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Mechanical vibration and shock — Evaluation of human exposure to whole-body vibration —

Part 5: Method for evaluation of vibration containing multiple shocks

Vibrations et chocs mécaniques — Évaluation de l'exposition des individus à des vibrations globales du corps —

Partie 5: Méthode d'évaluation des vibrations contenant des chocs répétés

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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).

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For an explanation on 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 the following URL: 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*.

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.

This second edition cancels and replaces the first edition (ISO 2631-5:2004), which has been technically revised. The main changes compared to the previous edition are an improved description of the physiological response function for the exposure and improved guidance on the associated risk.

A list of all the parts in the ISO 2631 series can be found on the ISO website.

This corrected version of ISO 2631-5:2018 incorporates the following corrections:

— Figure 1: subclause numbers in the "Severe conditions" box were corrected as follows:

  — "Measurement (5.1)";

  — "Signal conditioning (5.1.3)";

  — "Evaluation (5.2, 5.3)";

  — "Risk injury (Annexes B and C)".

Introduction

The purpose of this document is to define a method of quantifying whole-body vibration containing multiple shocks in relation to human health in the seated posture. In biodynamics, the term “shock” is used to describe a wide range of short-time, high-magnitude exposures. It covers the range of severity starting at mild shocks resulting only in annoyance and brief discomfort up to magnitudes of shock sufficient to cause pain, injury or substantial physiological distress.

The methods described in this document can be appropriate for assessing the risk of chronic injury from exposure to repeated shock as can be experienced in military, commercial or recreational off-road vehicles, including agricultural vehicles, heavy plant equipment and high-speed marine craft. The methods are not intended to assess the probability of acute damage from a single impact.

The assessment methods described are based on the predicted biomechanical response of the bony vertebral endplate (hard tissue) in an individual who is in good physical condition with no evidence of spinal pathology. However, the risk assessment methods and related models described in this document have not yet been systematically epidemiologically validated. The methods provide nevertheless a quantitative description of the exposure, which is necessary to assess relative differences between exposures, e.g. the effects of some protective measures and different exposure conditions.

This document solely addresses lumbar spine response on the basis of studies indicating that the lumbar spine can be adversely affected by exposures to whole-body vibration[6][7][8][9][10][11][38][39][47][48][54][55] which also contain multiple shocks. Other adverse health effects of exposure to repeated shock, such as damage to parts of the body other than the lumbar spine, or types of short or long term health effects other than damage to the vertebral end plates, are not specifically considered by this document. Such end plate damage often cannot be differentiated by damages caused by other exposures (heavy lifting) and diseases.

This document considers only the effects of compressive loads from multiple shocks. To this end, a seat-to-lumbar spine transfer function of the measured acceleration has been developed for a default posture, body height and lumbar spine level. Another method to describe the spinal response is given in Annex A, which is valid only for a limited range of acceleration magnitudes but includes the effect of different postures, body heights and lumbar spine levels.

A standardized approach to the prediction of injury for non-vertical or combined axes shocks is complicated by the range of different postures and body restraint systems that can be employed in different vehicles and the limitations of current capabilities for predicting injury from non-vertical shock. Shocks involving horizontal, rotational or multi-axial motion are known to occur in practice and can present a significant risk of injury.

The risk of injury in the lumbar spine depends on an exposure dose, which is a combination of an exposure quantity and a duration. A manifest injury can take several years to develop. Due to the complexity of the measurement of multiple shocks, it is at the moment not possible to measure the exposure of the lifetime dose directly. Instead, the exposure is measured in representative situations and the dose is extrapolated from this measurement to a recorded exposure duration in the past or an anticipated exposure duration in the future. To monitor constantly the lifetime dose at a workplace, alternative measurement equipment will need to be developed, e.g. dosemeters.

Mechanical vibration and shock — Evaluation of human exposure to whole-body vibration —

Part 5: Method for evaluation of vibration containing multiple shocks

1 Scope

This document addresses human exposure to multiple mechanical shocks, and it formulates requirements for the measurement of multiple shocks. The results of these measurements are then analyzed to provide information for the assessment of the risk of adverse health effects to the vertebral end-plates of the lumbar spine for seated individuals due to compression. Other injuries could develop even when there is no injury to the end plate.

NOTE 1 Multiple mechanical shocks are shocks of different magnitude and shape that occur frequently at regular and irregular intervals during the measurement period.

