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Mechanical vibration — Description and determination of seated postures with reference to whole-body vibration

National foreword

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TECHNICAL REPORT

ISO/TR 10687

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Mechanical vibration — Description and determination of seated postures with reference to whole-body vibration

Vibrations mécaniques — Description et détermination des postures assises en référence à des vibrations transmises à l'ensemble du corps

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Foreword

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ISO/TR 10687 was prepared by Technical Committee ISO/TC 108, *Mechanical vibration, shock and condition monitoring*, Subcommittee SC 4, *Human exposure to mechanical vibration and shock*.

Introduction

Seated persons exposed to whole-body vibration carry a risk for low-back pain and for spinal degeneration which is most likely increased by unfavourable postures. However, the biomechanical mechanism of this increase is not fully understood.

It is therefore necessary, as a first step, to determine the posture and ergonomic environment of a seated person with special focus on the spine.

To this end, this Technical Report summarizes descriptive quantities that

— are likely to be relevant for the assessment of adverse health effects due to whole-body vibration and unfavourable seated posture;

— can be determined using a variety of methods;

— are in accordance with the description of static, unfavourable seated postures as far as angles of body segments are concerned;

— include additional information, e.g. the presence of arm- or backrests.

It is recommended that the whole set of quantities be reported in order to

— facilitate the comparison of seated postures;

— be able to compare different methods for the determination of the seated posture;

— permit further investigation, e.g. in biomechanical laboratories, on the basis of the determined seated postures.

Due to limitations of the applied assessment methods, it might be necessary to combine different methods in order to be able to report a complete list of quantities.

This Technical Report does not recommend sampling strategies or evaluation methods.

Mechanical vibration — Description and determination of seated postures with reference to whole-body vibration

1 Scope

This Technical Report summarizes descriptive quantities for those responsible (e.g. scientists, safety engineers) for determination of postures for a seated person who is exposed to whole-body vibration. It is the intention that the results of different methods which also are summarized can be easily related to these quantities and that they allow for a common terminology between practitioners. The postures determined can also be used as a basis for further investigation or as a means of comparison for different methods. Although some of the approaches described here can be applied to standing or recumbent positions, additional considerations are likely to be required in these cases.

NOTE 1 This work is closely related to International Standards which focus on static postures (ISO 11226[4]) or on radiologically accessible landmarks, i.e. points on the body (ISO 8727[3]).

Additionally, this Technical Report deals with dynamic postures where body angles or associated movements are determined visually or by measuring points on the skin or clothing.

NOTE 2 Nevertheless, ISO 8727[3] and ISO 11226[4] put forward principles for further extensions which are followed in this Technical Report, in particular for measurements of body angles.

This Technical Report does not recommend sampling strategies or evaluation methods.

2 Description of posture quantities

2.1 General

This clause summarizes the description of measurable quantities used in 5.2. The basis of the descriptions is the points on the body as shown in Figure 1.

2.2 Points on the body

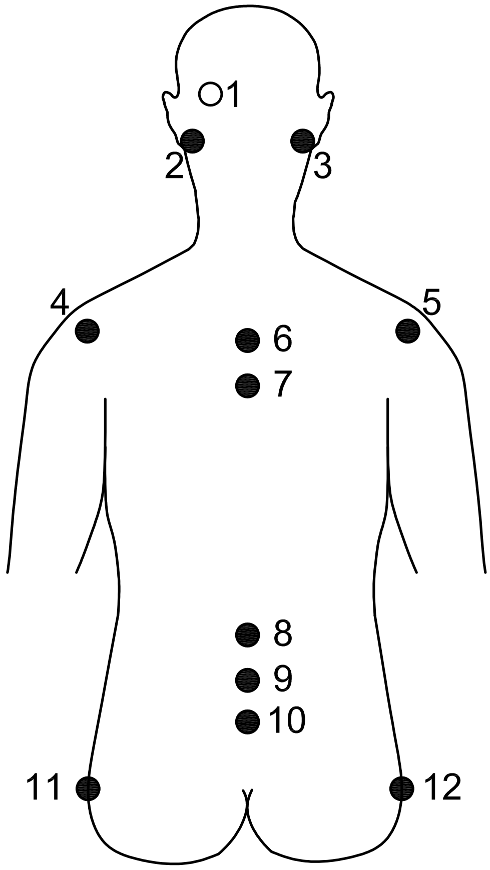
With the help of the points on the body presented in Figure 1, lines and planes can be defined, which in turn define a posture. They are chosen in such a way that their position in space is relevant for the strain on the spine.

