.58
	G4	26.0	26.7	2.0	25.3			
	G20	27.5	27.3	2.5	31.4			
	GR	27.0	26.3	2.3	25.5			
	All groups	26.8	26.6	2.4				
Biceps Circum. (cm)	G1	34.5	33.5	4.5	26.2	0.58	3	0.90
	G4	32	33.7	3.9	25.4			
	G20	34	34.5	5.4	29.2			
	GR	33	33.8	3.5	25.3			
	All groups	33	33.9	4.4				

8.3.2 Vibration perception threshold

Baseline vibrotactile perception thresholds for digit 2 (DII) and digit 5 (DV)

Table 8.3.2 Baseline vibrotactile perception thresholds (VPT, dB) for digits II and V at 32, 125, 250, and 500 Hz for each shaker handle group (G1: 1s-1; G4: 4s-1; G20: 20s-1; RS: random signal). Kruskal-Wallis tests with Monte Carlo correction (10,000 samples, seed = 2,000,000) were used to compare baseline VPT between groups.



		VPT media baseline DII and DV - dB (IQR)				**Test Summary**		
Finger	**Test Frequency**	**G1 exposed to 1 s -1 (N=13)**	**G4 exposed to 4 s -1 (N=13)**	**G20 exposed to 20 s -1 (N=13)**	**GR exposed to random vibration (N=13)**	**H**	**df**	**Monte Carlo sig.**
Digit II	**32 Hz**	112.3 (7.2)	112.6 (7.9)	112 (9.9)	113 (5.3)	0.920	3	0.828[a]
	125 Hz	98.6 (9.1)	102.1 (10.4)	99.7 (15.3)	100.8 (9.3)	0.466	3	0.931[a]
	250 Hz	106.3 (13.8)	109.8 (16.2)	110.4 (19.6)	109.9 (11.4)	1.346	3	0.727[a]
	500 Hz	122.3 (14)	124.8 (19.6)	126.2 (23.8)	123.8 (16.1)	0.992	3	0.812[a]
Digit V	**32 Hz**	113.4 (8.4)	112.7 (8.8)	117.3 (6.7)	113.9 (7.1)	1.572	3	0.670[a]
	125 Hz	100.2 (5.6)	100.3 (11.1)	100.1 (4.7)	102.9 (6.6)	0.783	3	0.849[a]
	250 Hz	101.9 (9.4)	107.8 (15.2)	103.5 (15.6)	107.5 (17.9)	2.374	3	0.511[a]
	500 Hz	121.8 (13.8)	127.1 (21.6)	120.8 (17.6)	130 (24)	2.317	3	0.523[a]

Vibrotactile perception thresholds for digit 2 (DII) – Friedman test

Vibration perception thresholds (VPT) across all groups and sessions (dB) – digit 2 (DII)

Group	Test Frequency	Session	Media (IQR)	Mean rank	Chi-Square	df	Monte Carlo Sig.
G1	**32 Hz**	BS	112.3 (7.2)	2.92	20.30	5.00	***<0.001**
		E1	110.8 (8.2)	3.46			
		E2	112.1 (6.7)	3.08			
		E3	112.2 (8.6)	2.62			
		E4	112.7 (7.5)	3.38			
		E5	119.5 (6.6)	5.54			
	125 Hz	BS	98.6 (9.1)	2.00	33.62	5.00	***<0.001**
		E1	97.7 (8.4)	3.08			
		E2	98.5 (7.6)	3.00			
		E3	99.2 (10.4)	3.00			
		E4	100.3 (9.5)	4.00			
		E5	109.5 (6.8)	5.92			
	250 Hz	BS	106.3 (13.8)	2.54	38.63	5.00	***<0.001**
		E1	104.2 (14)	2.00			
		E2	104.3 (16.9)	2.69			
		E3	107.9 (17.4)	3.77			
		E4	110.6 (15.7)	4.00			
		E5	121.8 (13.3)	6.00			
	500 Hz	BS	122.3 (14)	2.42	36.95	5.00	***<0.001**
		E1	119.8 (13.8)	2.04			
		E2	123.6 (22)	2.81			
		E3	125.9 (22.4)	3.73			
		E4	130.1 (19.8)	4.35			
		E5	138.3 (13.8)	5.65			
G4	**32 Hz**	BS	112.6 (7.9)	2.38	21.04	5.00	***<.001**
		E1	115.8 (7.3)	2.46			
		E2	115.8 (7.5)	3.54			
		E3	114.2 (8.9)	3.54			
		E4	117.6 (8.4)	3.77			
		E5	121.1 (7.2)	5.31			
	125 Hz	BS	102.1 (10.4)	1.92	40.12	5.00	***0.000**
		E1	105.9 (11.4)	2.31			
		E2	106.7 (8.8)	2.62			

		E3	109.2 (8)	4.15			
		E4	106.1 (8.2)	4.23			
		E5	113.5 (12)	5.77			
	250 Hz	BS	109.8 (16.2)	1.46	41.84	5.00	***0.000**
		E1	115.1 (11.1)	2.54			
		E2	118.3 (17.2)	3.00			
		E3	120.4 (14.8)	4.00			
		E4	122.2 (9.9)	4.23			
		E5	126.4 (12.2)	5.77			
	500 Hz	BS	124.8 (19.6)	1.31	38.67	5.00	***0.000**
		E1	135 (10.6)	2.85			
		E2	135.6 (11.9)	3.15			
		E3	137.4 (22.1)	4.00			
		E4	138.6 (15.4)	4.08			
		E5	143.9 (14.9)	5.62			
G20	**32 Hz**	BS	112 (9.9)	1.46	34.49	5.00	***0.000**
		E1	113.6 (9.3)	2.46			
		E2	115.6 (8.5)	3.62			
		E3	118.3 (7.3)	3.85			
		E4	116.7 (12.1)	4.31			
		E5	118.5 (10.8)	5.31			
	125 Hz	BS	99.7 (15.3)	1.69	26.23	5.00	***0.000**
		E1	109 (17.3)	3.15			
		E2	108 (16.4)	3.23			
		E3	110 (17.9)	3.54			
		E4	108.4 (20)	4.08			
		E5	112.8 (17)	5.31			
	250 Hz	BS	110.4 (19.6)	1.15	39.33	5.00	***0.000**
		E1	117.5 (24.1)	2.85			
		E2	114.5 (23.2)	3.54			
		E3	116.5 (23.9)	3.77			
		E4	120.4 (24.4)	4.15			
		E5	122.4 (30.3)	5.54			
	500 Hz	BS	126.2 (23.8)	1.46	31.20	5.00	***0.000**
		E1	134.7 (22.7)	2.85			
		E2	136 (22.4)	3.62			
		E3	137.9 (25.8)	3.77			
		E4	140.2 (29.1)	3.92			
		E5	141.5 (26.9)	5.38			
GR	**32 Hz**	BS	113 (5.3)	1.46	28.03	5.00	***0.000**

		E1	119.3 (11.1)	2.85			
		E2	124.3 (12.1)	4.69			
		E3	120.4 (6.2)	3.46			
		E4	122.7 (11)	4.69			
		E5	120.9 (7.5)	3.85			
	125 Hz	BS	100.8 (9.3)	1.31	25.97	5.00	***0.000**
		E1	111.7 (9.5)	3.08			
		E2	110.9 (15.8)	3.92			
		E3	112.9 (9.9)	4.00			
		E4	113.5 (12)	4.62			
		E5	110.3 (11.8)	4.08			
	250 Hz	BS	109.9 (11.4)	1.00	43.11	5.00	***0.000**
		E1	118.5 (13.5)	2.77			
		E2	122.6 (14.8)	3.42			
		E3	122.2 (13)	3.73			
		E4	125.9 (11.5)	5.08			
		E5	121.1 (10.5)	5.00			
	500 Hz	BS	123.8 (16.1)	1.23	32.16	5.00	***0.000**
		E1	137.6 (14)	3.08			
		E2	137.5 (14.1)	3.62			
		E3	137.5 (17.4)	3.54			
		E4	137.6 (11.9)	4.58			
		E5	138.1 (11.2)	4.96			

Vibrotactile perception thresholds for digit 5 (DII) – Friedman test

Table 8.3.3 All vibration perception thresholds (VPT) across all groups and sessions (dB) – digit 2 (DII). At 32, 125, 250, and 500 Hz for each shaker handle group (G1: 1s-1; G4: 4s-1; G20: 20s-1; RS: random signal). Friedman test

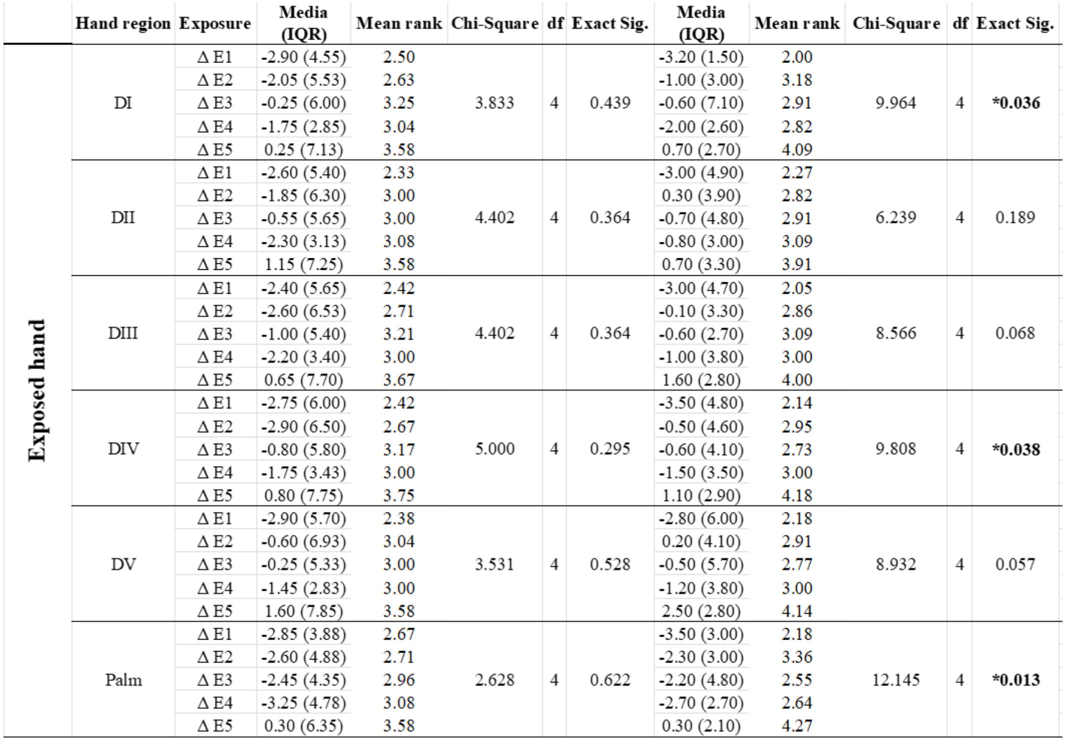
Vibration perception thresholds (VPT) across all groups and sessions (dB) – digit 5 (DV)							
	Test Frequency	**Session**	**Media (IQR)**	**Mean rank**	**Chi-Square**	**df**	**Monte Carlo Sig.**
G1	**32 Hz**	BS	113.4 (8.4)	1.77	31.066	5	*0.000
		E1	114.2 (8.1)	2.77			
		E2	117 (7.7)	3.85			
		E3	113.1 (9.1)	2.92			
		E4	116.1 (6.9)	4.23			
		E5	119.1 (7.5)	5.46			
	125 Hz	BS	100.2 (5.6)	2.85	28.780	5	*0.000
		E1	100 (5.6)	2.31			
		E2	101.8 (4.6)	3.23			
		E3	100.8 (9.1)	2.85			
		E4	102.4 (6.7)	4.00			
		E5	110.1 (9.3)	5.77			
	250 Hz	BS	101.9 (9.4)	1.62	43.857	5	*0.000
		E1	103.4 (11.8)	2.31			
		E2	105.4 (14.1)	3.00			
		E3	104.6 (17.8)	3.92			
		E4	108.3 (13.3)	4.23			
		E5	119.8 (11.1)	5.92			
	500 Hz	BS	118.1 (13.8)	1.96	41.476	5	*0.000
		E1	120.9 (19.8)	2.19			
		E2	120 (22.8)	2.73			
		E3	128.3 (24.5)	3.81			
		E4	131.7 (25.3)	4.96			
		E5	138.6 (44.8)	5.35			
G4	**32 Hz**	BS	112.7 (8.8)	2.15	19.780	5	*0.000
		E1	118 (7.6)	3.46			
		E2	119 (11.4)	3.04			
		E3	116.8 (6.8)	3.62			