NOTE 2 As proposed in the annexes, the assessment of the current injury risk is based on measured representative exposures in combination with the individual exposure history. Prospective risks can be assessed by anticipated exposure durations. Manufacturers of measurement equipment are encouraged to develop a possibility for an on-site evaluation of the exposure.

Two exposure regimes are distinguished in this document: one for severe conditions and one for less severe conditions.

NOTE 3 Clause 4 contains the delineation of the two regimes.

This document is applicable for unweighted vertical accelerations that have peak values up to 137,3 m/s^2 (14 g) measured at the seat-occupant interface beneath the ischial tuberosities over a 0,01 Hz to 80 Hz measurement bandwidth.

NOTE 4 The measurement bandwith is defined in 5.1.

Caution is necessary when applying the method to severe exposures, particularly since peak accelerations of 137,3 m/s^2 (14 g) are close to the physical limit that a spine can tolerate.

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 2631-1:1997, *Mechanical vibration and shock — Evaluation of human exposure to whole-body vibration — Part 1: General requirements*

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

ISO 10326-1, *Mechanical vibration — Laboratory method for evaluating vehicle seat vibration — Part 1: Basic requirements*

3 Terms, definitions and symbols

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 2041 and ISO 5805 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 http://www.electropedia.org/

3.2 Symbols (units)

$a_z(t)$	input acceleration in z-direction depending on time (1 m/s^2)
$a_z(\omega)$	Fourier transform of $a_z(t)$ (1 m/s)
$A_z(t)$	time dependent spinal acceleration response function (1 m/s^2)
$A_z(\omega)$	frequency dependent spinal acceleration response function (1 m/s)
$A_{z,i}$	i^{th} maximal value of $A_z(t)$ (1 m/s^2)
B	endplate area of a vertebra (1 mm^2)
C_{dyn}	response function of compressive force in Annex A (1 N)
$C_{dyn,i}$	i^{th} maximal value of C_{dyn} (1 N)
D_z	acceleration dose depending on $A_{z,i}$ for t_m (1 m/s^2)
D_{zd}	daily acceleration dose extrapolated for t_d (1 m/s^2)
$H(\omega)$	transfer function (1)
m_z	acceleration–compressive stress conversion factor depending on mass in Annex C [$1 \cdot 10^6$ Pa/(m/s^2) = 1 MPa/(m/s^2)]
N	number of exposure days per year (1)
Π	risk of vertebral failure, based on R (1)
R	stress variable for the risk calculation for model in Clause 5 (1)
R^A	risk factor based on S_d^A (1)
S_d	daily compression dose for model in Clause 5 (1 MPa)
S_{stat}	static stress for model in Clause 5 (based on gravitation) (1 MPa)
$S_{u,i}$	vertebral ultimate strength for model in Clause 5 for year i (1 MPa)
S^A	compressive dose in Annex A (1 MPa)
S_d^A	daily compressive dose in Annex A (1 MPa)
S_q^A	compressive dose for variable exposures in Annex A (1 MPa)
S_{stat}^A	static stress for model in Annex A (based on mean C_{dyn}) (1 MPa)
$S_{u,i}^A$	vertebral ultimate strength for model in Annex A for year i (1 MPa)
t	time (1 s)
t_d	duration of daily exposure (1 s)
t_m	measurement duration (1 s)
ω	angular frequency (1 Hz)

R_q^A risk factor based on S_q^A (1)

NOTE The quantities that describe the injury risk are defined in Annex C (model of Clause 5) and Annex E (model of Annex A). For Clause 5, the injury risk is described by $\Pi(R)$, which is a function of R. This stress variable R differs from the injury risk R^A for the model of Annex A, which is defined in Annex E.

4 Delineation of the two exposure regimes

The exposure conditions in this document differ from those for the basic evaluation of whole-body vibration as described in ISO 2631-1.

NOTE 1 ISO 2631-1:1997, Clause 6 contains criteria, when additional methods of evaluation need to be used, including ISO 2631-5.

There are two exposure regimes that have to be distinguished:

a) On the one hand, one finds severe conditions which are typical for military off-road vehicles or high speed marine craft, etc. These severe conditions can contain periods of free fall, they are dominated by accelerations in the z-axis, and the subjects can lose contact with the seat surface due to the exposure. These conditions are addressed in Clause 5 and in Annexes C and D. Here, the requirements for the measurement (bandwidth, signal conditioning) differ from those in ISO 2631-1, and the contributions of the x- and y-directions to the compressive forces in the spine are neglected since the exposure is dominant in the z-direction.

