Vibration Injury Network

Research Network on Detection and Prevention of Injuries due to Occupational Vibration Exposures

Design for a multi-centre experimental study of the acute effects of hand-transmitted vibration on the neurological and vascular systems

Appendix H3A to Final Report

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1. General

The aim of this report is to establish a common methodology of investigation among the various European Institutions that are involved in a multi-centre experimental study of the acute effects of hand-transmitted vibration on the peripheral neurological and vascular systems.
Various study designs and experimental procedures are discussed and proposed.
Four Institutions will participate in the experimental studies of the acute effects of hand-transmitted vibration:

1. The Institute of Occupational Medicine (**IOM**) of the University of Trieste, Italy;
2. The Human Factors Research Unit of the Institute of Sound and Vibration Research (**ISVR**) of the University of Southampton, United Kingdom;
3. The Occupational Hygiene and Work Physiology Unit (**HYTR**) of the Catholic University of Louvain, Belgium;
4. The Department of Technical Hygiene of the National Institute for Working Life (**NIWL**), Umeå Sweden.

IOM and ISVR will collaborate together in investigations of the acute effects of hand-transmitted vibration on digital circulatory function. Several indices of finger circulation, such as finger skin temperature (FST), finger systolic blood pressure (FSBP), and finger blow flow (FBF), will be measured before, during and after acute exposure to hand-transmitted vibration.

HYTR and NIWL will contribute to conduct experimental studies of the peripheral neurological changes induced by hand-transmitted vibration. The effects of acute vibration on sensorineural functions in the fingers and hands will be investigated by measuring vibration-induced changes in vibrotactile perception thresholds (VPT), thermal perception thresholds (TPT), pressure perception thresholds (PPT), manipulative dexterity (MD), maximal voluntary grip force (MVF), and possibly the distal sensory latency time (DSLT) in the median nerve.

The experiments shall be conducted according to the safety recommendations included in the International Standard ISO 13090-1. The experimental subjects shall give informed written consent to the study and the experimental procedures shall be approved by the local Ethical Committees.
Initially, the experimental subjects will include healthy individuals not exposed to occupational hand-transmitted vibration. Subsequently, when hypotheses on the pathogenic mechanisms of hand-transmitted vibration will be formulated on the basis of the experimental findings in the normal subjects, vibration-exposed workers with or without disorders of either the peripheral neurological or vascular systems will be tested using the same experimental procedures adopted for the healthy subjects.

In general, the changes in the circulatory and sensorineural functions in the fingers and hands of the experimental subjects will be tested by using hand-transmitted vibration with different magnitudes, frequencies and durations. In addition to investigate separately the influence of the various physical characteristics of hand-transmitted vibration, the studies at the different European centres will be designed to review the current frequency weighting and time dependency of vibration exposure adopted by the International Standard ISO 5349 and the European Standard ENV 25349.

2. Review of ISO 5349 frequency weighting

The international standard ISO 5349 provides methods for the assessment of vibration exposure at the workplace and for reducing vibration injuries, including vibration induced white finger (VWF).
The standard assumes that some characteristics of vibration (magnitude, frequency, duration) represent the principal exposure variables which account for the potential harmful effects on the vessels and nerves of the fingers and hands. According to International Standards ISO 8041 and ISO 5349, vibration acceleration should be weighted by a frequency weighting curve which has slopes of 0 dB below 16 Hz and –6 dB per octave above 16 Hz. This means that the sensitivity of the hand-arm system to acceleration is presumed to be independent of frequency below 16 Hz but reduces in inverse proportion to the vibration frequency between 16 and 1250 Hz.
This frequency weighting has an enormous effect on the exposure-response relation for VWF, information included in annex A to ISO 5349. In the annex the predicted prevalence of finger blanching is assumed to be directly proportional to the daily duration of vibration exposure, proportional to the square of the acceleration magnitude, proportional to the square of the years of exposure,