		E4	117.4 (5.3)	3.42			
		E5	122.4 (6.7)	5.31			
	125 Hz	BS	100.3 (11.1)	2.15	28.648	5	*0.000
		E1	101.9 (13.4)	2.46			
		E2	106.7 (14.5)	3.54			
		E3	103.8 (15.8)	3.62			
		E4	104.5 (18.3)	3.54			
		E5	111.9 (14.1)	5.69			
	250 Hz	BS	107.8 (15.2)	1.85	37.747	5	*0.000
		E1	114.4 (14.3)	2.38			
		E2	116.2 (20.9)	3.08			
		E3	117.2 (21)	3.31			
		E4	120.4 (26.3)	4.85			
		E5	125.4 (13.5)	5.54			
	500 Hz	BS	127.1 (21.6)	1.69	34.758	5	*0.000
		E1	133.6 (19.9)	2.85			
		E2	137.6 (21.4)	2.62			
		E3	139.1 (23.3)	4.00			
		E4	140.4 (21.7)	4.38			
		E5	148.2 (14.7)	5.46			
G20	**32 Hz**	BS	117.3 (6.7)	2.54	9.088	5	0.106
		E1	118.6 (9.7)	3.85			
		E2	118.1 (9.1)	3.23			
		E3	119.7 (11)	3.77			
		E4	118.1 (8.8)	3.08			
		E5	119.6 (7.4)	4.54			
	125 Hz	BS	100.1 (4.7)	2.08	24.385	5	*0.000
		E1	106.1 (14)	2.77			
		E2	107.5 (17.7)	3.85			
		E3	104.9 (14.6)	3.31			
		E4	106.9 (14.5)	3.54			
		E5	111.7 (13.9)	5.46			
	250 Hz	BS	103.5 (15.6)	1.31	37.747	5	*0.000
		E1	120 (16.8)	3.23			
		E2	116.1 (18.1)	3.46			
		E3	116.9 (22)	3.38			
		E4	117.9 (21.6)	3.85			
		E5	119.6 (20.6)	5.77			
	500 Hz	BS	120.8 (17.6)	1.35	37.269	5	*0.000

		E1	133.1 (22.1)	2.92			
		E2	130.4 (21.8)	3.38			
		E3	129.3 (22.2)	3.77			
		E4	136.6 (24.2)	3.88			
		E5	134.1 (25.2)	5.69			
GR	**32 Hz**	BS	113.9 (7.1)	1.62	25.615	5	*0.000
		E1	119.3 (10.8)	3.00			
		E2	119.5 (9.2)	3.23			
		E3	121.6 (8.6)	4.31			
		E4	123.1 (8.9)	5.00			
		E5	121.9 (8.5)	3.85			
	125 Hz	BS	102.9 (6.6)	1.08	27.637	5	*0.000
		E1	111.1 (16.6)	3.54			
		E2	114.3 (13)	3.92			
		E3	114 (10.8)	4.38			
		E4	112.3 (9.8)	3.92			
		E5	110.1 (14.8)	4.15			
	250 Hz	BS	107.5 (17.9)	1.00	35.286	5	*0.000
		E1	121.9 (23)	3.54			
		E2	119.2 (23.9)	3.31			
		E3	118.2 (24.7)	3.69			
		E4	120.9 (24.2)	4.46			
		E5	121.9 (20.4)	5.00			
	500 Hz	BS	128.5 (21)	1.00	37.488	5	*0.000
		E1	137.1 (18.8)	3.00			
		E2	135.5 (18.1)	3.29			
		E3	133.2 (19.4)	4.04			
		E4	137.5 (19.1)	4.46			
		E5	138.3 (21.8)	5.21			

8.3.3 Temperature reaction

Table 8.3.4 Palmar skin temperature changes (ΔT) were analyzed on the exposed hand across all exposure measurements and groups using the Friedman test. Extract from main table

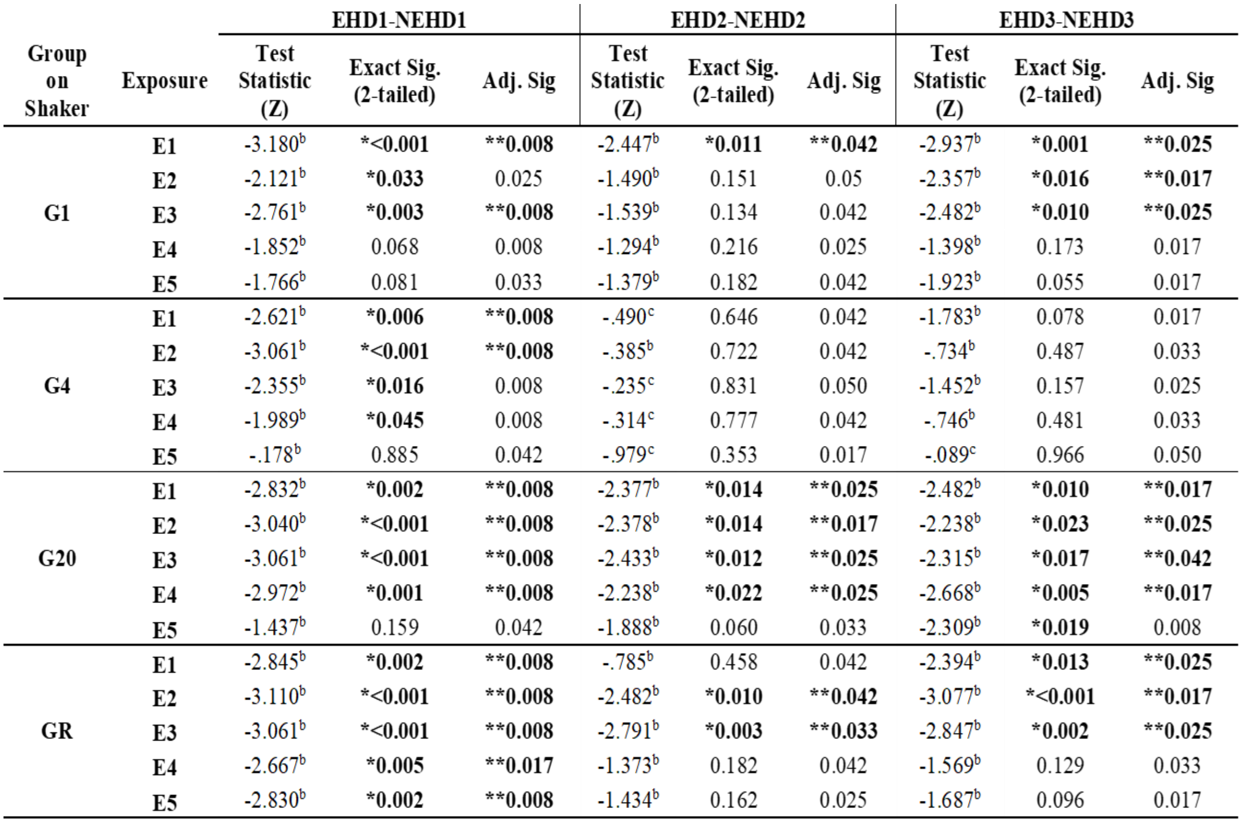


	Hand region	Exposure	Media (IQR)	Mean rank	Chi-Square	df	Exact Sig.	Media (IQR)	Mean rank	Chi-Square	df	Exact Sig.
Exposed hand	DI	Δ E1	-2.90 (4.55)	2.50	3.833	4	0.439	-3.20 (1.50)	2.00	9.964	4	***0.036**
		Δ E2	-2.05 (5.53)	2.63				-1.00 (3.00)	3.18			
		Δ E3	-0.25 (6.00)	3.25				-0.60 (7.10)	2.91			
		Δ E4	-1.75 (2.85)	3.04				-2.00 (2.60)	2.82			
		Δ E5	0.25 (7.13)	3.58				0.70 (2.70)	4.09			
	DII	Δ E1	-2.60 (5.40)	2.33	4.402	4	0.364	-3.00 (4.90)	2.27	6.239	4	0.189
		Δ E2	-1.85 (6.30)	3.00				0.30 (3.90)	2.82			
		Δ E3	-0.55 (5.65)	3.00				-0.70 (4.80)	2.91			
		Δ E4	-2.30 (3.13)	3.08				-0.80 (3.00)	3.09			
		Δ E5	1.15 (7.25)	3.58				0.70 (3.30)	3.91			
	DIII	Δ E1	-2.40 (5.65)	2.42	4.402	4	0.364	-3.00 (4.70)	2.05	8.566	4	0.068
		Δ E2	-2.60 (6.53)	2.71				-0.10 (3.30)	2.86			
		Δ E3	-1.00 (5.40)	3.21				-0.60 (2.70)	3.09			
		Δ E4	-2.20 (3.40)	3.00				-1.00 (3.80)	3.00			
		Δ E5	0.65 (7.70)	3.67				1.60 (2.80)	4.00			
	DIV	Δ E1	-2.75 (6.00)	2.42	5.000	4	0.295	-3.50 (4.80)	2.14	9.808	4	***0.038**
		Δ E2	-2.90 (6.50)	2.67				-0.50 (4.60)	2.95			
		Δ E3	-0.80 (5.80)	3.17				-0.60 (4.10)	2.73			
		Δ E4	-1.75 (3.43)	3.00				-1.50 (3.50)	3.00			
		Δ E5	0.80 (7.75)	3.75				1.10 (2.90)	4.18			
	DV	Δ E1	-2.90 (5.70)	2.38	3.531	4	0.528	-2.80 (6.00)	2.18	8.932	4	0.057
		Δ E2	-0.60 (6.93)	3.04				0.20 (4.10)	2.91			
		Δ E3	-0.25 (5.33)	3.00				-0.50 (5.70)	2.77			
		Δ E4	-1.45 (2.83)	3.00				-1.20 (3.80)	3.00			
		Δ E5	1.60 (7.85)	3.58				2.50 (2.80)	4.14			
	Palm	Δ E1	-2.85 (3.88)	2.67	2.628	4	0.622	-3.50 (3.00)	2.18	12.145	4	***0.013**
		Δ E2	-2.60 (4.88)	2.71				-2.30 (3.00)	3.36			
		Δ E3	-2.45 (4.35)	2.96				-2.20 (4.80)	2.55			
		Δ E4	-3.25 (4.78)	3.08				-2.70 (2.70)	2.64			
		Δ E5	0.30 (6.35)	3.58				0.30 (2.10)	4.27			