   NOTE 2 Issues arising from the limitation to a default posture and a purely vertical excitation are addressed in the Introduction and in Annex B.

b) On the other hand, less severe conditions are also covered by this document without free-fall events and where the subject remains seated throughout the measurement. These are more likely in an industrial context, e.g. driving with tractors, forestry machines and mobile earth-moving machinery over rough surfaces (off-road, potholes, frequent crossing of railroad tracks, etc.). These conditions are addressed in Annexes A and E. The requirements for the measurement are the same as for the unweighted acceleration time series described in ISO 2631-1.

   To determine the regime for a given exposure, two questions have to be used:

   i) Does the driver lose contact with the seat (or would the driver lose contact in absence of a restraint system)?

   ii) Does the exposure contain periods of free fall?

If either question is answered with yes, the method of Clause 5 and Annexes C and D has to be used.

In case of doubt, these criteria can be checked quantitatively by measuring a representative exposure with the method outlined in Clause 5 or in Annex A (the more likely one is chosen). The measured time series in z-direction at the person are then checked: after applying the band-limiting filters described in ISO 2631-1, the peak accelerations shall not exceed 9,81 m/s^2 for the use of Annexes A and E. If the peak accelerations thus obtained exceed 9,81 m/s^2, Clause 5 and Annexes C and D apply.

1) If one starts with the requirements for the severe conditions, one proceeds with the signal conditioning process up to the step before the band-limiting filter is applied. The check is performed with a copy of the signal, so that the correct band-limiting filter (see 5.1.3) can be applied after the successful check.

2) If one starts with the requirements for the less severe conditions, and if the check is successful, one can use the band-filtered signal from the check for the further evaluation.

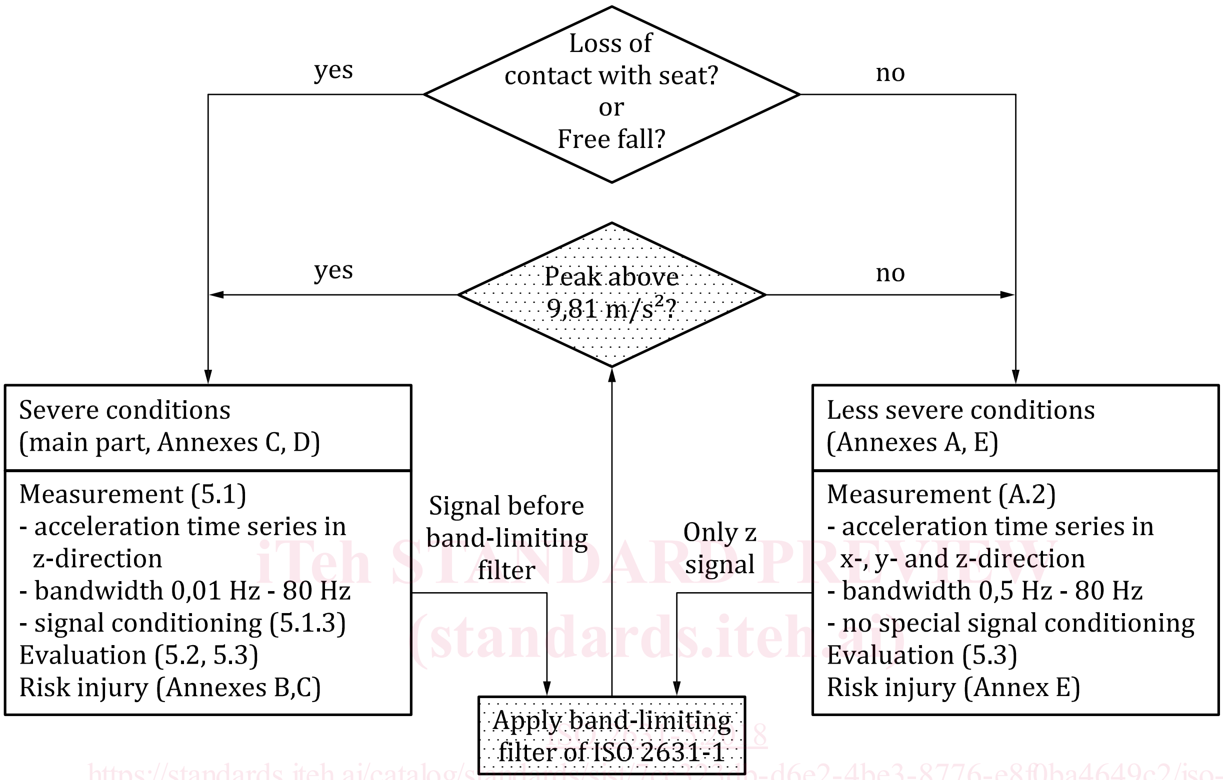
3) If the check does not confirm the first assumption of the exposure conditions, the measurement has to be repeated with the requirements of the other exposure condition.

