# INTERNATIONAL STANDARD

## ISO 13091-2

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# Mechanical vibration — Vibrotactile perception thresholds for the assessment of nerve dysfunction —

## Part 2:
## Analysis and interpretation of measurements at the fingertips

*Vibrations mécaniques — Seuils de perception vibrotactile pour l'évaluation des troubles neurologiques —*

*Partie 2: Analyse et interprétation des mesures obtenues à la pulpe des doigts*

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# Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 108, *Mechanical vibration, shock and condition monitoring*, Subcommittee SC 4, *Human exposure to mechanical vibration and shock*.

This second edition cancels and replaces the first edition (ISO 13091-2:2003), which has been technically revised.

The main changes compared to the previous edition are as follows:

— The contents of Annex A have been updated to include studies of the vibrotactile perception thresholds of healthy persons published since the first edition of the standard.

— The Bibliography has been updated to include the studies listed in Annex A.

A list of all parts in the ISO 13091 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

# Introduction

Early detection of peripheral neuropathies in the upper extremities, which are often manifest as changes in tactile function and hence changes in mechanoreceptor acuity, is of considerable interest. Such neuropathies can occur as a result of disease, or of exposure to chemical or physical, neurotoxic agents. With a suitable choice of measurement conditions, as provided in ISO 13091-1, separate responses from the slow-adapting type 1 (SAI) and fast-adapting types 1 and 2 (FAI and FAII) mechanoreceptor populations can be determined by using vibrotactile stimulation at different frequencies.

This document defines the analysis and interpretation of vibrotactile thresholds measured at the fingertips according to the provisions of ISO 13091-1. Procedures for describing statistically significant changes in vibrotactile perception thresholds are provided for the situation in which the threshold is determined on a single occasion, as well as when the threshold is determined repeatedly.

This edition of ISO 13091-2 contains an updated analysis of the vibrotactile perception thresholds for healthy males and females and provides reference thresholds for all frequencies specified in ISO 13091-1.

Values for the vibrotactile perception thresholds of healthy persons, applicable to thresholds determined according to the provisions of ISO 13091-1, are given in Annex A.

The implications of observed changes in vibrotactile perception thresholds are considered in Annex B.

# Mechanical vibration — Vibrotactile perception thresholds for the assessment of nerve dysfunction —

## Part 2:
## Analysis and interpretation of measurements at the fingertips

## 1 Scope

This document specifies methods and procedures for analysing and interpreting vibrotactile perception thresholds and threshold shifts. Procedures for describing statistically significant changes in vibrotactile perception thresholds are recommended.

This document is applicable to vibrotactile perception thresholds determined at the fingertips according to the provisions of ISO 13091-1.

## 2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 2041, *Mechanical vibration, shock and condition monitoring — Vocabulary*

ISO 5805, *Mechanical vibration and shock — Human exposure — Vocabulary*

ISO 13091-1, *Mechanical vibration — Vibrotactile perception thresholds for the assessment of nerve dysfunction — Part 1: Methods of measurement at the fingertips*

## 3 Terms, definitions, symbols and abbreviated terms

For the purposes of this document, the terms and definitions given in ISO 2041, ISO 5805 and ISO 13091-1 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

### 3.1 Terms and definitions

**3.1.1**
**healthy person**
person who, in the opinion of a qualified physician, is free from signs or symptoms of peripheral neurological disease as determined by physical examination and other clinical or objective tests deemed necessary to support the opinion, and who has not been exposed to a neurotoxic agent, vibration, or excessive repetitive motion, or diagnosed with diabetes or a metabolic disorder

### 3.1.2
**population group**
group of persons defined by one or more common factors

EXAMPLE    Common factors can be geography, age, sex, diet or occupation.

### 3.1.3
**baseline vibrotactile perception threshold**
initial vibrotactile perception threshold used for the comparison of results

### 3.1.4
**reference vibrotactile perception threshold**
value of the vibrotactile perception threshold for healthy persons

### 3.1.5
**reference threshold shift**
persistent shift in threshold from the corresponding *reference vibrotactile perception threshold* (3.1.4) recorded at the same frequency, or equivalent frequency

### 3.1.6
**relative threshold shift**
persistent shift in threshold from the corresponding value recorded previously for the same person at the same fingertip and frequency, or equivalent frequency, using the same measurement method

### 3.1.7
**predictive value**
prediction of the risk of disease, or symptoms, from the results of an objective test of some human property or function (see also positive and negative predictive values)

### 3.1.8
**positive predictive value**
fraction (or percentage) of a population group in whom the presence of disease, or symptoms, can be correctly predicted from the positive result of an objective test

### 3.1.9
**negative predictive value**
fraction (or percentage) of a population group in whom the absence of disease, or symptoms, can be correctly predicted from the negative result of an objective test

### 3.1.10
**association**
statistical measure of the chance of one human property or function observed in a person co-existing with the presence of a second property or function

### 3.1.11
**sensibility index**
ratio of the observed difference in threshold from a baseline of 150 dB to that of healthy persons of the same age from the same baseline, summed for each measurement frequency, or equivalent frequency

Note 1 to entry: An increase in vibrotactile perception threshold, which is associated with a reduction in acuity, will result in a decrease in the sensibility index from the value of unity for healthy persons.

### 3.1.12
**tactogram**
graphical representation of threshold shifts as a function of frequency

## 3.2 Symbols and abbreviated terms

The following symbols and abbreviated terms are used in this document:

| | |
|---|---|
| FAI | fast-adapting, type 1 mechanoreceptors |
| FAII | fast-adapting, type 2 mechanoreceptors |
| $N$ | number of subjects |
| $N_F$ | number of fingers |
| $p$ | probability |
| SAI | slow-adapting, type 1 mechanoreceptors |
| $s(f_j)$ | Gaussian distribution parameter for $T(f_j)_{ref}$ at frequency $f_j$ |
| $T(f_j)_{base}$ | baseline vibrotactile perception threshold at frequency $f_j$ |
| $T(f_j)_i$ | $i^{th}$ vibrotactile perception threshold at frequency $f_j$ |
| $T(f_j)_M$ | mean vibrotactile perception threshold at frequency $f_j$ |
| $T(f_j)_{obs}$ | observed vibrotactile perception threshold at frequency $f_j$ |
| $T(f_j)_{ref}$ | reference vibrotactile perception threshold at frequency $f_j$ |
| $T(f_j)_{ref,M}$ | mean reference vibrotactile perception threshold at frequency $f_j$ |
| $V(f_j)$ | test/retest variability at frequency $f_j$ |
| VPT | vibrotactile perception threshold |
| $\Delta T(f_j)_{ref}$ | reference threshold shift at frequency $f_j$ |
| $\Delta T(f_j)_{ref,i}$ | $i^{th}$ reference threshold shift at frequency $f_j$ |
| $\Delta T(f_j)_{ref,M}$ | mean reference threshold shift at frequency $f_j$ |
| $\Delta T(f_j)_{rel}$ | relative threshold shift at frequency $f_j$ |
| $\Delta T(f_j)_{rel,i}$ | $i^{th}$ relative threshold shift at frequency $f_j$ |
| $\Delta T(f_j)_{rel,M}$ | mean relative threshold shift at frequency $f_j$ |
| $\Delta T(SAI, FAI \text{ or } FAII)_{ref,M}$ | mean reference threshold shift for SAI, FAI, or FAII receptor population |
| $\Delta T(SAI, FAI \text{ or } FAII)_{rel,M}$ | mean relative threshold shift for SAI, FAI, or FAII receptor population |

NOTE    Symbols using an uppercase $T$ refer to thresholds expressed in dB (ref. $10^{-6}$ m/s$^2$). The equivalent threshold expressed in m/s$^2$ is given by the lower case symbol $t$.