			G20 (exposed to 20s^{1})					**GR (exposed to random signal)**				
	Hand region	**Exposure**	**Media (IQR)**	**Mean rank**	**Chi-Square**	**df**	**Exact Sig.**	**Media (IQR)**	**Mean rank**	**Chi-Square**	**df**	**Exact Sig.**
Exposed hand	DI	Δ E1	-2.80 (4.50)	3.27	10.110	4	***0.033**	-4.20 (6.80)	2.73	6.886	4	0.141
		Δ E2	-2.50 (4.70)	2.82				-3.70 (1.80)	2.09			
		Δ E3	-2.40 (5.30)	2.64				-2.50 (1.60)	3.05			
		Δ E4	-4.60 (2.20)	2.14				-1.70 (5.10)	3.50			
		Δ E5	0.90 (4.20)	4.14				-0.60 (7.50)	3.64			
	DII	Δ E1	-2.70 (4.00)	2.86	8.493	4	0.070	-2.60 (6.40)	3.00	2.691	4	0.633
		Δ E2	-3.00 (3.30)	2.95				-3.20 (4.20)	2.55			
		Δ E3	-3.90 (5.60)	2.55				-2.10 (2.30)	2.73			
		Δ E4	-3.70 (3.60)	2.45				-1.70 (5.20)	3.18			
		Δ E5	0.60 (2.50)	4.18				-0.50 (6.70)	3.55			
	DIII	Δ E1	-3.60 (3.70)	2.95	8.532	4	0.069	-3.20 (6.20)	2.82	2.982	4	0.581
		Δ E2	-3.20 (5.70)	2.86				-4.00 (2.40)	2.36			
		Δ E3	-3.70 (4.00)	2.45				-2.00 (3.10)	3.27			
		Δ E4	-3.60 (5.50)	2.55				-2.00 (4.90)	3.18			
		Δ E5	0.30 (3.10)	4.18				-1.00 (7.40)	3.36			
	DIV	Δ E1	-1.90 (4.30)	3.00	11.564	4	***0.016**	-3.50 (6.70)	2.73	4.509	4	0.352
		Δ E2	-3.10 (5.60)	2.55				-3.10 (2.80)	2.36			
		Δ E3	-3.00 (4.60)	2.82				-2.70 (3.80)	3.09			
		Δ E4	-4.70 (3.60)	2.27				-2.40 (4.60)	3.09			
		Δ E5	1.20 (2.70)	4.36				-0.30 (8.60)	3.73			
	DV	Δ E1	-1.60 (3.50)	3.00	9.818	4	***0.039**	-3.20 (5.40)	2.82	2.275	4	0.760
		Δ E2	-2.40 (6.80)	3.09				-3.50 (3.30)	2.55			
		Δ E3	-4.60 (4.80)	2.27				-2.30 (5.00)	3.36			
		Δ E4	-3.60 (2.60)	2.45				-1.70 (3.70)	2.91			
		Δ E5	1.80 (4.50)	4.18				0.50 (8.10)	3.36			
	Palm	Δ E1	-3.40 (5.50)	3.73	16.945	4	***0.001**	-3.40 (6.60)	3.09	4.202	4	0.388
		Δ E2	-3.00 (3.50)	2.82				-4.30 (3.00)	2.18			
		Δ E3	-3.50 (4.10)	2.18				-2.90 (3.60)	3.32			
		Δ E4	-4.70 (2.20)	2.00				-2.40 (4.50)	3.00			
		Δ E5	-0.30 (3.10)	4.27				-0.70 (6.60)	3.41			

Comparing Dorsum of Exposed vs. Dorsum of Non-Exposed Hand

Table 8.3.5 Delta temperature (°C) responses in the dorsal region of the exposed and non-exposed hands after repeated exposures (E1-E5) to vibration. Wilcoxon signed-rank tests were used to compare temperature changes between exposed (EHD) and non-exposed (NEHD) digits I-III for each exposure group (G1: 1s^{-1}*; G4: 4s*$^{-1}$*; G20: 20s*$^{-1}$*; GR: random vibration). Exact p-values (two-tailed) are reported with Benjamini-Hochberg correction for multiple comparisons. * $p < 0.05$, ** $p < 0.05$ after correction, .b. Based on negative ranks, c. Based on positive ranks. Extract from main table.*



		EHD1-NEHD1			EHD2-NEHD2			EHD3-NEHD3		
Group on Shaker	Exposure	Test Statistic (Z)	Exact Sig. (2-tailed)	Adj. Sig	Test Statistic (Z)	Exact Sig. (2-tailed)	Adj. Sig	Test Statistic (Z)	Exact Sig. (2-tailed)	Adj. Sig
G1	E1	-3.180^{b}	*<0.001	**0.008	-2.447^{b}	*0.011	**0.042	-2.937^{b}	*0.001	**0.025
	E2	-2.121^{b}	*0.033	0.025	-1.490^{b}	0.151	0.05	-2.357^{b}	*0.016	**0.017
	E3	-2.761^{b}	*0.003	**0.008	-1.539^{b}	0.134	0.042	-2.482^{b}	*0.010	**0.025
	E4	-1.852^{b}	0.068	0.008	-1.294^{b}	0.216	0.025	-1.398^{b}	0.173	0.017
	E5	-1.766^{b}	0.081	0.033	-1.379^{b}	0.182	0.042	-1.923^{b}	0.055	0.017
G4	E1	-2.621^{b}	*0.006	**0.008	-.490^{c}	0.646	0.042	-1.783^{b}	0.078	0.017
	E2	-3.061^{b}	*<0.001	**0.008	-.385^{b}	0.722	0.042	-.734^{b}	0.487	0.033
	E3	-2.355^{b}	*0.016	0.008	-.235^{c}	0.831	0.050	-1.452^{b}	0.157	0.025
	E4	-1.989^{b}	*0.045	0.008	-.314^{c}	0.777	0.042	-.746^{b}	0.481	0.033
	E5	-.178^{b}	0.885	0.042	-.979^{c}	0.353	0.017	-.089^{c}	0.966	0.050
G20	E1	-2.832^{b}	*0.002	**0.008	-2.377^{b}	*0.014	**0.025	-2.482^{b}	*0.010	**0.017
	E2	-3.040^{b}	*<0.001	**0.008	-2.378^{b}	*0.014	**0.017	-2.238^{b}	*0.023	**0.025
	E3	-3.061^{b}	*<0.001	**0.008	-2.433^{b}	*0.012	**0.025	-2.315^{b}	*0.017	**0.042
	E4	-2.972^{b}	*0.001	**0.008	-2.238^{b}	*0.022	**0.025	-2.668^{b}	*0.005	**0.017
	E5	-1.437^{b}	0.159	0.042	-1.888^{b}	0.060	0.033	-2.309^{b}	*0.019	0.008
GR	E1	-2.845^{b}	*0.002	**0.008	-.785^{b}	0.458	0.042	-2.394^{b}	*0.013	**0.025
	E2	-3.110^{b}	*<0.001	**0.008	-2.482^{b}	*0.010	**0.042	-3.077^{b}	*<0.001	**0.017
	E3	-3.061^{b}	*<0.001	**0.008	-2.791^{b}	*0.003	**0.033	-2.847^{b}	*0.002	**0.025
	E4	-2.667^{b}	*0.005	**0.017	-1.373^{b}	0.182	0.042	-1.569^{b}	0.129	0.033
	E5	-2.830^{b}	*0.002	**0.008	-1.434^{b}	0.162	0.025	-1.687^{b}	0.096	0.017

Comparing Palm of Exposed vs. Palm of Non-Exposed Hand, Delta-Temperature reaction

*Table 8.3.6 Delta temperature (°C) responses in the palmar region of the exposed and non-exposed hands after repeated exposures (E1-E5) to vibration. Wilcoxon signed-rank tests were used to compare temperature changes between exposed (EHD) and non-exposed (NEHD) digits II-III and palms (EH and NEH) for each exposure group (G1: $1s^{-1}$; G4: $4s^{-1}$; G20: $20s^{-1}$; GR: random vibration). Exact p-values (two-tailed) are reported with Benjamini-Hochberg correction for multiple comparisons. * $p < 0.05$, ** $p < 0.05$ after correction. Extract from main table.*

Group on Shaker	Exposure	EHD2-NEHD2		EHD3-NEHD3		EH-NEH	
		Test Statistic (Z)	Exact Sig. (2-tailed)	Test Statistic (Z)	Exact Sig. (2-tailed)	Test Statistic (Z)	Exact Sig. (2-tailed)
G1	E1	-3.008[b]	*<0.001	-2.691[b]	*0.004	-3.115[b]	*<0.001
	E2	-2.432[b]	*0.012	-3.062[b]	*<0.001	-3.062[b]	*<0.001
	E3	-1.503[b]	0.146	-2.353[b]	*0.016	-2.482[b]	*0.010
	E4	-1.713[b]	0.090	-2.098[b]	*0.033	-2.272[b]	*0.021
	E5	-1.569[b]	0.129	-1.766[b]	0.080	-2.237[b]	*0.022
G4	E1	-1.818[b]	0.071	-2.170[b]	*0.027	-2.971[b]	*0.001
	E2	-1.083[b]	0.305	-2.238[b]	*0.023	-3.184[b]	*<0.001
	E3	-.353[c]	0.747	-.432[b]	0.692	-3.061[b]	*<0.001
	E4	-.353[c]	0.749	-.393[b]	0.733	-3.061[b]	*<0.001
	E5	-.903[c]	0.388	-1.179[c]	0.265	-1.452[b]	0.157
G20	E1	-2.237[b]	*0.022	-2.667[b]	*0.005	-2.167[b]	*0.028
	E2	-2.727[b]	*0.004	-2.765[b]	*0.003	-3.186[b]	*<0.001
	E3	-2.535[b]	*0.008	-2.580[b]	*0.007	-2.936[b]	*<0.001
	E4	-2.490[b]	*0.010	-2.727[b]	*0.004	-3.181[b]	*<0.001
	E5	-2.413[b]	*0.012	-2.590[b]	*0.007	-3.078[b]	*<0.001
GR	E1	-1.608[b]	0.114	-1.992[b]	*0.048	-3.183[b]	*<0.001
	E2	-2.551[b]	*0.008	-2.691[b]	*0.005	-3.113[b]	*<0.001
	E3	-2.864[b]	*0.002	-2.237[b]	*0.022	-3.062[b]	*<0.001
	E4	-1.570[b]	0.125	-2.354[b]	*0.016	-3.061[b]	*<0.001
	E5	-1.679[b]	0.098	-1.888[b]	0.061	-2.447[b]	0.011