This check is optional and, therefore, shaded in Figure 1.

NOTE 3 The band-limiting filters for the z-direction in ISO 2631-1 are:

— High pass: two-pole filter with Butterworth characteristic, corner frequency 0,4 Hz,

— Low pass: two-pole filter with Butterworth characteristic, corner frequency 100 Hz.



NOTE The shaded parts allow for an optional, quantitative confirmation of the first decision.

Figure 1 — Flowchart for the application of the models used in this document

5 Description of the model

5.1 Vibration measurement

5.1.1 General considerations

Vibration measurement, including the direction of measurement, location of transducers, duration of measurement, and reporting of vibration conditions, shall follow the requirements given in ISO 2631-1 except as described in 5.1.2 to 5.1.4.

5.1.2 Measurement location and specific hardware requirements

The vertical acceleration $a_z(t)$ should be measured at the interface between the seat and the ischial tuberosities.

During data collection, the subject should remain seated and should not rise from the seat. The location of measurements on the seat and the design of the accelerometer disk on the seat pad shall be as specified in ISO 10326-1.

Contact switches, video recordings or other methods should be used to detect loss of contact between the subject and the seat surface. It is necessary to detect and report the loss of contact, since accelerations measured during loss of contact shall not be counted as exposure. In addition, it shall be ensured that the impact experienced landing on the seat (i.e., both the motion of the person *and* the motion of the seat) after free fall is fully taken into account.

The accelerometers and associated measuring equipment shall be appropriate for measuring the highest amplitude accelerations anticipated during the measurement period.

The recorded, digitized accelerations should have a flat acceleration frequency response from 0,01 Hz to at least 80 Hz. A sampling rate of 256 samples per second or greater can be necessary depending on the anti-aliasing method used.

Details of the measurement equipment, including description of the calibration methods used, shall be provided.

5.1.3 Signal conditioning

The different steps of the signal conditioning process are summarised in Figure 2.

1. Sign check (cranial +)
2. Elimination of loss of contact
3. Resampling
4. Offset correction
5. Tapering
6. Band-limiting filter

Figure 2 — Steps of the signal conditioning process

In the first step, it is important to check that the sign of acceleration signals (positive, negative) is correct as the analysis method is concerned with compressive spinal loading. In the basicentric coordinate system for seated persons, the direction of the z-axis acceleration is positive to cranial (i.e. upward is positive).

After the sign of the acceleration signals has been checked, the second step eliminates those parts of the signal where there is no contact between the accelerometer disk on the seat pad and the subject. This leads to separate parts of the signal to which the following steps are applied separately.

In the third step, if the data have to be re-sampled for analysis after being acquired at a higher frequency, then it is necessary to check that appropriate anti-aliasing filtering is used.

NOTE 1 Resampling functions provided by common data processing software packages, such as MATLAB®[1)], can apply suitable anti-aliasing filters automatically but it is important to check that this is the case.

In the fourth step, the measured acceleration should have an offset correction so that the recorded acceleration, with the accelerometer at rest (or with a symmetric signal), is (0 ± 0,1) m/s^2. Note that subtraction of the mean may not be appropriate if the recorded acceleration is asymmetric.

In the fifth step, if analysing a time history where the accelerometer was in motion at the start or end of the recording, then tapering the signal, for instance with a cosine taper applied over several seconds, may be appropriate before applying the band-limiting filters.

Finally, in the sixth step, the offset-corrected acceleration measurements shall be band-limited at 0,01 Hz and 80 Hz using second order Butterworth high pass filter with cut-off frequencies of 0,01 Hz

1) MATLAB® is the trademark of a product supplied by MathWorks. This information is given for the convenience of users of this document and does not constitute an endorsement by ISO of the product named.

and a fourth order Butterworth low pass filter with a cut-off frequency of 80 Hz. The band-limiting and weighting filters described in ISO 2631-1 should not be applied.