and inversely proportional to the square of the vibration frequency (at frequencies above 16 Hz). Thus if the vibration frequency is halved, the daily duration of exposure must be decreased by a factor of four, or the years of exposure must be decreased by a factor of two (assuming the acceleration magnitude and the predicted prevalence of VWF remain unchanged).
The ISO frequency weighting curve is basically derived from an adjustment of the subjective data obtained by Miwa (1967) in the frequency range 3 to 300 Hz. The author determined the mean equal sensation contours for vibration which gave rise to an unacceptable discomfort or unpleasantness in 10 subjects who pressed their hands on a flat horizontal surface. Thus the frequency weighting curve of ISO 5349 roughly reflects the vibration sensation in the human hand extrapolated up to the one third-octave band centre frequency of 1000 Hz.
It has been considered that although such sensations may be useful when assessing the sensory effects of hand-transmitted vibration, they are less obviously suitable for predicting some other injuries induced by vibration such as vascular disorders.
In general, experimental studies of the pathophysiological effects of vibration on digital vasculature have had no influence on the formulation of the frequency weighting and the exposure-response relation as presented in ISO 5349.
The present multi-centre experimental study will assess the appropriateness of the ISO frequency weighting method for hand-transmitted vibration by investigating whether vibrations with the same frequency-weighted acceleration derived from different combinations of frequencies and magnitudes of acceleration, cause the same circulatory and neurological effects in the fingers and hands. This aim may be achieved by using a sequence of different vibratory stimuli which have the same frequency-weighted root-mean-square (rms) acceleration.

2.1 PROPOSAL FOR AN EXPERIMENTAL STUDY DESIGNED TO ASSESS ACUTE VASCULAR RESPONSES TO THE FREQUENCY OF VIBRATION TRANSMITTED TO THE HAND

- **Subjects**: 10 healthy men with no occupational exposure to hand-transmitted vibration, possibly non-smokers and without disorders of the peripheral neurological, vascular musculoskeletal systems. They will give informed written consent to the experiment.

- **Measures of finger circulation:** Finger blood flow (FBF) and finger systolic blood pressure (FSBP) will be measured in the middle fingers of both the right and the left hand by means of a strain-gauge plethysmographic technique. Brachial systolic and diastolic blood pressures will be measured in the upper right arm by an ausculatory technique using a standard rubber cuff. The measures of finger and brachial blood pressures will be obtained at the beginning and at the end of each experimental session.

Finger skin temperature (FST) will be measured using k-type thermocouples connected to a thermal aesthesiometer.
The room temperature will be measured by a mercury-in-glass thermometer.

- **Experimental procedure:** The experiments will be performed in a laboratory room with controlled ambient temperature. The subjects will be requested to avoid caffeine consumption for two hours and alcohol for 12 hours prior to testing. The subjects will lie supine throughout the investigation with the hands resting on wooden platforms alongside the body at about the level of the heart. After a period of acclimatisation of about 15-20 minutes, FBF and FST will be measured in the middle fingers of both hands. After the pre-exposure measurements will be obtained, the subjects will be asked to apply a downward force of 10 N with their right hand on a wooden platform that is mounted on an electrodynamic vibrator. Visual feedback for the control of downward force will be supplied by means of an analogue force meter connected to a force cell mounted between the platform and the shaker. All fingers of the right hand will be in contact with the wooden platform.
  Sinusoidal vibration will be produced in the vertical direction with one of following combinations of frequency and rms magnitude: 5.5 ms^{-2} rms at 16 Hz; 11 ms^{-2} rms at 31.5 Hz; 22 ms^{-2} rms at 63 Hz; 44 ms^{-2} rms at 125 Hz; 88 ms^{-2} rms at 250 Hz. The frequencies and unweighted rms acceleration magnitudes of vibration are chosen so as to produce the same frequency-weighted acceleration magnitude (5.5 ms^{-2} rms) according to the frequency weighting recommended by ISO 5349. The duration of vibration exposure will be 15 minutes. This duration of exposure to a weighted rms acceleration of 5.5 ms^{-2} gives an 8-hour energy-equivalent exposure of 1.0 ms^{-2} according to the daily time dependency for hand-transmitted vibration assumed in current standards. The exposure-response relationship included in an annex to ISO 5349 predicts that vibration-induced white finger (VWF) would occur in 10% of an exposed population after about 21 years of daily exposure to a weighted acceleration magnitude equivalent to that used in this study.
  The measurements of FBF and FST will be made in both the exposed (right) and non-exposed (left) middle fingers immediately before vibration exposure, throughout the vibration exposure period, and for 45 minutes following exposure. The measures of finger circulation will be obtained at 0.5, 1.5, 3.5, 5.5, 7.5, and 15 minutes following the start of vibration. Measures will be taken at the same intervals following the cessation of vibration and then at each 7.5 minute interval during the remainder of the recovery period.
  A control condition will consist of the same procedure, with the vibration magnitude reduced to zero but the contact force on the wooden surface maintained at 10 N for 15 minutes.
  The exposure (vibration) and control (static load) conditions will be presented randomly in six separate experimental sessions with one to four days between the exposures.