Dorsal vs. Palmar Delta-temperature difference of exposed hand

*Table 8.3.7 Delta temperature (°C) differences between the dorsal and palmar regions of the exposed hand after repeated exposures (E1-E5). Wilcoxon signed-rank tests were used to compare temperature changes between dorsal (DD) and palmar (PD) regions for each digit (I-II) and the entire hand region (DHR vs. PHR) for each exposure group (G1: $1s^{-1}$; G4: $4s^{-1}$; G20: $20s^{-1}$; GR: random vibration). Exact p-values (two-tailed) are reported with Benjamini-Hochberg correction for multiple comparisons. * $p < 0.05$, ** $p < 0.05$ after correction. b. Based on negative ranks; c. Based on positive ranks. Extract from main table.*

Group on Shaker	Exposure	DD1 - PD1			DD2 - PD2			DHR - PHR		
		Z	Exact Sig. (2-tailed)	Adj. Sig	Z	Exact Sig. (2-tailed)	Adj. Sig	Z	Exact Sig. (2-tailed)	Adj. Sig
G1	E1	-3.040^{b}	*<0.001	**0.008	-1.712^{b}	0.094	0.033	-2.277^{c}	*0.021	0.017
	E2	-1.530^{b}	0.135	0.017	$-.039^{c}$	0.981	0.050	-3.062^{c}	*<0.001	**0.008
	E3	-2.905^{b}	*0.002	**0.008	-1.298^{b}	0.208	0.033	-2.275^{c}	*0.020	0.017
	E4	-1.823^{b}	0.070	0.017	$-.035^{b}$	0.988	0.050	-2.482^{c}	*0.010	0.008
	E5	$-.314^{b}$	0.776	0.033	$-.089^{b}$	0.967	0.042	$-.393^{d}$	0.723	0.025
G4	E1	$-.824^{b}$	0.437	0.017	$-.157^{b}$	0.896	0.042	-2.656^{c}	*0.005	**0.008
	E2	-1.328^{b}	0.197	0.017	$-.628^{b}$	0.555	0.033	-2.747^{c}	*0.003	**0.008
	E3	-1.646^{b}	0.106	0.042	-1.886^{b}	0.061	0.033	-2.746^{c}	*0.003	**0.008
	E4	$-.746^{b}$	0.481	0.050	-2.403^{b}	*0.016	**0.017	-3.061^{c}	*<0.001	**0.008
	E5	$-.178^{b}$	0.898	0.050	$-.578^{b}$	0.599	0.042	-2.712^{b}	*0.004	**0.008
G20	E1	-1.992^{b}	0.046	0.008	$-.315^{c}$	0.786	0.050	-1.853^{c}	0.065	0.017
	E2	-2.621^{b}	*0.006	**0.017	$-.666^{b}$	0.539	0.033	-2.971^{c}	*0.001	**0.008
	E3	-2.536^{b}	*0.008	**0.008	-1.175^{b}	0.273	0.033	-1.867^{d}	0.067	0.017
	E4	$-.550^{b}$	0.610	0.033	$-.595^{c}$	0.576	0.017	-2.902^{c}	*0.001	**0.008
	E5	$-.471^{b}$	0.664	0.025	$-.350^{b}$	0.744	0.033	-2.937^{b}	*0.001	**0.008
GR	E1	-1.778^{b}	0.083	0.025	$-.668^{b}$	0.533	0.033	-2.625^{c}	*0.006	**0.008
	E2	-2.482^{b}	*0.010	**0.017	-1.434^{b}	0.162	0.025	-2.830^{c}	*0.002	**0.008
	E3	-3.061^{b}	*<0.001	**0.008	$-.904^{b}$	0.390	0.050	-2.982^{c}	*<0.001	**0.017
	E4	-2.353^{b}	*0.016	**0.017	-1.413^{b}	0.169	0.025	-3.059^{c}	*<0.001	**0.008
	E5	-2.098^{b}	*0.034	0.008	-2.064^{b}	*0.038	0.017	-1.538^{c}	0.132	0.025

8.3.4 Grip strength and pinch strength

Hand grip strength (kg) at baseline (BS) and after the fourth exposure (Post E4)

Table 8.3.8 Hand grip strength (kg) at baseline (BS) and after the fourth exposure (Post E4) to vibration. Wilcoxon signed-rank tests were used to compare grip strength before and after exposure for each group (G1: 1s^{-1}; G4: 4s^{-1}; G20: 20s^{-1}; GR: random vibration). Exact p-values (two-tailed) are reported.

	Hand grip strength comparison baseline vs post 4th exposure				Test Summary	
Groups	**Hand**	**Exposure**	**Median (IQR)**	**Min – Max**	**Z value**	**p**
G1	**Exposed**	BS	41.9 (18.15)	19.6 – 58	-2.981	***0.003**
		Post E4	38.5 (14.2)	18.2 – 57		
	Non-Exposed	BS	36.1 (17.65)	20 – 52.9	-1.824	0.068
		Post E4	39.2 (17.65)	18.3 – 56.5		
G4	**Exposed**	BS	42.2 (23.25)	17.4 – 57.1	-0.035	1.000
		Post E4	41.8 (18.00)	16.8 – 55.4		
	Non-Exposed	BS	40.5 (18.55)	17.7 – 57.6	-0.245	0.839
		Post E4	42 (17.0)	16.9 – 51.6		
G20	**Exposed**	BS	44 (14.55)	28.1 – 64.4	-0.245	0.839
		Post E4	42.1 (16.1)	27.2 – 66		
	Non-Exposed	BS	38.8 (15.30)	27.8 – 58.9	-1.153	0.273
		Post E4	39.4 (13.35)	26.6 – 58.2		
GR	**Exposed**	BS	46.6 (5.3)	23.2 – 56.6	-0.105	0.946
		Post E4	45.7 (12.20)	22.3 – 58.4		
	Non-Exposed	BS	41.1 (12.15)	22.6 – 50.5	-2.342	***0.017**
		Post E4	45.6 (9.10)	21.8 – 53.4		

Hand grip strength – group comparison

Table 8.3.9 Comparison of grip strength (kg) between exposure groups (G1: 1s^{-1}; G4: 4s^{-1}; G20: 20s^{-1}; GR: random vibration) at baseline and after the fourth exposure. Kruskal-Wallis tests with Monte Carlo correction were used to compare grip strength between groups. p-values were calculated based on 10000 sampled tables with starting seed 2000000 b Based on 10000 sampled tables with starting seed 926214481

					Test Summary			
Hand	**Session**	**Groups**	**Median (IQR)**	**Min - Max**	**Mean Rank**	**df**	**X**	**p**
Exposed	**Baseline**	G1	44.4 (18.5)	32.1 - 57.5	22.50	2.90	3	.413[a]
		G4	44.43 (9.0)	28.9 - 55.6	21.35			
		G20	43.2 (15.3)	31.6 - 65.1	19.75			
		GR	47.2 (5.03)	44.0 - 56.6	28.59			
	Post 4th Exposure	G1	39.8 (16.6)	30.8 - 57.5	19.17	3.45	3	.331[a]
		G4	45.4 (9.1)	33.3 - 57.2	21.35			
		G20	44.3 (17.2)	30.9 - 66.2	22.75			
		GR	48.4 (10.0)	39.5 - 58.3	28.95			
Non-Exposed	**Baseline**	G1	38.3 (15.7)	21.6 - 57.6	20.25	1.15	3	.773[b]
		G4	41.1 (9.7)	30.6 - 56.3	24.30			
		G20	38.7 (15.0)	30.8 - 57.6	22.17			
		GR	42.6 (8.8)	34.0 - 49.3	25.73			
	Post 4th Exposure	G1	39.7 (17.4)	27.8 - 56.8	19.58	2.97	3	.407[b]
		G4	43.4 (11.4)	33.8 - 50.5	22.45			
		G20	39.4 (12.9)	33.4 - 56.8	21.71			
		GR	46.47 (6.3)	38.0 - 53.7	28.64			

Pinch strength - Maneuver 1

Table 8.3.10 Maneuver 1 - Key/lateral pinch strength (kg) at baseline (BS) and after the fourth exposure (Post E4) to vibration. Wilcoxon signed-rank tests were used to compare pinch strength before and after exposure for each group (G1: $1s^{-1}$; G4: $4s^{-1}$; G20: $20s^{-1}$; GR: random vibration). Exact p-values (two-tailed) are reported.

	Maneuver 1 strength comparison baseline vs post 4th exposure				Test Summary	
Groups	**Hand**	**Exposure**	**Median (IQR)**	**Min – Max**	**Z value**	**p**
G1	**Exposed**	BS	10 (2.75)	7.5 – 12.5	-1.095	0.274
		Post E4	9.5 (2.5)	7 – 12.5		
	Non-Exposed	BS	9.5 (1.5)	7 – 12	-0.979	0.327
		Post E4	9 (2.25)	6.5 – 12.5		
G4	**Exposed**	BS	10.5 (3.5)	8.5 – 12	-1.724	0.085
		Post E4	10 (2)	8 – 12.5		
	Non-Exposed	BS	10 (2.5)	7 – 12.5	-1.393	0.163
		Post E4	10 (2.75)	8 – 12.5		
G20	**Exposed**	BS	10.5 (3)	5.5 – 15	-2.365	***0.018**
		Post E4	9.5 (2.75)	5.5 – 14		
	Non-Exposed	BS	10 (3.75)	7.5 – 13.5	-0.181	0.856
		Post E4	9.5 (3.50)	7 – 13.5		
GR	**Exposed**	BS	10 (3.00)	7 – 13.5	-1.549	0.121
		Post E4	9.5 (3.50)	7 – 12.5		
	Non-Exposed	BS	9.5 (4.25)	7 – 13	-0.621	0.535
		Post E4	9 (3.0)	7 – 13		

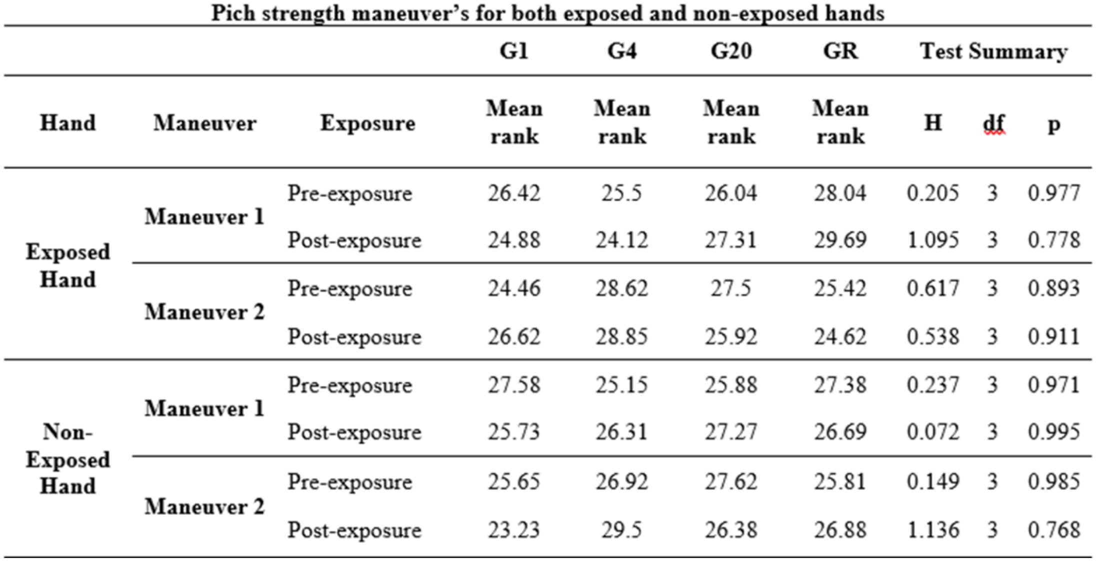
Pinch strength - Maneuver 2

Table 8.3.11 Maneuver 2 - Palmar/chuck pinch strength (kg) at baseline (BS) and after the fourth exposure (Post E4) to vibration. Wilcoxon signed-rank tests were used to compare pinch strength before and after exposure for each group (G1: $1s^{-1}$; G4: $4s^{-1}$; G20: $20s^{-1}$; GR: random vibration). Exact p-values (two-tailed) are reported.