A line between two points is represented by the respective normalized vector, $\boldsymbol{v}_{\text{l}}$. A plane is represented by three points and a normalized vector, $\boldsymbol{v}_{\text{pl}}$, perpendicular to that plane.

Their angles with respect to the coordinate system can in turn be correlated to movements of parts of the spine that are considered to be independent from one another.

A general vector in the coordinate system described in Clause 4 is represented in Figure 2.

Having defined suitable points on the body, two markers for optical measurement systems determine a line, $\boldsymbol{v}_{\text{l}}$, and three markers are needed for a plane, $\boldsymbol{v}_{\text{pl}}$. Triaxial accelerometers, on the other hand, combined with, e.g. gyroscopes or magnetic sensors, offer a possibility to measure a (local) line, $\boldsymbol{v}_{\text{l}}$, with only one sensor unit.



Key

1 left lateral canthus
2 left tragus
3 right tragus
4 left acromion
5 right acromion
6 C_7 (spinous process)
7 T_3 (spinous process)
8 L_5 (spinous process)
9 L_3 (spinous process)
10 L_1 (spinous process)
11 left greater trochanter
12 right greater trochanter

Figure 1 — Sketch of the human body with landmarks, i.e. points on the body that should be monitored if using a marker-based measurement system

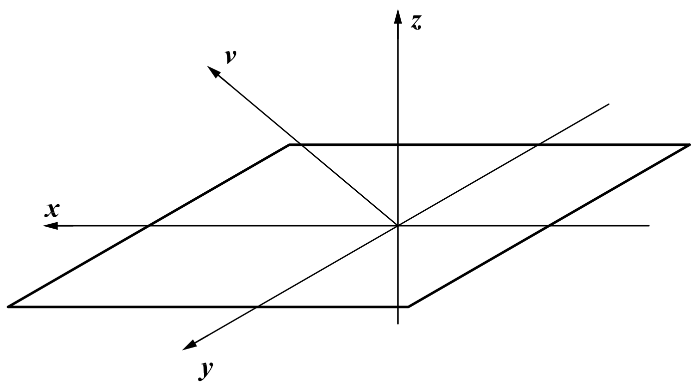


Figure 2 — Cartesian coordinate system for a general vector, *v*

Experiments that do not measure the absolute posture in space, but a relative posture, should measure the reference (the upright standing or seated posture) in the Cartesian coordinate system of Clause 4 in order to be able to transform their data later.