## 4 Treatment of vibrotactile perception thresholds

### 4.1 General

The information required for the reporting, analysis and interpretation of VPTs determined in accordance with the provisions of ISO 13091-1 is specified in ISO 13091-1:2001, Clause 7. A subject's VPTs are commonly measured on a single occasion. In order to be interpretable, it is necessary to know

the expected variability in the VPTs if the measurement were to be repeated on another occasion (e.g. a different day).

Two situations are considered in this document. If the VPT of a subject is determined repeatedly at the same fingertip over a period of several days, then the test/retest variability applicable to the mean value of the observed VPTs, expressed in decibels, shall be the standard deviation calculated from the observed VPTs when expressed in decibels. Alternatively, in circumstances in which it is not possible to calculate a meaningful standard deviation from the measurements performed (e.g. when only a single measurement is made of a subject's VPT), then the test/retest variability of the observed VPT shall be estimated for the measurement method employed. The estimate shall be based on repeated measurements conducted on healthy persons using the same measurement method.

## 4.2 Mean value of repeated measurements

If the VPT at a given stimulation frequency or equivalent frequency, $f_j$, is determined repeatedly at a fingertip according to the provisions of ISO 13091-1, then the mean value of the VPT shall be calculated as the mean of the observed VPTs expressed in dB (ref. $10^{-6}$ m/s$^2$), using Formula (1):

$$T(f_j)_M = \frac{1}{n}\sum_{i=1}^{n} T(f_j)_i \tag{1}$$

where $T(f_j)_i$ and $T(f_j)_M$ are expressed in dB (ref. $10^{-6}$ m/s$^2$).

NOTE    The mean VPT calculated from the arithmetic mean of observed VPTs expressed in dB (ref. $10^{-6}$ m/s$^2$), as in Formula (1), is equivalent to the geometrical mean of the observed VPTs expressed in m/s$^2$.

## 4.3 Test/retest variability of threshold measurements

If the VPT is repeatedly determined at the same fingertip of a subject on separate occasions (e.g. on different days), then the intra-individual test/retest variability in threshold shall be calculated for this subject. The test/retest variability, $V(f_j)$, at a given stimulation frequency or equivalent frequency, $f_j$, (calculated using Formula [2]) shall be expressed in decibels as one standard deviation from the mean value of the VPTs, expressed in decibels, as determined by repeated measurements. If the VPTs, $T(f_j)_i$, found by repeated measurements at a given stimulation frequency or equivalent frequency, $f_j$, are expressed in dB (ref. $10^{-6}$ m/s$^2$), then:

$$V(f_j) = \left\{ \frac{1}{n-1} \sum_{i=1}^{n} \left[ T(f_j)_i - T(f_j)_M \right]^2 \right\}^{1/2} \tag{2}$$

where $T(f_j)_M$ is the mean of $n$ repeated measurements expressed in dB (ref. $10^{-6}$ m/s$^2$).

Under circumstances in which it is not possible to calculate a meaningful standard deviation for a subject (e.g. when only a single measurement is made of a subject's VPT), then the test/retest variability of the observed VPT shall be estimated for the measurement method used. The estimate shall be derived from the standard deviation of VPTs determined at the fingertips of healthy persons using the same measurement method. The standard deviation shall be based on at least 10 measurements of VPTs performed on separate occasions (e.g. 10 different days). The measurements shall be performed in accordance with the provisions of ISO 13091-1, and the standard deviation, expressed in decibels, shall be calculated from the observed VPTs expressed in decibels using Formula (2). The within subject standard deviation recorded from three or more healthy persons at a given frequency, or equivalent frequency, shall be used as the estimate for the intra-individual test/retest variability at that frequency, or equivalent frequency (one-way analysis of variance).

Normal hormonal changes during the menstrual cycle induce changes of up to 20 dB in the FAII receptor thresholds of females. When estimating the test/retest variability for the FAII thresholds of females, that is, for VPTs at measurement frequencies of 100 Hz, 125 Hz and 160 Hz, this tendency for the threshold to cycle should be taken into account. The threshold changes occur several days before and after ovulation.

## 4.4 Treatment of unresolved errors

Under some circumstances, the examiner might believe that unresolved errors have occurred during threshold measurements. Also, errors might have been introduced by conducting measurements on a defective skin site, as described in ISO 13091-1.

In these situations, analysis and interpretation of VPTs using the methods and procedures contained in this document are only possible if additional information is obtained. A second set of measurements shall be performed according to the provisions of ISO 13091-1 if it is believed that more reliable VPTs may be obtained. The second set of VPTs shall be treated as described in this document.

NOTE    If, at a single measurement site, the VPTs are determined at two or more frequencies, or equivalent frequencies, mediated by the same mechanoreceptor population, then the consistency of the threshold shifts calculated according to the provisions of 5.6 can be examined to confirm the presence of errors.

## 4.5 Treatment of suspected increase in test/retest variability

Under some circumstances, the examiner might believe that the test/retest variability applicable to the measurement method is not applicable to a subject. The opinion might be based on the lack of consistency in determining ascending and descending thresholds as described in ISO 13091-1:2001, 6.3, or on other information.

In these situations, analysis and interpretation of VPTs using the methods and procedures contained in this document are only possible if the variability applicable to the subject is established. A subject-specific test/retest variability is established by conducting repeated threshold measurements on the subject according to the provisions of 4.3.

# 5 Calculation of threshold shift

## 5.1 General

The interpretation of VPTs is facilitated by calculation of the change in observed threshold from a predefined value. The calculation of threshold shift shall be performed for each frequency, or equivalent frequency, and fingertip at which VPTs have been obtained according to provisions of Clause 4.

## 5.2 Relative threshold shift

The relative threshold shift shall be calculated as the difference between two VPT values expressed in dB (ref. $10^{-6}$ m/s$^2$), or the ratio of the two VPT values expressed in m/s$^2$, one being the observed VPT and the other a baseline VPT. The two VPTs shall be obtained from the same fingertip of a subject using the same measurement method and measurement frequency, or equivalent frequency. The relative threshold shift, $\Delta T(f_j)_{\text{rel}}$, at the $j^{\text{th}}$ frequency, $f_j$, shall be expressed in decibels, and calculated at each measurement frequency, or equivalent frequency, using Formula (3):

$$\Delta T(f_j)_{\text{rel}} = T(f_j)_{\text{obs}} - T(f_j)_{\text{base}} \tag{3}$$

where the observed VPT at the $j^{\text{th}}$ frequency, $T(f_j)_{\text{obs}}$, and the baseline VPT at the same frequency, or equivalent frequency, $T(f_j)_{\text{base}}$, are expressed in dB (ref. $10^{-6}$ m/s$^2$).

The equivalent expression for the relative threshold shift calculated from thresholds expressed in m/s$^2$ is shown in Formula (4):

$$\Delta T(f_j)_{\text{rel}} = 20\lg\left[t(f_j)_{\text{obs}}\big/t(f_j)_{\text{base}}\right] \tag{4}$$

NOTE    The calculation of relative threshold shifts facilitates the identification of patterns of change in tactile acuity affecting an individual. Determining relative threshold shifts has proved beneficial in situations in which a known pathological, or repair, process is followed in an individual over a period of time. Under these circumstances, the baseline VPT is usually the original VPT recorded on the subject.