	Maneuver 2 strength comparison baseline vs post 4th exposure				Test Summary	
Groups	**Hand**	**Exposure**	**Median (IQR)**	**Min – Max**	**Z value**	**p**
G1	**Exposed**	BS	7.5 (2.25)	4.5 – 10	-0.06	0.952
		Post E4	7 (2.00)	4.5 – 11		
	Non-Exposed	BS	8 (3)	4 – 10	-0.641	0.521
		Post E4	8 (3)	5 – 10.5		
G4	**Exposed**	BS	8 (3.0)	4.5 – 9.5	0	1.000
		Post E4	7.5 (3)	4.5 – 9		
	Non-Exposed	BS	8 (2.25)	5 – 10	-1.426	0.154
		Post E4	8.5 (2)	6 – 9.5		
G20	**Exposed**	BS	7.5 (4.25)	2 – 13	-1.53	0.126
		Post E4	8 (3.25)	2.5 – 13.5		
	Non-Exposed	BS	7.5 (3.75)	4.5 – 13	-0.225	0.822
		Post E4	8 (3)	2.5 – 12		
GR	**Exposed**	BS	8 (3.5)	5 – 10.5	-0.395	0.693
		Post E4	8 (2.5)	5 – 9.5		
	Non-Exposed	BS	7.5 (4.50)	6 – 12	-0.344	0.731
		Post E4	8 (3.75)	5 – 11.5		

Pinch strength - group comparison

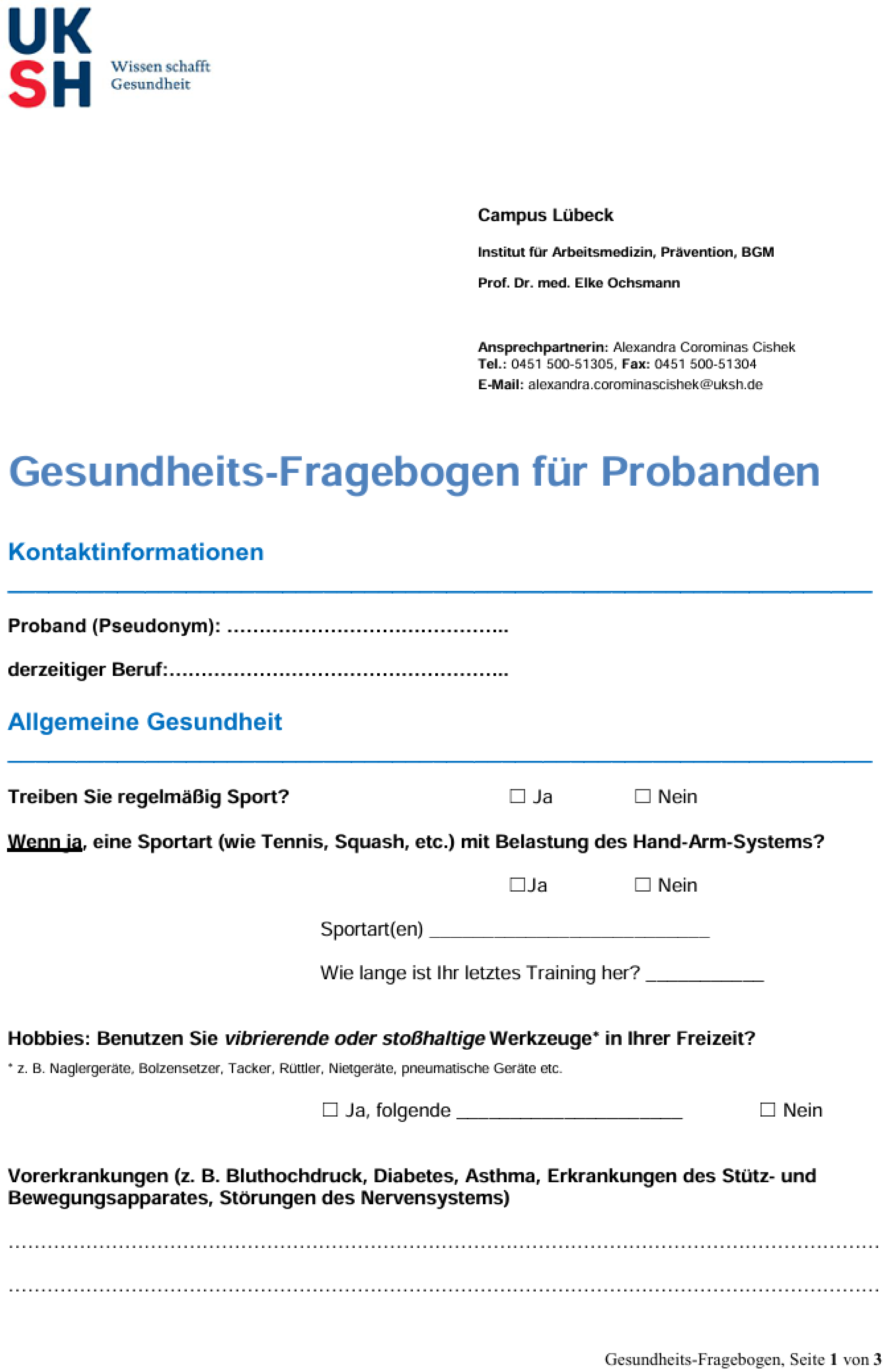
Table 8.3.12 Comparison of pinch strength (kg) between groups (G1: $1s^{-1}$; G4: $4s^{-1}$; G20: $20s^{-1}$; GR: random vibration) and between hands (exposed vs. non-exposed) before and after exposure to vibration. Maneuver 1: palmar/chuck pinch; Maneuver 2: key/lateral pinch. Kruskal-Wallis test, $p < 0.05$.



Pich strength maneuver's for both exposed and non-exposed hands

			G1	**G4**	**G20**	**GR**	**Test Summary**		
Hand	**Maneuver**	**Exposure**	**Mean rank**	**Mean rank**	**Mean rank**	**Mean rank**	**H**	**df**	**p**
Exposed Hand	**Maneuver 1**	Pre-exposure	26.42	25.5	26.04	28.04	0.205	3	0.977
		Post-exposure	24.88	24.12	27.31	29.69	1.095	3	0.778
	Maneuver 2	Pre-exposure	24.46	28.62	27.5	25.42	0.617	3	0.893
		Post-exposure	26.62	28.85	25.92	24.62	0.538	3	0.911
Non-Exposed Hand	**Maneuver 1**	Pre-exposure	27.58	25.15	25.88	27.38	0.237	3	0.971
		Post-exposure	25.73	26.31	27.27	26.69	0.072	3	0.995
	Maneuver 2	Pre-exposure	25.65	26.92	27.62	25.81	0.149	3	0.985
		Post-exposure	23.23	29.5	26.38	26.88	1.136	3	0.768

8.4 Health and post exposure symptoms questionnaire



Campus Lübeck

Institut für Arbeitsmedizin, Prävention, BGM

Prof. Dr. med. Elke Ochsmann

Ansprechpartnerin: Alexandra Corominas Cishek
Tel.: 0451 500-51305, **Fax:** 0451 500-51304
E-Mail: alexandra.corominascishek@uksh.de

Gesundheits-Fragebogen für Probanden

Kontaktinformationen

Proband (Pseudonym): ……………………………………..

derzeitiger Beruf:……………………………………………..

Allgemeine Gesundheit

Treiben Sie regelmäßig Sport? ☐ Ja ☐ Nein

Wenn ja, eine Sportart (wie Tennis, Squash, etc.) mit Belastung des Hand-Arm-Systems?

☐Ja ☐ Nein

Sportart(en) ___________________________

Wie lange ist Ihr letztes Training her? ___________

Hobbies: Benutzen Sie *vibrierende oder stoßhaltige* Werkzeuge* in Ihrer Freizeit?

* z. B. Naglergeräte, Bolzensetzer, Tacker, Rüttler, Nietgeräte, pneumatische Geräte etc.

☐ Ja, folgende ______________________ ☐ Nein

Vorerkrankungen (z. B. Bluthochdruck, Diabetes, Asthma, Erkrankungen des Stütz- und Bewegungsapparates, Störungen des Nervensystems)

………

………

Bisherige Operationen oder Krankenhausaufenthalte (ggf. Details)

....

....

Tragen Sie einen Hüftgelenkersatz oder Herzschrittmacher? ☐ Ja ☐ Nein

Sind Sie derzeit in ärztlicher Behandlung, gleich welcher Art? ☐ Ja ☐ Nein

Nehmen Sie regelmäßig Medikamente ein? ☐ Ja ☐ Nein

Falls ja, welche:

....

Fühlen Sie sich derzeit fit und leistungsfähig? ☐ Ja ☐ Nein

Körpergewicht .... **Körpergröße** ....

Muskel-Skelett-System

Ich bin: O Rechtshänder O Linkshänder O Beidhänder

Hatten Sie jemals Beschwerden im rechten Arm?
☐ Ja Wann?____________ ☐ Nein

Falls ja, welche? Mehrfachauswahl ist möglich:

☐ Verletzungen ☐ Schmerzen ☐ Bewegungseinschränkung
☐ Kältegefühl ☐ Kraftlosigkeit ☐ Sonstiges: __________________

Hatten Sie jemals Beschwerden in der rechten Hand?
☐ Ja Wann?_____________ ☐ Nein

Falls ja, welche? Mehrfachauswahl ist möglich:

☐ Verletzungen ☐ Schmerzen ☐ Bewegungseinschränkung
☐ Kältegefühl ☐ Kraftlosigkeit ☐ Sonstiges: __________________

Hatten Sie <u>in den letzten 7 Tagen</u> Beschwerden im rechten Hand-Arm-Bereich?

☐ Ja ☐ Nein

Falls ja, wo? ☐ Hand ☐ Arm

Falls ja, welche? Mehrfachauswahl ist möglich:

☐ Verletzungen ☐ Schmerzen ☐ Bewegungseinschränkung
☐ Kältegefühl ☐ Kraftlosigkeit ☐ Sonstiges: __________________

Haben Sie <u>jetzt</u> Beschwerden im rechten Hand-Arm-Bereich?

☐ Ja ☐ Nein

Falls ja, wo?