- **Safety and ethical aspects**: The study will be submitted for approval to the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research at the University of Southampton (UK).
  The safety aspects of the experiment will be considered according to guidelines included in the international standard ISO 13090.

2.2 PROPOSAL FOR AN EXPERIMENTAL STUDY DESIGNED TO ASSESS ACUTE NEUROLOGICAL RESPONSES TO THE FREQUENCY OF VIBRATION TRANSMITTED TO THE HAND

- **Subjects**: 10 healthy male subjects without any history of peripheral or central neuropathy, nor of upper limb disorders, who were never exposed to vibration and possibly non-smokers. They will give informed written consent to the experiment.

- **Evaluation of the neurological response**:
  Five sensory and functional tests will be performed on the right hand:
  - Vibration perception threshold (VPT) at 31.5 and 125 Hz on the 2^{nd} and 5^{th} fingers
  - Pressure perception threshold (PPT), using the monofilaments of Semmes-Weinstein on the 2^{nd} and 5^{th} fingers
  - Nerve conduction through distal sensory latency (DSL) of the median nerve between the wrist and the 2^{nd} finger
  - Maximum voluntary grip force (MVF)
  - Purdue Pegboard test (PPB) to test the manual dexterity

  Additionally, a questionnaire will be used to collect the opinion of the subjects concerning tingling and numbness on a scale ranging from 0 (none) to 6 (very strong).

- **Experimental procedure**: The experiments will be performed in a laboratory with ambient temperature controlled between 22 and 25°C. The subjects will be requested to avoid caffeine consumption for two hours and alcohol for 12 hours prior to testing.
  The posture of the subject will be standardised, sitting with the arm along the trunk, the forearm bent at 90° and resting on a soft support adjusted in height, the hand in prono-supination.
  This set of experiments will involve exposure to sinusoidal vibration in the vertical direction with one of following 9 combinations of frequency and rms magnitude: 5, 20 and 80 ms^{-2} (unweighted) at 31.5 Hz (conditions 1 to 3), 125 Hz (conditions 4 to 6), and 500 Hz (conditions 7 to 9), plus a reference condition (numbered 0) without vibration. The 10 exposure conditions will be randomised, a period of at least 24 h separating two consecutive experiments.

The frequencies and unweighted rms acceleration magnitudes of vibration are chosen so as to produce the same frequency-weighted acceleration magnitude for conditions 1, 5, 9 according to the frequency weighting recommended by ISO 5349.
Before the exposure to vibration, during a period of acclimatisation of about 15-20 minutes, all the tests will be performed three times (except for DSL performed only once).
After these pre-exposure measurements will be obtained, the subjects will be asked to grab, with a force of 20 N, a vertical handle mounted on a shaker, the axis of vibration being therefore the axis Y as defined in ISO 5349. The handle will be thermoregulated at a temperature of 32°C and equipped with a strain gauge making possible to monitor the grip force. Visual feedback for the control of gripping force will be supplied by means of an analogue force meter. The system will be set so the lifting force and torque be about nil.
The exposure to vibration will last 32 minutes.
The tests are repeated as soon as possible after exposure, and every 5 minutes thereafter, until the initial values are reached for all the tests.
Each experiment will last about 90 minutes.