## 5.3 Reference threshold shift

The reference threshold shift shall be calculated as the difference between the observed and reference VPT values when both are expressed in dB (ref. $10^{-6}$ m/s$^2$), or the ratio of the two VPT values expressed in m/s$^2$. The reference threshold shift, $\Delta T(f_j)_{\text{ref}}$, at the $j^{\text{th}}$ frequency, $f_j$, shall be expressed in dB, and calculated at each measurement frequency, or equivalent frequency, using Formula (5):

$$\Delta T\left(f_j\right)_{\text{ref}} = T\left(f_j\right)_{\text{obs}} - T\left(f_j\right)_{\text{ref}} \tag{5}$$

where the observed VPT at the $j^{\text{th}}$ frequency, $T(f_j)_{\text{obs}}$, and the reference VPT at the same frequency, or equivalent frequency, $T(f_j)_{\text{ref}}$, are expressed in dB (ref. $10^{-6}$ m/s$^2$).

The equivalent expression for the reference threshold shift calculated from thresholds expressed in m/s$^2$ is shown in Formula (6):

$$\Delta T\left(f_j\right)_{\text{ref}} = 20\lg\left[t\left(f_j\right)_{\text{obs}}/t\left(f_j\right)_{\text{ref}}\right] \tag{6}$$

NOTE    The calculation of reference threshold shifts facilitates the identification of patterns of tactile abnormality that are interpretable in terms of changes in mechanoreceptor or nerve function. An association has been found between reference threshold shifts and symptom reports. Reference threshold shifts can be associated with neuropathies affecting the upper extremities.

## 5.4 Mean value of threshold shift

If the threshold shift for a given stimulation frequency, or equivalent frequency, is determined repeatedly at a fingertip under circumstances in which it is not expected to change, then the arithmetic mean value of the relative, or reference, threshold shift shall be calculated from the threshold shifts expressed in decibels. The mean relative threshold shift at frequency, $f_j$, expressed in dB, is calculated using Formula (7):

$$\Delta T\left(f_j\right)_{\text{rel,M}} = \frac{1}{n}\sum_{i=1}^{n}\Delta T\left(f_j\right)_{\text{rel},i} \tag{7}$$

The mean reference threshold shift at frequency, $f_j$, expressed in dB, is calculated using Formula (8):

$$\Delta T\left(f_j\right)_{\text{ref,M}} = \frac{1}{n}\sum_{i=1}^{n}\Delta T\left(f_j\right)_{\text{ref},i} \tag{8}$$

## 5.5 Tactogram

A tactogram shall consist of a logarithmic plot of frequency, or equivalent frequency, on the abscissa and threshold shift expressed in dB on the ordinate, as shown in Figure 1. The threshold shift can range from, typically, −20 dB to 60 dB. The frequency ranges in which thresholds are mediated by different mechanoreceptor populations may be indicated.

NOTE 1    The frequency ranges at which VPTs determined according to the provisions of ISO 13091-1 are mediated by the SAI, FAI or FAII mechanoreceptor populations are listed in ISO 13091-1:2001, Table 3.

A tactogram can be constructed for individual fingers, hands, subjects, or groups of subjects, and the applicable values of the relative, or reference, threshold shifts shall be plotted as ordinates. Values at different frequencies, or equivalent frequencies, for individual fingers, hands, subjects, or groups of subjects, as applicable, may be connected by lines.

If the tactogram is for one or both hands of an individual, the threshold shifts for individual fingers shall be identified by different symbols. Thresholds shifts for fingers on the right hand should be indicated by circles, and for fingers on the left hand by squares.

NOTE 2    It can be convenient to indicate the finger by a number within the symbol for the hand, or by different coloured symbols. Fingers are numbered as follows:

— digit 1, thumb;

— digit 2, index finger;

— digit 3, middle finger;

— digit 4, ring finger;

— digit 5, little finger.



**Key**
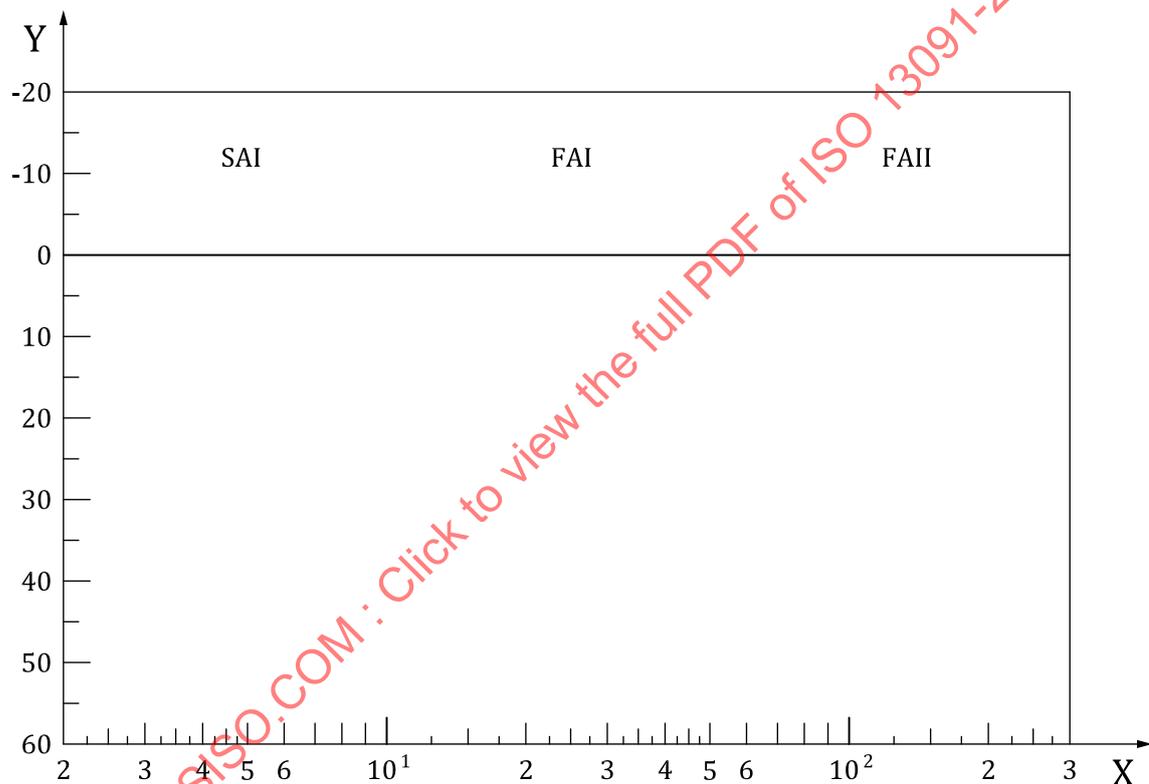
X    frequency, in Hz
Y    threshold shift, in dB

**Figure 1 — Tactogram**

## 5.6   Consistency of threshold shifts

If VPTs have been determined at a single measurement site at more than one frequency, or equivalent frequency, mediated by a given mechanoreceptor population according to the provisions of ISO 13091-1, then the consistency of the relative, or reference, threshold shifts may be examined. The consistency is expressed by the difference in dB between the relative or reference threshold shifts for frequencies, or equivalent frequencies, at which VPTs were mediated by a single mechanoreceptor population (see ISO 13091-1:2001, Table 3).