☐ Hand ☐ Arm

Falls ja, welche? Mehrfachauswahl ist möglich:

☐ Verletzungen ☐ Schmerzen ☐ Bewegungseinschränkung
☐ Kältegefühl ☐ Kraftlosigkeit ☐ Sonstiges: ________________

Sonstiges

Sind Sie heute mit dem Fahrrad angereist? ☐ Ja ☐ Nein

Haben Sie heute Kaffee getrunken? ☐ Ja ☐ Nein

Falls ja:
Wann haben Sie das letzte Mal Kaffee getrunken? Vor ______ Stunden

Trinken Sie Alkohol? ☐ Ja ☐ Nein

Falls ja:
☐regelmäßig (3-5-mal pro Woche) ☐gelegentlich (1-2-mal pro Woche) ☐ selten
(weniger als 4-mal pro Monat)

Haben Sie in den <u>letzten 12 Stunden Alkohol getrunken</u>? _____

Rauchen Sie? ☐ Ja ☐ Nein ☐ Ex-Raucher

Falls ja oder Ex-Raucher:
Seit wann rauchen Sie / haben Sie geraucht? _______
Wie viele Zigaretten am Tag rauchen Sie / haben Sie geraucht? _______
Wann haben Sie Ihre letzte Zigarette geraucht? _______

Herzlichen Dank für Ihre Mitarbeit!

Ihre Daten werden vertraulich behandelt und ausschließlich pseudonymisiert verarbeitet.

8.5 Informed consent

UNIVERSITÄTSKLINIKUM
Schleswig-Holstein
UKSH, Campus Lübeck, Ratzeburger Allee 160,
23538 Lübeck

Studienleiter :
Prof. Dr. med. Elke Ochsmann, MHBA

Wiss. Mitarbeiterin:
Alexandra Corominas

Studieninformation, Version 1.2 – 27.02.2020

Campus Lübeck
Institut für Arbeitsmedizin, Prävention, BGM
Direktorin: Prof. Dr. med. Elke Ochsmann, MHBA

Telefon: 0451 500 51300
Fax: 0451 500 51304
E-Mail: elke.ochsmann@uksh.de
Sekretariat: info.arbeitsmedizin.luebeck@uksh.de

Datum: 27.02.2020

Studieninformation und Einwilligungserklärung

Projekttitel	**Einzelstöße auf das Hand-Arm-System durch Maschinen und Werkzeuge: Expositionen, Übertragung und gesundheitliche Effekte (SSHE) – [Hauptstudie]**
Studienleiter und Kooperationspartner	**Prof. Dr. med. Elke Ochsmann, MHBA** Institutsdirektorin, Fachärztin für Arbeitsmedizin Universitätsklinikum Schleswig-Holstein Institut für Arbeitsmedizin, Prävention und betriebliches Gesundheitsmanagement Ratzeburger Allee 160, 23562 Lübeck Tel. 0451/500 51300, Fax: 0451 500 51304 E-Mail: elke.ochsmann@uksh.de **Dipl.-Ing. Uwe Kaulbars** Ingenieur für Vibrationsschutz Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung (IFA) Alte Heerstraße 111, 53757 Sankt Augustin Tel. 0301/3001 3440 Email: uwe.kaulbars@dguv.de **Dipl.-Ing. Hans Lindell** Researcher, Sound & Vibration, Produktentwicklung RISE Research Institutes of Sweden Argongatan 30, SE431 53 Mölndal, Sweden Tel. +46 707 80 60 02 Email: hans.lindell@ri.se
Studienzentren	Universitätsklinikum Schleswig-Holstein Institut für Arbeitsmedizin, Prävention und betriebliches Gesundheitsmanagement / Luebeck Institute of Occupational Health (LIOH) Ratzeburger Allee 160, 23562 Lübeck Institutsdirektorin: Prof. Dr. med. Elke Ochsmann, MHBA Tel. 0451/500-51300 Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung (IFA) Alte Heerstraße 111, 53757 Sankt Augustin Leiter der Hand-Arm-Vibrationen Abteilung: Dipl.-Ing. Uwe Kaulbars Tel. 030/13001 3400
Finanzierung	DGUV (Deutsche gesetzliche Unfallversicherung); Alte Heerstraße 111, 53757 Sankt Augustin

Sehr geehrter Studieninteressent,

wir möchten Sie einladen, an dieser Studie über den Einfluss von Einzelstößen auf das Hand-Arm-System bei gesunden Männern teilzunehmen. Auf den folgenden Seiten möchten wir Sie über den Hintergrund und den Ablauf der Studie informieren und Sie nach Ihrer Bereitschaft zur Teilnahme an der Studie befragen. Wenn Sie weitere Fragen zu der Studie haben – vor und auch nach einer Einwilligung – steht Ihnen das Studienteam jederzeit zur Verfügung.

1. Allgemeine Informationen

Die Studie, die wir Ihnen hier vorstellen, wurde von der zuständigen Ethikkommission der Universität zu Lübeck beraten und zur Durchführung empfohlen. **Die Studie wird im Institut für Arbeitsmedizin, Prävention und betriebliches Gesundheitsmanagement des Universitätsklinikums Schleswig-Holstein, Campus Lübeck oder im Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung (IFA), Sankt Augustin durchgeführt.**

Ihre Teilnahme an dieser Studie ist freiwillig. Sofern Sie nicht an der Studie teilnehmen oder später nicht mehr daran teilnehmen möchten, entstehen Ihnen daraus keine Nachteile. Ein Abbruch der Studie ist jederzeit auch ohne Angabe von Gründen möglich.

Die nachfolgende Studieninformation soll Ihnen die Ziele und den Ablauf erläutern. Bitte lesen Sie diese sorgfältig durch. Anschließend steht Ihnen das Studienpersonal für Fragen zur Verfügung. Bitte zögern Sie nicht, alle Punkte anzusprechen, die Ihnen unklar sind.

Falls Sie sich zur Teilnahme an dieser Studie entscheiden, werden Sie gebeten, eine Einwilligungserklärung zu unterzeichnen. Das erste Exemplar dieser Einwilligungserklärung, welches von Ihnen und dem Studienpersonal unterzeichnet wird, bekommen Sie. Das zweite Exemplar der Einwilligungserklärung verbleibt im Studienzentrum.

2. Warum wird diese Studie durchgeführt?

Hand-Arm-Vibrationseffekte durch immer wieder auftretende Einzelstöße sind bei verschiedenen beruflichen Tätigkeiten bekannt, z.B. bei der Arbeit mit Bolzenschussgeräten, Druckluftnaglern oder Schmiedehämmern. Man vermutet, dass solche niederfrequenten Einzelstoßexpositionen auf das Hand-Arm-System eine gesundheitliche Belastung des Hand-Arm-Systems darstellen können, die möglicherweise über der einer "normalen" Vibrationsexposition liegt. Daher werden Untersuchungen der folgenden "Zielorgane" durchgeführt: periphere Gefäße, periphere Nerven und der Bewegungsapparat des Hand-Arm-Bereichs.

Das Ziel dieser Studie ist es, wissenschaftliche Erkenntnisse in Bezug auf die Auswirkungen von Einzelstößen auf das Hand-Arm-System zu gewinnen. Da es hierzu bislang noch keine systematischen Studien gibt, weiß man noch wenig über die Dosis-Wirkung-Beziehung bei der Tätigkeit mit diesen Geräten und Maschinen.

3. Wer kann an dieser Studie teilnehmen?

Die Studie richtet sich an gesunde, arbeitsfähige Männer alle im Alter zwischen 18 und 65 Jahren, die beruflich keiner Belastung mit den entsprechenden Werkzeugen ausgesetzt sind. Ist der Teilnehmer aktiver Raucher oder leidet er an einer Herzkrankheit, einer Skelettmuskelerkrankung (wie z.B. Arthrose oder früheren Frakturen sowie aktuellen Beschwerden im rechten Arm), ist eine Teilnahme nicht möglich.

4. Was sind die möglichen Vorteile bei einer Teilnahme?

Der Hauptnutzen der Studie liegt in der Aussage über die akuten oder frühen gesundheitlichen Effekte der Anwendung von Werkzeugen, die Einzelstöße auf das Hand-Arm-System übertragen, der zwar nicht für den einzelnen Teilnehmer wichtig ist, aber für die Entwicklung von Präventionsprogrammen für exponierte Berufstätige. Denn hieraus soll eine Abschätzung über das Risiko von Personen erfolgen, die durch ihre berufliche Tätigkeit langfristig gegenüber Einzelstößen exponiert sind.

5. Wie ist der Ablauf der Studie und was muss ich bei der Teilnahme beachten?

Die Studie beginnt in Lübeck im April 2020.

Die Untersuchungen erfolgen am Institut für Arbeitsmedizin, Prävention und betriebliches Gesundheitsmanagement des Universitätsklinikums Schleswig-Holstein, Campus Lübeck, Ratzeburger Allee 160, **D - 23538** Lübeck oder im Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung (IFA), Alte Heerstraße 111, **D - 53757** Sankt Augustin. Dort wird eine etwa vier-stündige Untersuchung durchgeführt bei der Sie immer wieder (fünfmal fünf Minuten) an einem sogenannten Shaker (Gerät das Einzelstöße (Hammerschläge) simulieren kann) Einzelstöße erfahren, oder mit einem Werkzeug (Hammer, Bolzensetzer) eine bestimmte Tätigkeit ausüben.

Im Rahmen der Untersuchung werden vor, während und nach der Einzelstoß-Exposition mit verschiedenen nicht-invasiven Untersuchungsmethoden die Auswirkungen der Belastung auf die kleinen Gefäße, Nerven sowie das Muskel-Skelett-System im Hand-Arm-Bereich untersucht.

Sie werden also einer insgesamt 25-minütigen Einzelstoßexposition ausgesetzt, die folgende Frequenzen (willkürlich zugeordnet) hat: 1 Hz, 4 Hz, 20 Hz (Burst-Signal) Random-Signal (zwischen 25 und 250 Hz). Eine der Expositionen ist aber auf jeden Fall das Random-Signal.