- **Safety and ethical aspects**: The study will be submitted for approval to the Ethics Committee of the Institutes or Universities involved in this project. The safety aspects of the experiment will be considered according to guidelines included in the international standard ISO 13090.

3. Review of ISO 5349 time dependency

In current standards (BS 6842, ISO/CD 5349-1) and the proposal of European Union Directive on physical agents (94/C 230/03), daily vibration exposure is expressed as 8-hour energy-equivalent frequency-weighted rms acceleration [$A(8)=a_{h,w}(T/T_8)^{1/2}$], a measure of vibration dose which assumes an inverse relation between daily exposure duration (T) and the square of the frequency-weighted magnitude of the vibration ($a_{h,w}$). A “second power” time dependency is convenient for instrumentation and measurement procedures and is commonly assumed in rms averaging methods. However, there is a shortage of both epidemiologic and experimental data to establish that such an “energy-equivalent” time dependency reflects human response to vibration of different daily exposure durations.

A further aim of the present European multi-centre study will be to carry out experiments to investigate whether exposures to the same energy-equivalent frequency-weighted acceleration magnitude derived from different combinations of vibration frequencies, magnitudes, and durations produce the same acute effects in the digital vasculature and in the skin mechanoreceptors and their afferent nerve fibres. By varying the duration of exposure, the effects of hand-transmitted with different magnitudes and frequencies such as a^2t=constant, will be assessed by measuring the peripheral circulatory and sensorineural outcomes according to the techniques and methods previously mentioned.

3.1 PROPOSAL FOR AN EXPERIMENTAL STUDY DESIGNED TO ASSESS ACUTE VASCULAR RESPONSES TO DIFFERENT COMBINATIONS OF VIBRATION FREQUENCIES, MAGNITUDES AND DURATIONS WITH THE SAME ENERGY-EQUIVALENT FREQUENCY-WEIGHTED ACCELERATION MAGNITUDE

- **Subjects**: 10 healthy men with no occupational exposure to hand-transmitted vibration, possibly non-smokers and without disorders of the peripheral neurological, vascular musculoskeletal systems. They will give informed written consent to the experiment.

- **Measures of finger circulation:** Finger blood flow (FBF) and finger systolic blood pressure (FSBP) will be measured in the middle fingers of both the right and the left hand by means of a strain-gauge plethysmographic technique. Brachial systolic and diastolic blood pressures will be measured in the upper right arm by an ausculatory technique using a standard rubber cuff. The measures of finger and brachial blood pressures will be obtained at the beginning and at the end of each experimental session.
  Finger skin temperature (FST) will be measured using k-type thermocouples connected to a thermal aesthesiometer.
  The room temperature will be measured by a mercury-in-glass thermometer.

- **Experimental procedure:** The experiments will be performed in a laboratory room with controlled ambient temperature. The subjects will be requested to avoid caffeine consumption for two hours and alcohol for 12 hours prior to testing. The subjects will lie supine throughout the investigation with the hands resting on wooden platforms alongside the body at about the level of the heart. After a period of acclimatisation of about 15-20 minutes, FBF and FST will be measured in the middle fingers of both hands. After the pre-exposure measurements will be obtained, the subjects will be asked to apply a downward force of 10 N with their right hand on a wooden platform that is mounted on an electrodynamic vibrator. Visual feedback for the control of downward force will be supplied by means of an analogue force meter connected to a force cell mounted between the platform and the shaker. All fingers of the right hand will be in contact with the wooden platform.
  Sinusoidal vibration will be produced in the vertical direction with one of following combinations of frequency, magnitude and duration:

Frequency (Hz)	Unweighted acceleration (ms^{-2} rms)	Weighted acceleration (ms^{-2} rms)	Exposure time (minutes)
125	44	5.5	30
125	62	7.75	15
125	88	11	7.5
125	125	15.6	3.75
125	176	22	1.88

According to the International Standard ISO 5349, the combinations of vibration frequency, acceleration magnitudes, and durations of exposure included in this experimental study give the same 8-hour energy-equivalent frequency-weighted acceleration magnitude of about 1.4 ms^{-2} rms. According to the dose-response relationship included in annexes to the standards, vibration-induced white finger is expected to occur in 10% of the individuals of a worker population after about 15 years of exposure to an equivalent weighted acceleration magnitude of 1.4 ms^{-2} rms.
The measurements of FBF and FST will be made in both the exposed (right) and non-exposed (left) middle fingers immediately before vibration exposure, throughout the vibration exposure period, and for 45 minutes following exposure. The measures of finger circulation will be obtained at 0.5, 1.5, 3.5, 5.5, 7.5, and 15 minutes following the start of vibration. Measures will be taken at the same intervals following the cessation of vibration and then at each 7.5 minute interval during the remainder of the recovery period.
The exposure conditions will be presented randomly in five separate experimental sessions with one to four days between the exposures.

- **Safety and ethical aspects**: The study will be submitted for approval to the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research at the University of Southampton (UK).
  The safety aspects of the experiment will be considered according to guidelines included in the international standard ISO 13090.

3.2 PROPOSAL FOR AN EXPERIMENTAL STUDY DESIGNED TO ASSESS ACUTE NEUROLOGICAL RESPONSES TO DIFFERENT COMBINATIONS OF VIBRATION FREQUENCIES, MAGNITUDES AND DURATIONS WITH THE SAME ENERGY-EQUIVALENT FREQUENCY-WEIGHTED ACCELERATION MAGNITUDE

- **Subjects**: 10 healthy male subjects without any history of peripheral or central neuropathy, nor of upper limb disorders, who were never exposed to vibration and possibly non-smokers. They will give informed written consent to the experiment.

- **Evaluation of the neurological response:**
  Five sensory and functional tests will be performed on the right hand:
  - Vibration perception threshold (VPT) on the 2^{nd} and 5^{th} fingers
  - Pressure perception threshold (PPT), using the monofilaments of Semmes-Weinstein on the 2^{nd} and 5^{th} fingers
  - Nerve conduction through distal sensory latency (DSL) of the median nerve between the wrist and the 2^{nd} finger
  - Maximum voluntary grip force (MVF)
  - Purdue Pegboard test (PPB) to test the manual dexterity

Additionally, a questionnaire will be used to collect the opinion of the subjects concerning tingling and numbness on a scale ranging from 0 (none) to 6 (very strong).

- **Experimental procedure**: The experiments will be performed in a laboratory with ambient temperature controlled between 22 and 25°C. The subjects will be requested to avoid caffeine consumption for two hours and alcohol for 12 hours prior to testing.
  The posture of the subject will be standardised, sitting with the arm along the trunk, the forearm bent at 90° and resting on a soft support adjusted in height, the hand in pronosupination.
  This set of experiments will involve exposure to sinusoidal vibration in the vertical direction with one of following five combinations of duration and rms magnitude:

Exp N°	Frequency (Hz)	Unweighted acceleration (ms^{-2} rms)	Weighted acceleration (ms^{-2} rms)	Exposure time (minutes)
1	125	28	3.5	40
2	125	40	5	20
3	125	56	7	10
4	125	40	5	40
5	125	40	5	10

  The five exposure conditions will be randomised, a period of at least 24 h separating two consecutive experiments.