The consistency may be degraded in situations in which VPTs outside the range of expected values for healthy persons defined in 6.5 are found in only one mechanoreceptor population at the measurement

site. Under these circumstances, it is possible for thresholds at some frequencies normally mediated by this population to be mediated by another receptor population with VPTs within the limits of expected values for healthy persons.

NOTE    The calculation of the consistency between mechanoreceptor-specific threshold shifts determined according to the provisions of ISO 13091-1 facilitates the identification of errors in subject performance. Threshold shifts mediated by the same receptor population that are error free will be identical.

## 5.7    Mean mechanoreceptor population threshold shift

If VPTs have been determined at a single measurement site at more than one frequency, or equivalent frequency, mediated by a given mechanoreceptor population according to the provisions of ISO 13091-1, then the relative or reference threshold shift can be expressed in terms of the mean mechanoreceptor population threshold shift. The mean mechanoreceptor population threshold shift is the arithmetic mean of the relative or reference threshold shifts expressed in decibels for all frequencies, or equivalent frequencies, at which the VPTs were mediated by a single mechanoreceptor population. The allowed measurement frequencies are given in ISO 13091-1:2001, Table 3. The mean mechanoreceptor population threshold shift shall be expressed in decibels.

The mean relative threshold shift for a given mechanoreceptor population, $\Delta T(\text{SAI, FAI or FAII})_{\text{rel,M}}$, is calculated using Formula (9):

$$\Delta T(\text{SAI, FAI or FAII})_{\text{rel,M}} = \frac{1}{m}\sum_{j=1}^{m} \Delta T(f_j)_{\text{rel}} \qquad (9)$$

where the summation is over the $m$ frequencies, or equivalent frequencies, at which the threshold is mediated by the same receptor population.

The mean reference threshold shift for a given mechanoreceptor population, $\Delta T(\text{SAI, FAI or FAII})_{\text{ref,M}}$, is calculated using Formula (10):

$$\Delta T(\text{SAI, FAI or FAII})_{\text{ref,M}} = \frac{1}{m}\sum_{j=1}^{m} \Delta T(f_j)_{\text{ref}} \qquad (10)$$

where the summation is over the $m$ frequencies, or equivalent frequencies, at which the threshold is mediated by the same receptor population.

The procedure should be applied with caution to situations in which VPTs outside the range of expected values for healthy persons defined in 6.5 are found in only one mechanoreceptor population at the measurement site. Under these circumstances, thresholds at some frequencies normally mediated by this population can be mediated by another receptor population with VPTs within the limits of expected values for healthy persons.

NOTE    The calculation of the mean mechanoreceptor-specific threshold shift facilitates the identification of small changes in mechanoreceptor, and hence tactile, acuity.

## 6    Interpretation of vibrotactile perception thresholds and threshold shifts

### 6.1    General

Values of VPTs and threshold shifts at the fingertips provide information related to peripheral sensory nerve function in the finger, hand and arm of the limb under investigation. The magnitude of changes in threshold may be reported in one or more of the following ways indicated in 6.2 to 6.5.

## 6.2 Measurement error and statistical significance of observed VPTs

If the VPT at a fingertip is determined repeatedly according to the provisions of ISO 13091-1, then the measurement error applicable to the mean value of the observed VPTs, expressed in decibels, shall be the standard deviation calculated according to Formula (2) from the observed VPTs expressed in dB.

Under circumstances in which it is not possible to calculate a meaningful standard deviation (e.g. if the VPT at a fingertip is determined only on one occasion), then the measurement error assumed applicable to the observed VPT shall be the test/retest variability estimated for the measurement method according to the provisions of 4.3. This shall be expressed in dB as the standard deviation applicable to the observed VPT and should be used for statistical analyses.

## 6.3 Measurement error and statistical significance of relative threshold shifts

If the relative threshold shift at a fingertip is determined repeatedly, then the measurement error applicable to the mean value of the relative threshold shifts shall be the standard deviation, expressed in decibels, calculated from the observed relative threshold shifts expressed in decibels.

If the relative threshold shift at a fingertip is determined only once, that is, from two VPT values, then the measurement error applicable to the observed value of relative threshold shift shall be 1,414 times the test/retest variability estimated for the measurement method according to the provisions of 4.3. This shall be expressed in decibels as the standard deviation applicable to the observed relative threshold shift and should be used for statistical analyses.

## 6.4 Vibrotactile perception thresholds for healthy persons

It is often required to compare the VPTs observed at the fingertips of one person with those of a reference population group consisting of healthy persons. Values of VPTs for healthy persons at age 30 years are provided in Annex A in dB (ref. $10^{-6}$ m/s$^2$), and in m/s$^2$. The values are expressed in terms of the 2,5, 15, 50 (mean value), 85 and 97,5 percentiles of the population group for each stimulation frequency, or equivalent frequency, specified in ISO 13091-1. The thresholds approximate a Gaussian distribution when expressed in dB.

The values in Annex A may be used for the interpretation of VPTs determined according to the provisions of ISO 13091-1. The 50 percentile values shall be used as the reference thresholds for the calculation and interpretation of reference threshold shifts, for example for the term $T(f_j)_{ref}$ in Formula (5), and for $t(f_j)_{ref}$ in Formula (6).

NOTE 1    The mean VPTs of healthy persons increase with age by approximately 0,03 dB per year at frequencies mediated by SAI receptors, 0,08 dB per year at frequencies mediated by FAI receptors, and from 0,25 dB per year to 0,35 dB per year at frequencies mediated by FAII receptors.

NOTE 2    For epidemiological studies, the VPTs used for the reference population group can be derived from a control group.

## 6.5 Deviations from the VPTs of healthy persons

Deviations from the VPTs of healthy persons, and reference threshold shifts, shall be assessed in terms of the probability of the observed deviation from the mean value for healthy persons. The measurement errors associated with observed VPTs are determined according to the provisions of 6.2. There is no measurement error associated with the mean reference vibrotactile perception thresholds specified for healthy persons.

The 2,5 and 97,5 percentile threshold values for healthy persons given in Annex A may be taken as the upper and lower limits for the expected values to be obtained on an individual using a measurement method complying with the provisions of ISO 13091-1. Observed values of VPTs less than those experienced by 2,5 %, or greater than those experienced by 97,5 %, of healthy persons should be considered to be outside the range of expected values. Equivalently, observed values of reference

threshold shift in excess of the reference threshold shift experienced by 2,5 % or 97,5 % of healthy persons should be considered to be outside the range of expected values.

NOTE    For an individual, the probability of a given deviation in the threshold from the mean value for healthy persons, or reference threshold shift, does not necessarily correspond to a positive, or negative, predictive value for a symptom, disturbance or disorder believed to be associated with peripheral sensory nerve dysfunction.

## 6.6   Physiological and clinical implications of changes in VPTs

The physiological, functional and clinical implications of threshold shifts are described in Annex B.

Vibrotactile perception may be used as an objective test for the detection of peripheral neuropathies, either generalized or focal, arising from disease and from exposure to neurotoxic chemical and physical agents. When VPTs are determined at several stimulation frequencies, or equivalent frequencies, calculating the sensibility index or plotting a tactogram can prove beneficial in the interpretation of the results. A repeated measurement of the relative threshold shift can prove beneficial in situations in which a pathological or recovery process is followed over time.

Changes in VPTs and reference threshold shifts can influence specific aspects of tactile function and reflect underlying disease. Reference threshold shifts recorded at different frequencies, or equivalent frequencies, are found to possess distinctive patterns when plotted as tactograms. Examples are given in Annex B.