In der Anfangsphase werden Beschleunigungsmesser an Handgelenk, Ellenbogen und Schulter angebracht sowie Elektroden, um die elektrische Aktivität des Muskels zu erfassen. Vor und nach jeder Exposition werden die Greif- und Kneifkraft, die Finger- bzw. Handtemperatur mit der Infrarot-Kamera und die Vibrationsempfindungsschwelle gemessen. **Die voraussichtliche Zeit für jeden Probanden liegt bei ca. 4 Stunden.**

Die folgende Grafik gibt den Ablauf der Untersuchung wieder:

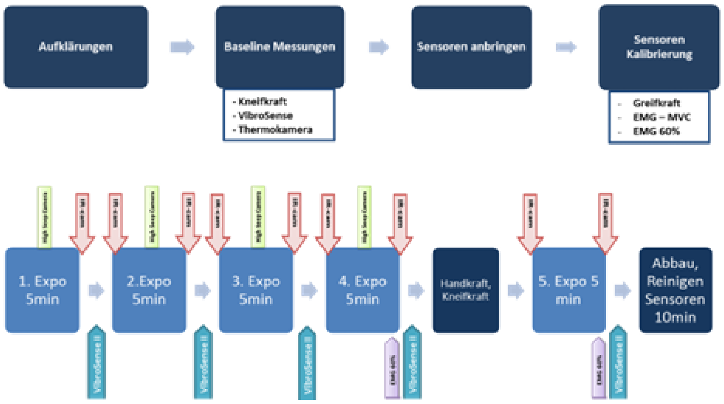


Abbildung: Ablauf der Untersuchungen

5.1. Verhalten vor der Untersuchung

Wir bitten Sie, die nachfolgenden Hinweise vor der Untersuchung zu lesen und zu berücksichtigen:

- **5 Stunden vor der Untersuchung:**

1. Keine Vibrations- oder Stoßexposition Ihrer Hände und Finger, z.B. durch vibrierende Werkzeuge aller Art (Tacker, Handhämmer, Bolzensetzgeräte etc.)
2. Keine repetitive Arbeit oder statische Belastung der Arme oder Handgelenke (z.B. durch Installationsarbeiten, schweres Heben)
3. Kein Konsum alkoholischer Getränke

- **3 Stunden vor der Untersuchung:**

1. Kein Kaffee oder andere koffeinhaltige Getränke
2. Kein Nikotinkonsum
3. Keine anstrengende körperliche Aktivität (z.B. Sport)

5.2. Simulation der Stoßexposition - Shaker

Bei dem verwendeten Shaker handelt sich um einen elektrodynamischen Shaker, der für die vorliegende Studie kurze repetitive Stöße erzeugt und über einen Griff an die Versuchsperson überträgt. Am Griff erfolgt parallel die Messung der Ankopplungskräfte der Versuchsperson.

Die Versuchsperson umfasst den Griff des Shakers und steht dabei mit einer definierten Körperhaltung und mit einem im Winkel von größer 90 ° angewinkelten Ellenbogen. Die vom Shaker erzeugten Stöße übertragen sich auf das Hand-Arm-System.

Die **physikalische Belastung durch den Shaker kann kurzfristig Symptome wie z.B. Kribbeln, Kälteempfinden hervorrufen.** Bei dieser kurzen Expositionsdauer (reine Kontaktdauer mit dem vibrierenden Griff von ca. 25 Minuten) sind keine gesundheitlichen Auswirkungen zu erwarten. Sogenannte Auslösewerte, ab denen lediglich bei täglicher beruflicher Exposition Maßnahmen zur Verringerung von Vibrationsexposition nötig wären, werden nicht erreicht. Grenzwerte für Vibration gemäß Lärm- und Vibrations-Arbeitsschutzverordnung werden keinesfalls überschritten.

Mögliche Komplikationen: kurzfristig Symptome wie z.B. Kribbeln. Abgesehen davon sind keine gesundheitlichen Auswirkungen zu erwarten (ggf. „Muskelkater“ durch Greif-/Andruckkraft)

5.3. Messung der Greifkraft

Die Messung der Greifkraft wird mit dem elektronischen Hand Dynamometer Deyard EH101 durchgeführt.

Das Deyard EH101 ist ein Standardgerät, das für die Messung der Handkraft/Greifkraft/Kraft des Oberkörpers gebräuchlich ist. Das Deyard EH101 wird isometrisch angewendet, fast ohne ersichtliche Bewegung der Griffe, unabhängig von der Griffstärke. Dies ermöglicht genaue und wiederholbare Resultate.

Mögliche Komplikationen: Es sind keine Komplikationen zu erwarten.

5.4. Messung der Kneifkraft

Die Messung der Kneifkraft wird mit dem hydraulischen Finger-Kraftmesser SAEHAN durchgeführt.

Das SAEHAN ist ein Standardgerät, das schon seit Jahren zur Messung der Kneifkraft zwischen Daumen und Finger in Gebrauch ist. Es wird isometrisch angewendet, fast ohne ersichtliche Bewegung, unabhängig von der Griffstärke. Dies ermöglicht genaue und wiederholbare Resultate.

Mögliche Komplikationen: Es sind keine Komplikationen zu erwarten.

5.5. Messung der Sensibilität am Hand-Finger Bereich

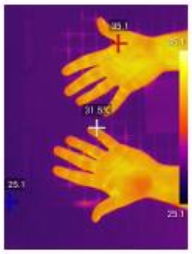
Die Messung der Sensibilität am Hand-Finger Bereich wird mit dem VibroSense® (VS II) durchgeführt.

Das VS II ist ein innovatives Gerät für die Messung und die Analyse der Vibrationsempfindungsschwelle an Händen oder Füßen. Es untersucht die Fähigkeit, nach Intensität und Frequenz abgestufte Vibrationen in den Fingerspitzen wahrzunehmen.

Dieses Gerät wird verwendet, um Ihre Vibrationswahrnehmung bei verschiedenen Frequenzen zu untersuchen. Die Untersuchung erfordert Ihre Mitarbeit, da Sie in Abhängigkeit von Ihrer Wahrnehmung einen Knopf gedrückt halten sollen, bzw. loslassen müssen. Die Untersuchung ist schmerzfrei und dauert pro Testung zwischen 15 – 20 Minuten.

Mögliche Komplikationen: Es sind keine Komplikationen zu erwarten.

5.6. Messung der Temperatur im Hand-Finger Bereich / Infrarotkamera



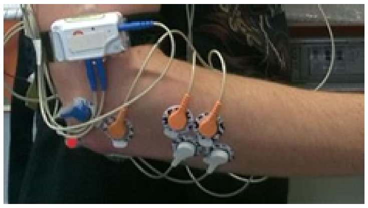
Die Messung der Temperatur im Hand-Finger Bereich wird mit einer Infrarotkamera (FLIR One Pro®) durchgeführt.

Vor und nach den Messungen werden Fotos von Ihren Händen gemacht. Diese dienen dazu, physiologische Reaktionen des Gefäß-Systems im Hand-Finger Bereich zu erfassen. Die Methode ist völlig schmerzfrei und nicht invasiv.

Bei der Studie dient sie der Untersuchung, ob durch die Anwendung bestimmter Werkzeuge eine Auswirkung auf die Funktion von Gefäßen (Gefäßverengung - Temperaturreduktion) nachweisbar ist.

Mögliche Komplikationen: Es sind keine Komplikationen zu erwarten.

5.7. Oberflächen-Elektromyographie - EMG



Die Oberflächen-Elektromyographie (EMG) misst die elektrische Muskelaktivität einer Körperregion. Hierzu werden Elektroden auf die Haut geklebt.

Das EMG ist eine Untersuchungsmethode der Neurophysiologie, welche die natürlicherweise auftretende elektrische Spannung in einem Muskel misst ("Ableitung"). Mit der Methode kann festgestellt werden, ob eine Erkrankung des Muskels bzw. eine Reizleitungsstörung der zu versorgenden Nerven vorliegt.

Bei der vorliegenden Studie dient sie der Untersuchung, ob durch die Anwendung bestimmter Werkzeuge eine Auswirkung auf die Funktion von Muskeln oder Nerven (Ermüdung) nachweisbar ist.

Mögliche Komplikationen: Es sind keine Komplikationen zu erwarten.

5.8. Fotoaufnahmen / Hochgeschwindigkeitskamera

Während der Messungen werden Fotos vom Messaufbau sowie Messungen des Bewegungsablaufes des Hand-Arm-Systems mittels einer Hochgeschwindigkeitskamera gemacht. Diese dienen dazu, Bewegungsabläufe und weitere Reaktionen des Hand-Arm-Systems zu erfassen. Die Methode ist völlig schmerzfrei und nicht invasiv. Der Fokus der Aufnahmen liegt auf dem Hand-Arm-Schulter-System.

Nach dem geltenden EU-Datenschutzrecht sind Foto- und Videoaufnahmen, auf denen Personen zu erkennen sind, grundsätzlich nur mit schriftlicher Einwilligung des/der Abgebildeten möglich. Daher wird in der Einwilligungserklärung folgende Passage aufgeführt.

Hiermit stimme ich zu, dass im Rahmen der Studie „SSHE“ Foto- und Videoaufnahmen von mir erstellt werden. Ich erlaube dem Institut für Arbeitsmedizin, Prävention und BMG, diese Aufnahmen für wissenschaftliche Zwecke auszuwerten und in Publikationen zu verwenden. **Zum Schutz meiner Identität werden sämtliche Aufnahmen (faktisch) anonymisiert, beispielsweise durch Maskierungsfunktionen wie Gesichtsverpixelung, sofern sich die Aufnahme des Kopfbereiches durch die Kameraeinstellung nicht grundsätzlich vermeiden lässt.**

Mögliche Komplikationen Es sind keine Komplikationen zu erwarten.

5.9. Fragebögen

Am Tag der Untersuchungen werden Sie gebeten mehrere Fragebögen im Laufe der Untersuchungen auszufüllen:

- Anamnese (u.a. allgemeine medizinische Daten, bekannte Vor-Erkrankungen, vor allem des Muskel-Skelett-Systems, Medikamenteneinnahme, Nikotinkonsum, Körpergröße, Gewicht)
- Vor und nach Exposition werden wahrgenommene Symptome bzw. Beschwerden erfasst (z. B. Kribbeln, Taubheitsgefühl, Kälteempfinden, etc.).

6. Welche Risiken und Belastungen sind mit der Teilnahme an der Studie verbunden?

Gesundheitliche Risiken sind bei der Teilnahme an der Studie nicht zu erwarten. Die Expositionen durch die ausgewählten Geräte und Maschinen liegen unterhalb derzeit gültiger Auslösewerte. Gesetzlich vorgeschriebene Grenzwerte werden niemals erreicht. Zum Vergleich: ein Hobbyhand- und –heimwerker, der am Wochenende tätig wird, erfährt eine deutlich höhere Exposition als in der vorliegenden Studie vorgesehen.

Darüber hinaus werden bei der Erfassung von gesundheitlichen Effekten lediglich nicht- invasive Verfahren verwendet, z. B.

- Temperaturmessungen an den Fingerkuppen kontaktlos über eine Infrarot-Kamera (ggf. nach vorheriger Kälte- oder Wärmeexposition)
- Aufnahmen mit einer Hochgeschwindigkeitskamera
- Messungen der Muskelaktivität mit Hilfe eines EMGs (Klebeelektroden, wie beim EKG)
- Vibrationsempfindungsschwellen-Untersuchung
- körperliche Untersuchung des Hand-Arm-Systems

Als möglicher Nachteil bei der Teilnahme ist vorwiegend der zeitliche Aufwand zu nennen (ca. 4 Stunden), der durch die Teilnahme entsteht. Andere nennenswerte Nachteile sind nicht zu erwarten. **Als Aufwandsentschädigung erhalten Sie aber 50 Euro.**

Alle Daten werden pseudonymisiert, d.h. Sie werden als Person nicht namentlich erfasst. Alle (pseudonymisierten) Untersuchungsbefunde sind außerdem nur für die Mitarbeiter des Projekts am Institut für Arbeitsmedizin, Prävention und BGM einzusehen. Nach Auswertung werden die Ergebnisse nur auf Gruppenbasis präsentiert, so dass ein Rückschluss auf einzelne Personen ausgeschlossen ist.