  The objectives of experiments 1, 2 and 3 is to compare the effects resulting from exposure to the same 8-hour energy-equivalent frequency-weighted acceleration magnitude of about 1.0 ms^{-2} rms.
  The objectives of experiments 4 and 5 contrasted with experiment 2 is to study the evolution of the effect with time.
  Before the exposure to vibration, during a period of acclimatisation of about 15-20 minutes, all the tests will be performed three times (except for DSL performed only once).
  After these pre-exposure measurements will be obtained, the subjects will be asked to grab, with a force of 20 N, a vertical handle mounted on a shaker, the axis of vibration being therefore the axis Y as defined in ISO 5349. The handle will be thermoregulated at a temperature of 32°C and equipped with a strain gauge making possible to monitor the grip force. Visual feedback for the control of gripping force will be supplied by means of an analogue force meter. The system will be set so the lifting force and torque be about nil.
  The tests are repeated as soon as possible after exposure, and every 5 minutes thereafter, until the initial values are reached for all the tests

- **Safety and ethical aspects**: The study will be submitted for approval to the Ethics Committee of the Institutes or Universities involved in this project. The safety aspects of the experiment will be considered according to guidelines included in the international standard ISO 13090.

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In summary, the results of the experiments at the various European centres will indicate the influence of the magnitude, frequency and duration of vibration on the peripheral neurological and circulatory functions, and will be used to propose alternative methods of frequency weighting of vibration as well as to assess various time dependencies of vibration exposure.
A control condition differing only in respect of the vibration magnitude being 0 ms^{-2} should be included in each experiment unless previous published studies with identical conditions have shown that there is no change in the dependent variables under the conditions of the experiment.
The influence of other exposure variables relevant to the neurological and vascular effects of hand-transmitted vibration, such as direction of vibration, vibration impulsiveness, area of contact with vibration, contact force (grip force, push force, and pull force), intermittence of exposure, posture of the finger, hand, and arm, and some environmental factors (e.g. temperature), will be also assessed by appropriate experimental procedures. These results will provide valuable information for the assessment of the exposure-response relationships in the epidemiological studies which will be conducted in the context of Work Package 2 of this European Union project program.

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4. Pathophysiological mechanisms of vibration-induced disorders

In addition to contribute to the improvement of current standards for hand-transmitted vibration, a further purpose of the present multi-centre experimental study is to contribute to the understanding of the pathophysiological mechanisms underlying the disorders in the fingers of vibration-exposed workers, in particular vibration-induced adverse vascular effects. Previous investigations have shown that complex vasomotor mechanisms, mediated both centrally and locally, are involved in the reaction of digital vessel to acute vibration (Bovenzi and Griffin, 1997). There is some evidence that the circulatory effects of hand-transmitted vibration may be mediated by both intrinsic (local) and extrinsic (neural or endocrine) vasoregulatory factors. However, to date the relative roles of local, humoral or central sympathetic reflex mechanisms in the vasomotor changes elicited by hand-transmitted vibration are still unclear. To differentiate roughly between local and central pathophysiological mechanisms, in this multi-centre study unilateral vibration will be applied to the experimental subjects and the changes in FST, FSBP and FBF will be measured in the fingers of both the ipsilateral (exposed) hand and the contralateral (unexposed) hand. The assessment of Heart Rate Variability indices by monitoring ECG and respiration signals may also provide useful

physiological information on the involvement of the central sympathetic nervous system in the changes of circulatory function induced by acute exposure to hand-transmitted vibration.
Possibly, blood samples will be obtained from the subjects before, during and after vibration exposure to test whether the vibration causes changes in the serum levels of vasoactive substances, such as catecholamines, platelet-derived factors and endothelial derived relaxing (prostacyclin) and constricting (endothelin-1) factors.
These experimental procedures will make possible to investigate whether different pathophysiological mechanisms are involved in the acute response to vibration in normal subjects without symptoms and vibration-exposed workers with the disorders of the hand-arm vibration syndrome.