# Annex A
## (informative)

# Vibrotactile perception thresholds for healthy persons

Numerous studies of the VPTs of healthy persons have used test methods essentially in agreement with the provisions of ISO 13091-1. Studies conducted using Method B, and Method A when the hand is oriented with palm facing upwards (see ISO 13091-1:2001, Figure 1), are listed in Table A.1.

NOTE 1    VPTs obtained using Method A when the hand is oriented palm downwards with the fingertip resting on top of the stimulating probe (see upper left sketch in ISO 13091-1:2001, Figure 1) often deviate from the results of measurements conducted using Method B or the other orientation of the hand used in Method A.

The sources of the threshold values are identified in the left-hand column of Table A.1. The reported probe diameter and surround diameter, if used, are listed in columns 2 and 3. All studies employed a controlled skin-stimulator contact force or skin indentation and, in addition, a controlled skin-surround contact force when a surround was used. The psychophysical algorithm type is also identified in the Table, as are the sex (male - M, and female - F) of the subjects, their mean age and the number in the population group, $N$.

A brief description is provided of the human population group(s) from which the VPTs were obtained (column 8). A history usually obtained by questionnaire concerning symptoms of peripheral neurological disease and exposure to neurotoxic agents or to hand-arm vibration is summarized when reported. The medical screening of subjects for symptoms of peripheral neurological disease is also reported when performed. The VPTs in all studies are for healthy persons.

Ranges of values for the VPTs of healthy males and females are given in Table A.2 in dB (ref. $10^{-6}$ m/s$^2$), and Table A.3 in m/s$^2$. They are applicable to all methods of measurement in ISO 13091-1 except Method A when the hand is oriented palm down with the fingertip resting on top of the stimulating probe. The values are expressed in terms of the 2,5, 15, 50 (mean value), 85 and 97,5 percentiles of a population group for each stimulation frequency, or equivalent frequency, specified in ISO 13091-1:2001, Table 1. The thresholds approximate a Gaussian distribution when expressed in dB. Thresholds for percentiles other than the mean may be estimated for VPTs expressed in dB (ref. $10^{-6}$ m/s$^2$) at a given frequency, or equivalent frequency, $f_j$, using Formula (A.1):

$$p\left[T\left(f_j\right)_{\text{ref}}\right] = \frac{1}{\sqrt{2\pi}\cdot s\left(f_j\right)}\,\mathrm{e}^{-\left[T\left(f_j\right)_{\text{ref}} - T\left(f_j\right)_{\text{ref,M}}\right]^2 \Big/ \left[2s^2\left(f_j\right)\right]} \tag{A.1}$$

where the values for the mean reference VPT, $T(f_j)_{\text{ref,M}}$, and $s(f_j)$ are given in Table A.2 and Table A.4, respectively.

The VPTs in Table A.2 and Table A.3 are constructed from the VPTs reported in the data sets listed in Table A.1, and have been adjusted to a stimulating probe diameter of 4 mm and a mean age of 30 years. The adjustments applied to VPTs at frequencies of 100 Hz, 125 Hz and 160 Hz to obtain values for a 4 mm diameter stimulating probe are given after Table A.1: There is no adjustment at lower frequencies. The mean VPTs of healthy persons increase with age by approximately 0,03 dB per year at frequencies of 3,15 Hz, 4 Hz, and 5 Hz, 0,08 dB per year at frequencies of 20 Hz, 25 Hz, and 31,5 Hz, and 0,25 dB per year at 100 Hz, 0,3 dB per year at 125 Hz, and 0,35 dB per year at 160 Hz. The mean VPTs for healthy persons at ages other than 30 years may be estimated from this information. For an individual, the change in threshold with age may deviate significantly from that of the mean VPT for healthy persons, and so should not be estimated from this information.

The total number of fingers from which the thresholds in Table A.2 and Table A.3 are calculated, $N_{\text{F}}$, is shown for each stimulation frequency, or equivalent frequency. The VPTs are derived from thresholds

obtained on digits 2 and 3 (see Note 2 in 5.5), and digit 5 if there was no significant difference observed between thresholds mediated by the median and ulnar nerves.

NOTE 2    Small differences in VPTs can occur from using the alternate measurement methods specified in ISO 13091-1. The residual, unexplained difference between the mean VPTs for each study listed in Table A.1 results in the range of VPTs at each percentile in Table A.2 and Table A.3. Large differences from the values in Table A.2 and Table A.3 have been recorded in some studies using Method A when the hand was oriented palm down with the fingertip resting on top of the stimulating probe. An increase in VPT (i.e. reduction in acuity) has been observed in fingers innervated by the ulnar nerve in some studies.

Normal hormonal changes during the menstrual cycle influence the VPTs of females, particularly at frequencies mediated by the FAII receptors (i.e. 100 Hz, 125 Hz and 160 Hz).

The 50 percentile values in Table A.2 and Table A.3 are to be used as reference thresholds for the calculation and interpretation of reference threshold shifts. Thus, values for the term $T(f_j)_{\mathrm{ref}}$ in Formula (5), and for $t(f_j)_{\mathrm{ref}}$ in Formula (6), are given by the mid-range 50 percentile values in Table A.2 and Table A.3, respectively.

**Table A.1 — Sources of VPTs for healthy persons**

| Source | Probe diameter (mm) | Surround (mm) | Algorithm | Subjects | | | |
|---|---|---|---|---|---|---|---|
| | | | | Sex (male, M / female, F) | Number of subjects (N) | Mean age (years) | Population description |
| Reference [4] | 3 | none | up-down (staircase) | M | 38 | 40,8 | Caucasian and Asian professional and manual workers, medically screened, no occupational exposure to vibration or other neurotoxic agents |
| Reference [18] | 6 | 10 | von Békésy | M | 10 | 29,7 | Healthy office workers |
| Reference [19] | 6 | 10 | von Békésy | M | 55 | 34,8 | Healthy white- and blue-collar workers, no history of occupational exposure to vibration or neurological symptoms |
| Reference [19] | 6 | 10 | von Békésy | M | 10 | 30,1 | Healthy blue-collar workers, no history of occupational exposure to vibration or neurological symptoms |
| Reference [19] | 6 | 10 | von Békésy | F | 14 | 31,9 | Healthy blue-collar workers, no history of occupational exposure to vibration or neurological symptoms |
| Reference [22] | 6 | 10 | von Békésy | M | 30 | 31,2 | Healthy people, no history of neuromuscular or vascular disorders, no occupational exposure to vibration or injuries to the hands |
| Reference [22] | 6 | 10 | von Békésy | F | 13 | 30,8 | Healthy people, no history of neuromuscular or vascular disorders, no occupational exposure to vibration or injuries to the hands |
| Reference [23] | 6 | 10 | von Békésy | M | 8 | 24 | Healthy males, no known vascular or neurological disease |
| Reference [25] | 6 | 10 | von Békésy | M | 12 | 24,4 | Healthy males, no history of vibration injuries, occupational exposure to vibration or relevant illness |
| Reference [26] | 6 | 10 | up-down (2 AFC)[a] | M | 12 | 24,6 | Healthy students or office workers, no history of exposure to severe vibration or neurological disorders |

[a] 2 AFC — two alternative forced choices with three-down one-up tracking procedure.

[b] Age at which VPTs were reported.