7. Kann meine Teilnahme an der Studie vorzeitig beendet werden?

Die Teilnahme an dieser Studie ist freiwillig, das heißt Sie können jederzeit ohne Angabe von Gründen die Teilnahme an der Studie beenden. Dadurch entstehen Ihnen keine Nachteile. Wenn Sie sich dazu entscheiden, aus der Studie auszutreten, bitten wir Sie darum dies dem Studienpersonal umgehend mitzuteilen. Bestenfalls informieren Sie das Studienpersonal dabei über Ihre Gründe. Dies ist wünschenswert aber keine Pflicht und bleibt Ihnen frei überlassen. Sie haben das Recht, die Löschung Ihrer bis dahin gesammelten Daten zu verlangen.

8. Entstehen Kosten für mich? Erhalte ich eine Aufwandsentschädigung?

Die Teilnahme an dieser Studie ist mit keinen Kosten verbunden. Für Ihren zeitlichen Aufwand erhalten Sie nach Abschluss der Studie eine **Aufwandsentschädigung in Höhe von 50 Euro.**

9. Wie bin ich während der Teilnahme an der Studie versichert?

Das Institut für Arbeitsmedizin, Prävention und BGM schließt für jeden Teilnehmer eine studienspezifische Probandenversicherung ab. Der Versicherungsschutz tritt dann in Kraft, wenn bei der Durchführung der Studie bei einem Teilnehmer ein gesundheitlicher Schaden auftritt. Adresse des Versicherers: Chubb European Group SE; Lurgiallee 12, 60439 Frankfurt am Main, Deutschland

10. Was geschieht mit meinen Daten?

Wenn Sie diese Einwilligungserklärung unterschreiben, geben Sie Ihr Einverständnis dafür, dass im Rahmen dieses Forschungsvorhabens der Studienleiter und das Studienpersonal personenbezogene Daten von Ihnen erheben und verarbeiten dürfen (z.B. Ihr Alter, Ihr Geschlecht, Daten zu Ihrer physischen Gesundheit und andere Daten, die während Ihrer Teilnahme an der Studie erhoben wurden (ggf. Handynummer und E-Mail-Adresse)). Diese

Daten werden ausschließlich für die Verwaltung der Studie sowie für Forschung und statistische Analysen verwendet. Für die Datenverarbeitung sind Prof. Dr. med. Elke Ochsmann und Alexandra Corominas verantwortlich. ´

Die Dokumentationen der Visiten werden in Papierform und auf Datenträgern an der Universität zu Lübeck, Institut für Institut für Arbeitsmedizin, Prävention und betriebliches Gesundheitsmanagement, Ratzeburger Allee 160, D-23562 Lübeck aufgezeichnet und nach 10 Jahren gelöscht. Die Daten werden ohne Probandennamen eingegeben und verschlüsselt (pseudonymisiert), das heißt der Name und andere Identifikationsmerkmale (z.B. Teile des Geburtsdatums) werden durch eine achtstellige Zahlenkombination, auch Code genannt, ersetzt, um die Identifizierung des Studienteilnehmers auszuschließen oder wesentlich zu erschweren. Zugriff auf Ihre Daten haben nur Mitarbeiter der Studie. Diese Personen sind zur Verschwiegenheit verpflichtet. Die Daten sind vor fremden Zugriff geschützt. Sobald der Forschungszweck es zulässt, wird die Schlüsselliste gelöscht und die erhobenen Daten damit anonymisiert. Eine Zuordnung der Daten zum Studienteilnehmer ist ab diesem Zeitpunkt nicht mehr möglich.

Die Bestimmungen der Datenschutzgrundverordnung (DSGVO) werden eingehalten.

Sie haben das Recht, über die von Ihnen erhobenen personenbezogenen Daten Auskunft zu erhalten, auch in Form einer unentgeltlichen Kopie, ebenso haben Sie das Anrecht auf Korrektur eventueller Ungenauigkeiten. In diesem Fall wenden Sie sich bitte an den Studienleiter.

Die Einwilligung zur Verarbeitung Ihrer Daten ist freiwillig. Sie können jederzeit, ohne Angabe von Gründen oder Nachteilen, der Weiterverarbeitung Ihrer von uns erhobenen Daten und/oder weiteren Untersuchung Ihrer Blut- und Stuhlproben widersprechen und ihre Löschung bzw. Vernichtung verlangen. Eine Löschung bereits anonymisierter Daten ist nicht möglich. Zur Löschung Ihrer Daten wenden Sie sich bitte an den Studienleiter (Kontaktdaten siehe Anfang dieses Dokuments).

Im Falle einer Beschwerde wenden Sie sich an den Datenschutzbeauftragten des Universitätsklinikums Schleswig-Holstein, Dr. Stefan Reuschke, Ratzeburger Allee 160, 23538 Lübeck, E-Mail: stefan.reuschke@uksh.de. Sie können sich mit einer Beschwerde auch an die zuständige Datenschutzaufsichtsbehörde wenden: Unabhängiges Landeszentrum für Datenschutz Schleswig-Holstein, Holstenstraße 98, 24103 Kiel, E-Mail: mail@datenschutzzentrum.de.

Dieses Forschungsvorhaben ist durch die zuständige Ethikkommission ethisch und fachrechtlich beraten worden.

11. Wer bezahlt die Studie?

Finanziert wird die Studie von der DGUV (Deutsche gesetzliche Unfallversicherung), Alte Heerstraße 111, 53757 Sankt Augustin, Tel. 030 13001-0, Fax. 030 13001-9876

12. An wen wende ich mich bei Fragen?

Sie haben stets die Möglichkeit zu einem weiteren Beratungsgespräch durch die Studienleiter oder die beteiligten Wissenschaftler. Bitte entnehmen Sie die Kontaktdaten der Tabelle auf Seite 1-2 dieser Aufklärung.

UNIVERSITÄTSKLINIKUM
Schleswig-Holstein

Studieninformation, Version 1.2 – 27.02.2020

Version „Studienzentrum“

Einwilligungserklärung

für die freiwillige Teilnahme an der Studie:

Einzelstöße auf das Hand-Arm-System durch Maschinen und Werkzeuge: Expositionen, Übertragung und gesundheitliche Effekte (SSHE) - Hauptstudie

Einwilligungserklärung zur Verarbeitung von Daten sowie der Analyse von physiologischen Untersuchungen auf die kleinen Gefäße, Nerven sowie das Muskel-Skelett-System am Hand-Arm-Bereich nach Simulation von Stoßexposition zu Zwecken von Forschung und Entwicklung. Die Verwendung der Angaben über meine Gesundheit erfolgt nach den gesetzlichen Bestimmungen der Bundesrepublik Deutschland und der Europäischen Union, insbesondere der Datenschutz-Grundverordnung **(DSGVO)** und dem Bundesdatenschutzgesetz **(BDSG).** Ich gebe folgende Einwilligungserklärung ab:

Hiermit erkläre ich

________________________	________________________	____________________
Vorname	Name	Geburtsdatum

Das ich durch Herrn/Frau ____

(Name des Studienarztes/ der Studienärztin, beteiligte Wissenschaftler/in)

die schriftliche Patienteninformation zur oben genannten Studie erhalten, gelesen und verstanden habe. Ich hatte Gelegenheit alle meine Fragen zu stellen. Diese wurden zufriedenstellend und vollständig beantwortet. Ich wurde ausführlich — mündlich und schriftlich — über die Ziele und Methoden, die möglichen Risiken und den Nutzen der Studie informiert worden. Ich habe die Studieninformation gelesen und den Inhalt verstanden, meine Rechte und Pflichten, den mir zustehenden Versicherungsschutz und die Freiwilligkeit der Teilnahme durch den Studienarzt/die Studienärztin aufgeklärt.

Ich erkläre hiermit meine Teilnahme an der oben genannten Studie. Ich wurde darauf hingewiesen, dass meine Teilnahme freiwillig ist und dass ich das Recht habe, diese jederzeit ohne Angabe von Gründen zu beenden, ohne dass mir dadurch Nachteile entstehen.

☐ Hiermit stimme ich zu, dass im Rahmen der Studie „SSHE“ Foto- und Videoaufnahmen von mir erstellt werden. Ich erlaube dem Institut für Arbeitsmedizin, Prävention und BMG, diese Aufnahmen für wissenschaftliche Zwecke auszuwerten und in Publikationen zu verwenden. **Zum Schutz meiner Identität werden sämtliche Aufnahmen nach Möglichkeit (faktisch) anonymisiert, beispielsweise durch Maskierungsfunktionen wie Gesichtsverpixelung.**

Datenschutzrechtliche Einwilligungserklärung

Ich bin mit der Erhebung und Speicherung der in der Probandeninformation genannten Daten, insbesondere der sensiblen personenbezogenen Daten einverstanden. Ich wurde über die Möglichkeiten eines Auskunfts- sowie Widerspruchsrechtes informiert.

Ich wurde über meine Datenschutzrechte informiert. Mit der Erhebung, Verarbeitung und Speicherung meiner Daten, sowie der Übermittlung im Rahmen der Studie bin ich einverstanden.

Ich bin damit einverstanden, dass im Rahmen der Studie *meine erhobenen Daten* aufgezeichnet und *pseudonymisiert* (d. h. ohne Namensnennung verschlüsselt) zur Auswertung der Ergebnisse verwendet werden. Alle im Rahmen der Studie erhobenen Daten werden strikt vertraulich gemäß dem Datenschutz behandelt.

Einer wissenschaftlichen Auswertung der Daten und einer möglichen Veröffentlichung der vollständig anonymisierten Ergebnisse stimme ich zu.

Beim Widerruf werden auf mein Verlangen alle erhobenen Daten gelöscht.

Ich gebe hiermit meine freiwillige Zustimmung zur Teilnahme an dieser Studie.
Eine Kopie dieser Einwilligung und eine Kopie der Studieninformation habe ich erhalten.

____________________	____
Ort, Datum	Unterschrift Studienteilnehmerin / Studienteilnehmer
____________________	____
Ort, Datum	Unterschrift Studienaufklärer / Name in Druckbuchstaben

Chapter 9: Acknowledgements

This doctoral thesis would not have been possible without the support of many individuals. I extend my deepest gratitude to all who contributed to its conception, execution, and completion.

First and foremost, I am indebted to my doctoral advisor EO, Director of the Institute for Occupational Medicine, Prevention and Occupational Health Management. Her guidance, constructive criticism, and unwavering support were invaluable throughout this journey. I am particularly grateful for the opportunity she provided me to explore this topic.

I also want to express my sincere appreciation to JW, whose pilot study laid the groundwork for this project. His contributions were instrumental in shaping the research design and implementation.

The exceptional interdisciplinary collaboration of UK and BE from the Institute for Occupational Safety and Health of the DGUV was crucial to the success of the measurements conducted in Sankt Augustin. Their expertise in this area proved indispensable.

I am further indebted to RW from the Clinic for Orthopedics and Trauma Surgery. His invaluable assistance and creative problem solving were essential in overcoming the challenges of EMG data evaluation.

This journey would not have been possible without the unwavering support of my loved ones. My deepest gratitude goes to my partner, whose presence was a constant source of strength, even when I struggled to find my own. I am also incredibly thankful for my family, friends and colleagues, whose encouragement and understanding helped me persevere through the challenges of doctoral studies. Their belief in me, coupled with their patience, provided the stability I needed to navigate this demanding chapter of my life.