2.3 Flexions and axial rotations

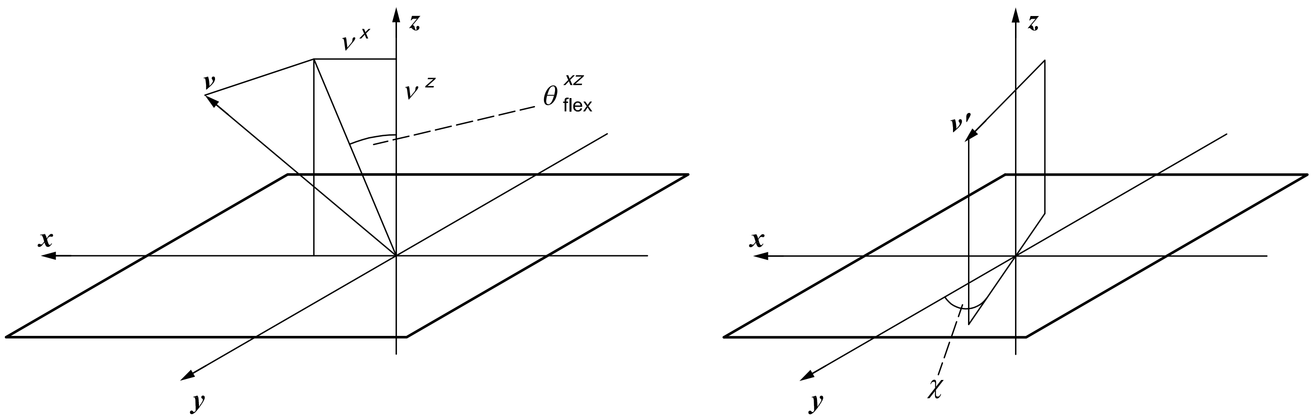
Once the posture of a part of the body is defined by a vector, $\boldsymbol{v}$, its sagittal flexion can be defined by the angle $\theta_{\text{flex}}^{xz}$ of the projection of $\boldsymbol{v}$ on to the xz-plane and the z-axis:

$$\theta_{\text{flex}}^{xz} = \arctan\frac{v^x}{v^z} \tag{1}$$

This is shown in Figure 3 a). A sagittal extension is given by $v^x < 0$. The lateral flexion is defined accordingly by the angle of the projection of $\boldsymbol{v}$ on to the yz-plane and the z-axis:

$$\theta_{\text{flex}}^{yz} = \arctan\frac{v^y}{v^z} \tag{2}$$

Here, the sign of v^y determines left and right lateral flexion.



a) Sagittal flexion of a vector $\boldsymbol{v}$

b) Rotation of a vector $\boldsymbol{v}$

Figure 3 — Sagittal flexion and rotation of a vector $\boldsymbol{v}$

The effects of flexions and extension on a given vector $\boldsymbol{v}_{\text{rot}}'$ parallel to $\boldsymbol{z}$ can be described by applying a rotary matrix to that vector $\boldsymbol{D}^{-1}(\theta,\phi)\boldsymbol{v}_{\text{rot}}' = \boldsymbol{v}_{\text{rot}}$ where θ, ϕ are the polar angles of $\boldsymbol{v}_{\text{rot}}$. Consequently, the effects can be eliminated by the inverse rotary matrix $\boldsymbol{v}_{\text{rot}}' = \boldsymbol{D}(\theta,\phi)\boldsymbol{v}_{\text{rot}}$. This is used to describe axial rotation independently from flexions and extension.

If $\boldsymbol{v}_{\text{rot}}$ is the rotation axis around which another unit vector $\boldsymbol{v}$ is rotated, and if $\boldsymbol{v}_{\text{rot}}' = \boldsymbol{D}(\theta,\phi)\boldsymbol{v}_{\text{rot}}$ is parallel to $\boldsymbol{z}$, then $\boldsymbol{v}' = \boldsymbol{D}(\theta,\phi)\boldsymbol{v}$ defines the vector $\boldsymbol{v}'$ which in this Technical Report is always chosen to be orthogonal to $\boldsymbol{v}_{\text{rot}}'$ and $\boldsymbol{z}$, see Figure 3 b).

This defines the rotation angle of $\boldsymbol{v}$ around $\boldsymbol{v}_{\text{rot}}$, independent from flexions and extension, with respect to $\boldsymbol{y}$ by the scalar product

$$\chi = \arccos(\boldsymbol{v}' \cdot \boldsymbol{y}) \tag{3}$$

This is illustrated in Figure 3 b).

Annex A gives examples for the application of these definitions to different body segments. Angles pertinent to different body segments are shown in 5.2.2 to 5.2.10.