Adjustment to VPTs at frequencies of 100, 125 and 160 Hz to obtain values for a 4 mm dia. stimulating probe

| Probe diameter used (mm) | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|
| Adjustment (dB) | −4,3 | −1,2 | 0 | 0,7 | 1,3 |

**Table A.1** *(continued)*

| Source | Probe diameter mm | Surround mm | Algorithm | Sex male, M female, F | Number of subjects N | Mean age years | Subjects — Population description |
|---|---|---|---|---|---|---|---|
| Reference [26] | 6 | 10 | up-down (2 AFC)[a] | M | 12 | 24,3 | Healthy students or office workers, no history of occupational exposure to vibration or neurological disorders |
| Reference [26] | 6 | 10 | von Békésy | M | 12 | 25,9 | Healthy students or office workers, no history of occupational exposure to vibration or neurological disorders |
| Reference [27] | 6 | 10 | von Békésy | M | 16 | 26,5 | Males, no significant exposure to vibration or history of peripheral neuropathy |
| Reference [28] | 6 | 10 | von Békésy | M | 30 | 31,2 | Healthy people |
| Reference [28] | 6 | 10 | von Békésy | F | 13 | 29,9 | Healthy people |
| Reference [29] | 6 | 10 | von Békésy | M | 20 | 23,5 | Students or office workers, no regular exposure to vibration, no reported cardiovascular or neurological disorders, or injuries to the hands |
| Reference [29] | 6 | 10 | von Békésy | F | 20 | 23,5 | Students or office workers, no regular exposure to vibration, no reported cardiovascular or neurological disorders or injuries to the hands |
| Reference [30] | 6 | 10 | von Békésy | M | 30 | 31,3 | Healthy office workers with no history of undue exposure to vibration |
| Reference [30] | 6 | 10 | von Békésy | F | 17 | 29,8 | Healthy office workers with no history of undue exposure to vibration |
| Reference [33] | 6 | 10 | von Békésy | M | 14 | 23,9 | Healthy office workers, no history of occupational exposure to vibration |
| Reference [34] | 6 | 10 | von Békésy | M | 14 | 24,8 | No significant exposure to vibration or known causes of peripheral neuropathy |

[a]   2 AFC — two alternative forced choices with three-down one-up tracking procedure.

[b]   Age at which VPTs were reported.

Adjustment to VPTs at frequencies of 100, 125 and 160 Hz to obtain values for a 4 mm dia. stimulating probe

| Probe diameter used (mm) | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|
| Adjustment (dB) | −4,3 | −1,2 | 0 | 0,7 | 1,3 |

**Table A.1** *(continued)*

| Source | Probe diameter mm | Surround mm | Algorithm | Sex male, M female, F | Number of subjects N | Mean age years | Subjects Population description |
|---|---|---|---|---|---|---|---|
| Reference [35] | 6 | 10 | von Békésy | M | 165 | 40[b] | Professional and manual workers, medically screened, no exposure to vibration, or other neurotoxic agents |
| Reference [35] | 6 | 10 | von Békésy | F | 126 | 40[b] | Professional and manual workers, medically screened, no exposure to vibration, or other neurotoxic agents |
| Reference [37] | 3 | 6 | up-down (staircase) | M | 12 | 30 | Office workers, medically screened, no occupational exposure to vibration or other neurotoxic agents, no injuries to the hands |
| Reference [37] | 3 | 6 | up-down (staircase) | F | 9 | 29 | Office workers, medically screened, no occupational exposure to vibration or other neurotoxic agents, no injuries to the hands |

a   2 AFC — two alternative forced choices with three-down one-up tracking procedure.

b   Age at which VPTs were reported.

Adjustment to VPTs at frequencies of 100, 125 and 160 Hz to obtain values for a 4 mm dia. stimulating probe

| Probe diameter used (mm) | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|
| Adjustment (dB) | −4,3 | −1,2 | 0 | 0,7 | 1,3 |

**Table A.2 — Vibrotactile perception thresholds for healthy persons expressed in dB (ref. $10^{-6}$ m/s²)**

| | | Age Years | Frequency Hz 3,15 | 4 | 5 | 20 | 25 | 31,5 | 100 | 125 | 160 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Males** | 2,5 percentile | 30 | 64,0–69,5 | 69,6–72,1 | 71,0–73,5 | 83,7–85,7 | 87,7–89,2 | 89,9–92,4 | 95,2–99,2 | 96,5–98,0 | 97,0–98,5 |
| | 15 percentile | 30 | 68,1–73,6 | 73,7–76,2 | 75,1–77,6 | 87,8–89,8 | 91,8–93,3 | 94,8–97,3 | 100,1–104,1 | 102,1–103,6 | 101,9–103,4 |
| | 50 percentile | 30 | 73,8–78,3 | 78,4–80,9 | 79,8–82,3 | 92,5–94,5 | 96,5–98,0 | 100,2–102,7 | 105,5–109,5 | 108,3–109,8 | 107,3–108,8 |
| | 85 percentile | 30 | 77,5–83,0 | 83,1–85,6 | 84,5–87,0 | 97,2–99,2 | 101,2–102,7 | 105,6–108,1 | 110,9–114,9 | 114,5–116,0 | 112,7–114,2 |
| | 97,5 percentile | 30 | 81,6–87,1 | 87,2–89,7 | 88,6–91,1 | 101,3–103,3 | 105,3–106,8 | 110,5–113,0 | 115,8–119,8 | 120,1–121,6 | 117,6–119,1 |
| | Number of fingers used in the estimate, $N_F$ | | 69 | 207 | 108 | 267 | 168 | 1 070 | 267 | 979 | 267 |
| **Females** | 2,5 percentile | 30 | 63,0–67,5 | 65,1–68,1 | 68,3–70,3 | 84,6–87,6 | 87,5–89,5 | 90,3–92,3 | 91,0–97,0 | 91,5–100,0 | 91,4–100,4 |
| | 15 percentile | 30 | 67,1–71,6 | 69,2–72,2 | 72,4–74,4 | 88,7–91,7 | 91,6–93,6 | 95,2–97,2 | 95,9–101,9 | 97,1–105,6 | 96,3–105,3 |
| | 50 percentile | 30 | 71,8–76,3 | 73,9–76,9 | 77,1–79,1 | 93,4–96,4 | 96,3–98,3 | 100,6–102,6 | 101,3–107,3 | 103,3–111,8 | 101,7–110,7 |
| | 85 percentile | 30 | 76,5–81,0 | 78,6–81,6 | 81,8–85,8 | 98,1–101,1 | 101,0–103,0 | 106,0–108,0 | 106,7–112,7 | 109,5–118,0 | 107,1–116,1 |
| | 97,5 percentile | 30 | 80,6–85,1 | 82,7–85,7 | 85,9–87,9 | 102,2–105,2 | 105,1–107,1 | 110,9–112,9 | 111,6–117,6 | 115,1–123,6 | 112,0–121,0 |
| | Number of fingers used in the estimate, $N_F$ | | 70 | 70 | 70 | 96 | 96 | 452 | 96 | 200 | 96 |