For purpose of information, a collection of abstracts from experimental studies of the acute effects of hand-transmitted vibration on the neurological (36 studies) and circulatory (52 studies) systems is included in an annex to this report.

5. Resources for the experimental multi-centre study

The Participants in this multi-centre study have provided the following information to the task leader about the resources of their laboratories with respect to the istrumentation and arrangement for generating vibration and controlling contact force and for measuring the neurological and vascular outcomes.

5.1 Institute of Occupational Medicine, University of Trieste, Italy

A) Instrumentation for the assessment of circulatory function

- Two-channel strain-gauge plethysmograph Digitmatic DM2000, Medimatic A/S (Copenhagen), equipped with a digit cooling system, for measuring finger blood flow and finger systolic blood pressure before and after local cooling
- Digit cooling system SP2, Medimatic A/S (Copenhagen)
- One-channel photoelectric plethysmograph Battaglia Rangoni (Bologna) for measuring finger blood flow
- Two-channel impedance plethysmograph BR/1I ATE (Bologna) for measuring finger blood flow
- Directional Doppler 806-C, Parks Electronics Laboratory (Oregon), for measuring arterial blood velocity and pressure
- Six-channel recorder C6b Ote Biomedica (Firenze), equipped with preamplifiers for recording electrocardiographic tracings and for measuring arterial blood pressure, finger skin temperature, and finger blood flow by means of photoelectric, piezoelectric and impedance plethysmographic techniques
- Nine-channel digital thermistor Termist-N LSI (Milano) for measuring finger skin temperature
- Nine-channel digital thermometer Ellab CTD85 (Copenhagen), connected to thermocouples, for measuring finger skin temperature

B) Instrumentation for the assessment of neurological function

- Set of medical devices for the traditional neurological examination (pain, temperature, light touch, vibrotactile sensation)
- Aesthesiometers, as developed by Carlson *et al.* (1979), for measuring two point discrimination (range 0 to 6 mm) and depth sense perception (range 0 to 1.5 mm) in the fingertips
- Dynamometers Jamar PC5031J1 (dynamic range 0-90 kg) and Jamar PC5030HPG (dynamic range 0-20 kg) for measuring maximal voluntary force and pinch force, respectively
- Set of goniometers for the measurement of range of motion in the upper limbs

5.2 Institute of Sound and Vibration Research, University of Southampton, United Kingdom

A) Instrumentation for the generation of vibration

- Electrodynamic vibrator Derritron VP4 and 100 watt amplifier
- Electrodynamic vibrator Derritron VP30 and 300 watt amplifier
- Electrodynamic vibrator Derritron VP85 and 1500 watt amplifier
- Force cells and purpose-built strain gauges to control force
- Set of about 60 piezo-electric or piezo-resistive accelerometers of varying shapes and sizes
- Various amplifiers, including several systems developed within the laboratory for acceleration and force transducers
- *HVLab* data acquisition and analysis software (ISVR, Southampton)

B) Instrumentation for the assessment of circulatory function

- Two-channel strain-gauge plethysmograph Digitmatic DM2000, Medimatic A/S (Copenhagen), equipped with a digit cooling system, for measuring finger blood flow and finger systolic blood pressure before and after local cooling
- *HVLab* 8-channel Temperature monitor (ISVR, Southampton) for computer based measurement of finger skin temperature following cold provocation of the hand
- *HVLab* Multi-Channel Plethysmograph (ISVR, Southampton) for computer based measurement of finger systolic blood pressure following cold provocation of the fingers
- *HVLab* Thermal Aesthesiometer (ISVR, Southampton) connected to thermocouples for measuring finger skin temperature

C) Instrumentation for the assessment of neurological function

- *HVLab* Tactile Vibrometer (ISVR, Southampton, frequency range 16 to 500 Hz, amplitude range 0.01 to 50 ms^{-2} rms) for computer controlled measurement of vibrotactile perception thresholds