NOTE 2 The low frequency limit is reduced from that in ISO 2631-1 to prevent distortion of the acceleration signal if there is a period of free fall before a severe impact. Free-fall periods in excess of 0,5 s have been observed for fast naval craft. High pass filtering at 0,5 Hz causes the –1 g free-fall acceleration to be shifted back to zero by the time the impact occurs. This causes the peak acceleration of the impact to be incorrectly offset by up to +1 g. Calculations with a limited number of fast naval craft motions suggested errors of 10 % could be caused. Abrupt changes in terrain contour or steep slopes can cause a similar effect. If there is little movement at the measurement location at frequencies below 0,5 Hz, then errors caused by distortions of the time history due to the filter are likely to be small.

5.1.4 Measurement duration

The duration of the measurement shall be sufficient to ensure that measured results are representative of the exposure, i.e. that the measured multiple shocks are typical of the exposures that are being assessed.

Since shock events may be infrequent, consideration should be given to estimating the duration required to obtain a sufficient number of representative impacts. The duration of measurement should be appropriate to the assessment of the overall exposure.

NOTE 1 It is not practical to specify a sufficient number of impacts as this depends on how variable the impacts are. If the severity of impacts is variable with some at relatively low magnitudes and a few severe shocks, then a longer measurement is likely to be necessary to increase the probability of capturing these severe shocks.

NOTE 2 In repeatable tasks (e.g. mine haul trucks), recording at least a complete work cycle would be representative. In non-repeatable tasks (e.g. off-road travel, military transport), the sufficient duration depends also on the variability in the terrain.

Careful consideration shall always be given to controlling the shock and vibration exposure of any personnel involved in the trial. It may be appropriate to take shorter measurements initially to gain confidence that exposures will not be excessive. Trials where humans are exposed to repeated shock are likely to require careful risk assessment.

5.2 Determination of spinal response

A seat-to-lumbar spine transfer function has been developed based on experimental results and numerical modelling of seated occupants[4][5][15][72]-[75].

The frequency response of the transfer function between the seat and the spine is given in Formula (1) in terms of one complex zero and six complex poles.

$$H(\omega)=\frac{1+2\zeta_1\frac{j\omega}{\omega_1}+\left(\frac{j\omega}{\omega_1}\right)^2}{\left\{\begin{array}{l}\left[1+2\zeta_2\frac{j\omega}{\omega_2}+\left(\frac{j\omega}{\omega_2}\right)^2\right]\left[1+2\zeta_3\frac{j\omega}{\omega_3}+\left(\frac{j\omega}{\omega_3}\right)^2\right]\\\left[1+2\zeta_4\frac{j\omega}{\omega_4}+\left(\frac{j\omega}{\omega_4}\right)^2\right]\left[1+2\zeta_5\frac{j\omega}{\omega_5}+\left(\frac{j\omega}{\omega_5}\right)^2\right]\\\left[1+2\zeta_6\frac{j\omega}{\omega_6}+\left(\frac{j\omega}{\omega_6}\right)^2\right]\left[1+2\zeta_7\frac{j\omega}{\omega_7}+\left(\frac{j\omega}{\omega_7}\right)^2\right]\end{array}\right\}} \quad (1)$$

where

j $=\sqrt{-1}$;

ω_1 = 34 rad/s;

ζ_1 = 0,35;

ω_2 = 31 rad/s;

ζ_2 = 0,21;

ω_3 = 230 rad/s;

ζ_3 = 0,88;

ω_4 = 260 rad/s;

ζ_4 = 0,80;

ω_5 = 320 rad/s;

ζ_5 = 0,40;

ω_6 = 380 rad/s;

ζ_6 = 0,75;

ω_7 = 420 rad/s;

ζ_7 = 0,65.

Tolerances for any implementation of this transfer function by analogue or digital means are

a) ±2,5 % of the peak magnitude (i.e. ±0,04) about the target magnitude response and ±π/(10 rad) about the target phase response from zero to 40 Hz;

b) ±5 % of the peak magnitude (i.e. ±0,08) about the target magnitude response from 40 Hz to 80 Hz (no phase requirement);

c) ±5 % of the peak magnitude (i.e. +0,08) about the target magnitude response above 80 Hz (no lower bound and no phase requirement).

The frequency response of the seat to spine transfer function with tolerances is shown in Figure 3.