**Table A.3 — Vibrotactile perception thresholds for healthy persons expressed in m/s²**

| | | Age years | Frequency Hz | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 3,15 | 4 | 5 | 20 | 25 | 31,5 | 100 | 125 | 160 |
| **Males** | 2,5 percentile | 30 | 0,001 67–0,003 0 | 0,003 0–0,004 0 | 0,003 5–0,004 7 | 0,015–0,019 | 0,024–0,029 | 0,031–0,042 | 0,058–0,091 | 0,067–0,079 | 0,071–0,084 |
| | 15 percentile | 30 | 0,002 5–0,004 8 | 0,004 8–0,006 5 | 0,005 7–0,007 6 | 0,025–0,031 | 0,039–0,046 | 0,055–0,073 | 0,10–0,16 | 0,13–0,15 | 0,13–0,15 |
| | 50 percentile | 30 | 0,004 4–0,008 2 | 0,008 3–0,011 | 0,009 8–0,013 | 0,042–0,053 | 0,067–0,079 | 0,10–0,14 | 0,19–0,30 | 0,26–0,31 | 0,23–0,28 |
| | 85 percentile | 30 | 0,007 5–0,014 | 0,014–0,019 | 0,017–0,022 | 0,072–0,091 | 0,12–0,14 | 0,19–0,25 | 0,35–0,56 | 0,53–0,63 | 0,43–0,51 |
| | 97,5 percentile | 30 | 0,012–0,023 | 0,023–0,031 | 0,027–0,036 | 0,12–0,15 | 0,18–0,22 | 0,34–0,45 | 0,62–0,98 | 1,01–1,20 | 0,76–0,90 |
| | Number of fingers used in the estimate, $N_F$ | | 69 | 207 | 108 | 267 | 168 | 1 070 | 267 | 979 | 267 |
| **Females** | 2,5 percentile | 30 | 0,001 4–0,002 4 | 0,001 8–0,002 5 | 0,002 6–0,003 3 | 0,017–0,024 | 0,024–0,030 | 0,033–0,041 | 0,036–0,071 | 0,038–0,10 | 0,037–0,10 |
| | 15 percentile | 30 | 0,002 3–0,003 8 | 0,002 9–0,004 1 | 0,004 2–0,005 2 | 0,027–0,039 | 0,038–0,048 | 0,058–0,072 | 0,062–0,12 | 0,072–0,19 | 0,065–0,18 |
| | 50 percentile | 30 | 0,003 9–0,006 5 | 0,005 0–0,007 0 | 0,007 2–0,009 0 | 0,047–0,066 | 0,065–0,082 | 0,11–0,13 | 0,12–0,23 | 0,15–0,39 | 0,12–0,34 |
| | 85 percentile | 30 | 0,006 7–0,011 | 0,008 5–0,012 | 0,012–0,016 | 0,080–0,11 | 0,11–0,14 | 0,20–0,25 | 0,22–0,43 | 0,30–0,79 | 0,23–0,64 |
| | 97,5 percentile | 30 | 0,011–0,018 | 0,014–0,019 | 0,020–0,025 | 0,13–0,18 | 0,18–0,23 | 0,35–0,44 | 0,38–0,76 | 0,57–1,51 | 0,40–1,12 |
| | Number of fingers used in the estimate, $N_F$ | | 70 | 70 | 70 | 96 | 96 | 452 | 96 | 200 | 96 |

**Table A.4 — Values of $s(f_j)$ for Formula (A.1), expressed in dB**

| | Age years | | | | | | | Frequency Hz | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 3,15 | 4 | 5 | 20 | 25 | 31,5 | 100 | 125 | 160 | | | |
| $s(f_j)$ | 30 | 4,5 | 4,5 | 4,5 | 4,5 | 4,5 | 5,25 | 5,25 | 6,0 | 5,25 | | | |
| Number of fingers used in the estimate, $N_F$ | | 139 | 277 | 178 | 320 | 221 | 1 257 | 320 | 906 | 320 | | | |

# Annex B
(informative)

# Implications of changes in vibration perception thresholds

## B.1 Use in clinical medicine

Interest in determining the perception of vibration as an aid to neurological diagnosis has been documented for over 100 years. Early investigators reported reduced vibrotactile perception (i.e. increased VPTs) in cases of diabetes mellitus, peripheral neuritis and pernicious anaemia, and hypersensitivity (i.e. reduced VPTs) in cases of Parkinson's disease. More recently, vibrotactile perception has been proposed as a technique for detecting various peripheral neurological disturbances, either generalized or focal, arising from disease or from exposure to chemical or physical agents. The technique has been applied to a diverse range of conditions including carpal tunnel syndrome, radial tunnel syndrome, repetitive strain injury, ulnar neuropathy, polyneuropathy, and persons exposed to hand-arm vibration. When VPTs are determined at several stimulation frequencies, or equivalent frequencies, calculating the sensibility index or plotting a tactogram has proved beneficial in the interpretation of the results.

A repeated measurement of relative threshold shift, provided it is conducted using the same apparatus and measurement protocol, has proved beneficial in situations in which a known pathological process is followed over time. In this way, systematic errors introduced by the apparatus are avoided, and the utility of the test then depends ultimately on the intra-subject test/retest variability. The use of relative threshold shifts as a measure of disease severity has been reported for diabetics, renal dialysis patients, cancer patients undergoing chemotherapy, and for workers exposed to chemical and physical neurotoxic agents. Relative threshold shifts have also been used to monitor the progress of nerve repair and rehabilitation of hand function.

The use of VPTs as an objective test in clinical medicine has also been validated. The associations between VPTs and other methods for assessing peripheral nerve dysfunction, and in particular nerve conduction and other modalities of quantitative sensory testing, have been documented. These subjects are considered in the following.

The absence of standardized methods for determining VPTs and the limited sources of normative values for healthy hands have, in the past, hindered widespread acceptance of the technique in clinical practice. These limitations are addressed in this document. The standardization of measurement methods that result in VPTs mediated only by one population of mechanoreceptors at a given stimulation frequency, or equivalent frequency, provides more information concerning tactile nerve function than generally available in the past. The implications of this additional information are also considered in this annex.

## B.2 Tactile physiology and threshold shifts

The tactile performance of the hand depends on the neural activity in up to four populations of specialized nerve endings located at the fingertips. The different mechanoreceptor populations are usually classified by their response to skin indentation and by the extent of their receptive fields. The VPTs of three of the populations may be determined by the methods of ISO 13091-1. The fourth receptor population, for which no method of measurement is provided in ISO 13091-1, signals skin stretch.

The three mechanoreceptor populations at the fingertips for which VPTs may be obtained are: the slow-adapting type 1 receptors (SAI) which correspond anatomically to the Merkel disks; the fast-adapting type 1 receptors (FAI) which correspond anatomically to the Meissner corpuscles; and the fast-adapting type 2 receptors (FAII) which correspond anatomically to the Pacinian corpuscles. SAI receptor acuity primarily determines the resolution of spatial features of a surface, such as ridges and texture. In contrast, FAI and FAII receptor acuity is primarily responsible for information obtained

from the motion of surfaces across the skin. In addition to tactile exploration, the gripping of objects between the fingertips and thumb depends on the detection of microscopic slippage of the object, which is signalled primarily by the FAI receptors, and so is effectively controlled by tactile acuity rather than by neuromuscular function.

Changes in the VPTs of SAI, FAI and FAII receptors may thus be expected to influence specific aspects of tactile function, and the holding and manipulation of objects. In a clinical setting, the changes can reflect underlying disease. The threshold shifts recorded at the fingertips at different frequencies are found to possess distinctive patterns. The patterns are most easily distinguished by plotting the threshold shifts as tactograms, as shown for two fingers (from different subjects) in Figure B.1. Reference threshold shifts have been plotted in each case.