- *HVLab* Thermal Aesthesiometer (ISVR, Southampton, temperature range 5° to 55°C) for computer controlled measurement of thermal perception thresholds
- Dynamometer Jamar PC5031J1 (dynamic range 0-90 kg) for measuring maximal voluntary force

5.3 Occupational Hygiene and Work Physiology Unit, Catholic University of Louvain, Belgium

A) Instrumentation for the generation of vibration

- Single frequency signal generator Tektronix TM 503
- Power amplifier Harfield 2U600 MOS-FET (10 Hz-25 kHz)
- Brüel & Kjaer Vibration Exciter 4808 (5 Hz-10 kHz, max. accel. 700 ms^{-2})
- Brüel & Kjaer Sound Level Meter 2209
- Brüel & Kjaer Accelerometer 4366
- Two thermoregulated handles JDT (range 20-40°C) allowing vibration exposures along Y-axis and X-and Z-axes, respectively
- Strain-gauge system JDT SGM 96 mounted on the handles to control grip force (dynamic range 20 kg)
- Scientific Instrument Graphic Recorder 320

B) Instrumentation for the assessment of neurological function

- Brüel & Kjaer minishaker 4810 (10 Hz-10 kHz, max. accel. 1000 ms^{-2}), connected to an amplifier Akai AM033 and a modified Madsen Micromate 304 Audiometer (dynamic range 50-160 dB, steps of 5 dB), for measuring vibrotactile perception thresholds (frequency range 8-500 Hz, constant force on the finger 0.20 N)
- *HVLab* Thermal Aesthesiometer (ISVR, Southampton, temperature range 5° to 55°C) for computer controlled measurement of thermal perception thresholds
- Semmes-Weinstein Aesthesiometer, consisting of a set 20 nylon monofilaments of progressively larger diameters, for measuring pressure perception thresholds
- Digital Electroneurometer Nervepace Neutron Medical S200 for measuring distal sensory latency time in the median and ulnar nerves
- Thermometer Ultrakust M202, connected to an infrared probe, for measuring finger skin temperature
- Set of metal pegs, washers, and sleeves to be assembled on a peg-board for the assessment of manipulative dexterity (Purdue pegboard test)
- Dynamometers Jamar PC5031J1 (dynamic range 0-90 kg) and Jamar PC5030HPG (dynamic range 0-20 kg) for measuring maximal voluntary force and pinch force, respectively
- Goniometer Penny & Giles for measuring ulnar-radial and flexion-extension wrist angles

5.4 Department of Technical Hygiene National Institute of Working Life, Umeå, Sweden

A) Instrumentation for the generation of vibration

- Various vibration exciters shaking masses weighting up to 200 kg
- A handle, especially designed for laborative exposure to hand-transmitted vibration, which includes force cells and purpose-built strain gauges to control and/or monitor grip, push and pull forces applied by the subject
- Set of several piezo-electric or piezo-resistive accelerometers of varying shapes and sizes
- Various amplifiers, including several systems developed within the laboratory for acceleration and force transducers
- *HVLab* data acquisition and analysis software (ISVR, Southampton)
- Brüel & Kjaer PULSE system for data analysis
- LabView system for both vibration generation and data acquisition and analysis

B) Instrumentation for the assessment of neurological function

- Computer based system (VibroMedic AB, Model 8500, Sweden) for measuring vibrotactile perception thresholds (Method: von Békésy; frequency range 8-500 Hz; amplitude range 0.01 to 100 ms^{-2} rms)
- Computer based system LabView for measuring vibrotactile perception thresholds in terms of acceleration (ms^{-2}), dynamic force (N) and absorbed power (W) at the fingertips
- Thermotest (Somedic, Sales AB, Sweden) for measuring thermal perception thresholds
- Equipment for measuring two-point discrimination
- Equipment for measuring skin temperature (thermistor/infrared light)
- Instrumentation for the assessment of proprioception
- Semmes-Weinstein monofilaments (Somedic Sales AB, Sweden) for measuring pressure perception thresholds

6. References

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