**Key**
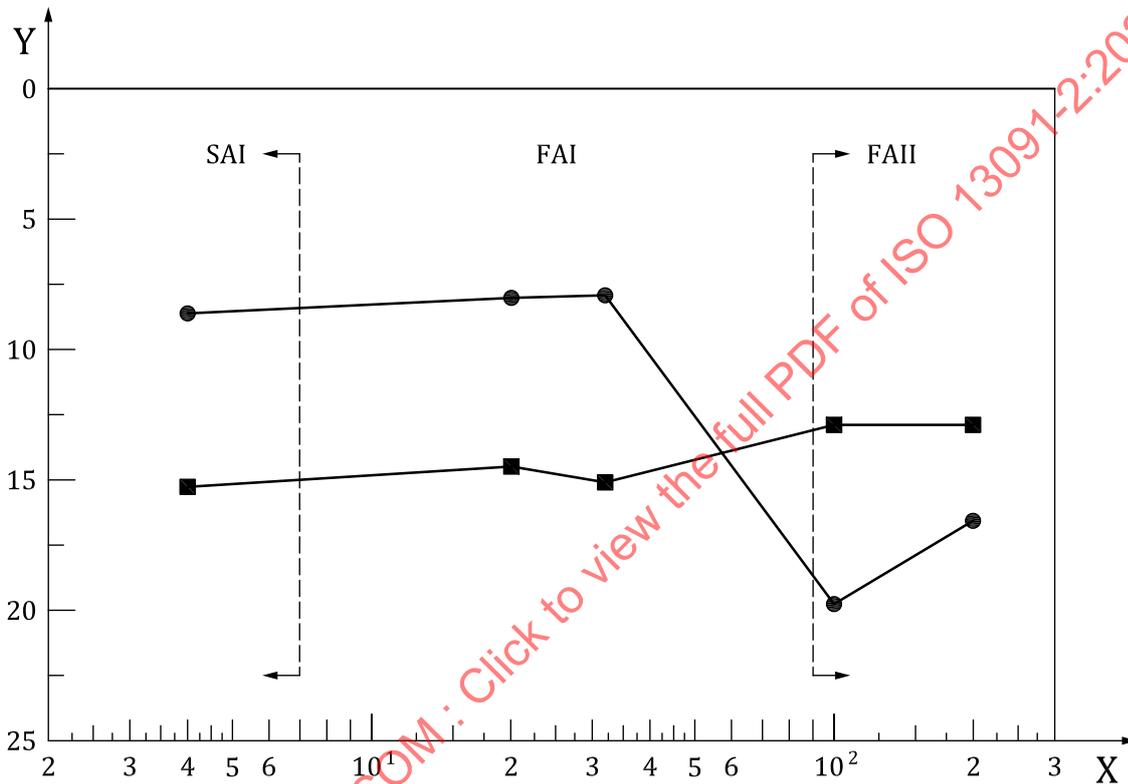
X    frequency, in Hz

Y    threshold shift, in dB

**Figure B.1 — Tactogram showing patterns of reference threshold shift in the fingers of two chain saw operators**

As shown by these examples, threshold shifts of similar magnitude are usually observed at frequencies mediated by the same mechanoreceptor population (e.g. at 20 Hz and 31,5 Hz). In some fingers, the threshold shifts are found to be similar in magnitude for all receptor populations, as shown by the filled squares in the example of Figure B.1. The threshold shifts can, however, differ between different receptor populations in the same fingertip. Thus, the threshold shifts shown by the filled circles in Figure B.1 can be seen to be of similar magnitude for the SAI and FAI receptor populations, but are of greater magnitude for the FAII receptors. The difference in threshold shift between that of the FAII population and those of other receptor populations in this finger is statistically significant.

The patterns of threshold shift provide information on the nature of changes in sensory nerve function, or nerve injury, and are suggestive of either changes occurring in the whole nerve (squares in Figure B.1) or of changes involving only in one or two receptor populations (circles in Figure B.1). The latter may imply selective distal involvement of nerve fibres or receptors.

## B.3   Association between VPTs, common clinical tests and nerve conduction

There have been several studies of persons with upper extremity complaints to assess the efficacy of different clinical tests. In one such study involving both vibrotactile perception and nerve conduction, neurological symptoms were reported by 98 % of shipyard employees who used power tools at work. In this population group, the VPTs at 120 Hz were uniformly elevated when compared with an industrial group of healthy manual workers and were consistently the most abnormal of the laboratory tests, including nerve conduction.

In another study, the associations between VPTs measured on digits 1 and 5 of each hand (see NOTE 2 in 5.5), the results of a traditional neurological examination of the hand and arm involving the perception of vibration (tuning fork) and pain (pin prick), proprioception (joint position) and nerve conduction were established in a series of patients attending for an unrelated diagnostic evaluation. The strongest associations were found between VPTs and the tuning fork data from the same finger ($p < 0,001$). A statistically significant association was also found between VPTs and proprioception ($p < 0,01$), and a weaker association between VPTs and pin prick ($p < 0,05$). A similar association was also observed between VPTs and the sensory nerve compound action potentials and conduction velocities in the corresponding finger ($p < 0,05$). The associations were of similar magnitude for fingers innervated by the median and the ulnar nerves.

The use of VPTs as a diagnostic aid for carpal tunnel syndrome has led to conflicting results. At least part of the reason must lie in the performance limitations of the apparatus used to obtain the VPTs, none of which satisfied the requirements of ISO 13091-1. A prevailing view is that the associations are extremely dependent on the normative values used, as well as the diagnostic criteria employed for the target disorder, an observation that is equally applicable to other applications of VPTs as an aid to diagnosis.

The finding of a lack of an association between VPTs and the results of another test modality in a group of subjects is not necessarily a cause for concern, as one test may detect physiological or pathological changes undetectable by the other. An example of a tactogram from a case series with normal nerve conduction and non-specific hand dysfunction is shown in Figure B.2. This 42-year-old former shipyard grinder with wrist pain and difficulty coordinating the movements of a computer control puck possesses statistically significant reference threshold shifts in the SAI and FAI receptors of both hands, but not the FAII receptors. The subject was assessed as neurologically normal by nerve conduction. Moreover, the threshold shifts are strikingly similar in digits 3 and 5 of each hand, and the same pattern was observed in both hands.

## B.4   Association between threshold shifts and hand function

The determination of VPTs provides a quantitative procedure for evaluating the somatosensory pathways conveying tactile information to the brain. From a functional perspective, the afferent output is essential for the tactile identification of objects and, as part of the sensorimotor loop, for the manipulation and control of objects.

An association between VPTs at the fingertips and symptoms of reduced manipulative function established by responses to a questionnaire has been demonstrated in a group of manual workers. In this study, mechanoreceptor-specific vibrotactile thresholds were determined for the SAI, FAI and FAII receptors at the fingertip using a measurement procedure consistent with ISO 13091-1. Statistically significant reference threshold shifts were found in the SAI and/or FAII receptor populations for persons responding affirmatively to questions concerning finger or hand numbness and difficulty in buttoning clothing. The best predictors of the observed reference threshold shifts were questions relating to the difficulty in manipulating small objects, and buttoning clothing, which yielded positive predictive values from 90 % to 100 % and false positive rates from 0 % to 2,8 %.

The potential for early detection of relative and reference threshold shifts in order to prevent the development of functional incapacity in the case of deteriorating acuity, and to follow nerve repair or recovery in the case of improving acuity, has also been studied. A cohort of manual workers (operating lightweight chain saw) has been followed, 30 % of whom reported symptoms suggestive of changes in neurosensory or neuromuscular function at the commencement of the study. The VPTs were compared