2.4 Symbols

C_1 to C_7	vertebrae of the cervical spine
$\boldsymbol{D}$	rotary matrix
L_1 to L_5	vertebrae of the lumbar spine
N	normalization constant
T_1 to T_{12}	vertebrae of the thoracic spine
th, ls	subscripts indicating the thoracic and lumbar spine
$\boldsymbol{v} = \overrightarrow{AB}$	vector between points A and B
$\boldsymbol{v} = (v^x, v^y, v^z)$	vector, represented by its Cartesian coordinates
$\boldsymbol{v}' = \boldsymbol{Dv}$	vector without influence of flexion and extension
$\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z}$	unit vectors of the Cartesian coordinate system
χ	angle between two vectors
θ, ϕ	polar angles, the z-axis of the coordinate system as polar axis

3 Biomechanical background

3.1 General

This clause provides the biomechanical background for the selection of relevant quantities with respect to the spinal load of seated persons subject to whole-body vibration.

3.2 Spinal segments

In order to describe the spinal load as closely as possible, the range of motion of different parts of the spine in flexion, extension, and axial rotation has to be considered. A summary is given in Table 1 which indicates that the lumbar, thoracic and cervical spine show different mobility and should, therefore, be treated separately.

Table 1 — Maxima and minima of spinal tolerances towards movement according to Reference [6]

Type of movement	Maxima (vertebrae)	Minima (vertebrae)
Sagittal flexion	C_0/C_1, C_4/C_5, L_4/L_5	T_9/T_{10}
Sagittal extension	C_0/C_1, C_4/C_5, L_5/S_1	T_9/T_{10}
Lateral flexion	C_1/C_2, C_7/T_1, L_3/L_4	T_5/T_6
Axial Rotation	C_1/C_2, T_{12}/L_1	T_5/T_6
NOTE C_0 is the occiput.		

Due to the large mobility in the cervical spine (vertebrae C_1 to C_7), it is more feasible to describe its movement by the position of the head (sagittal flexion/extension, lateral flexion, axial rotation).

The thoracic spine (vertebrae T_1 to T_{12}) is separated from the lumbar spine by a distinct minimum for all types of movement. Therefore, the axial rotation, sagittal flexion/extension and lateral flexion of the thoracic spine are investigated separately.

The lower part of the lumbar spine is closely connected to the pelvis. The forward and backward tilting of the pelvis leads concomitantly to the lordosis or kyphosis of the lumbar spine (vertebrae L_1 to L_5). This is an additional degree of freedom which has already been addressed in ISO 11226.[4] As for the other degrees of freedom of the lumbar spine, it is sufficient to measure the sagittal flexion/extension and lateral flexion, since the axial rotation is negligible for the seated person.

3.3 Body segments apart from the spine

Appendicular body segments (i.e. the upper and lower limb) are known to affect the biomechanical response of the seated body. The position of the lower limb can affect the apparent mass and transmissibility as can the position of the upper limb. For drivers, the position of the upper limb can be dictated by the nature of the driving task, the nature and position of controls. The position of the lower limb can be dictated by the presence of pedals, the seat height, and upholstery in the vehicle.

In order to fully describe the position and loading on the spine of the seated subject, it is necessary to consider the position of all body segments as this affects the position of the centre of mass which the musculoskeletal system is required to support.

3.4 Other quantities

Detailed segmental positions alone do not fully describe the loading on the body. For example, one set of segment angles could be stable or unstable depending on whether a seat was present or not. Similarly, they do not allow for a description of the biomechanical response as it is known that the presence of a backrest affects the apparent mass and transmissibility.

4 Coordinate system

In most cases, the person is seated in a vehicle with the position of the pelvis in the seat pointing forward. Because the direction of the seat might not correspond to the direction of motion of the vehicle, the seat might not have a clear front (e.g. a stool) or the coordinate systems used in other whole-body vibration standards, e.g. ISO 2631-1,[1] may not match this coordinate system; consequently, appropriate transformations can be necessary.

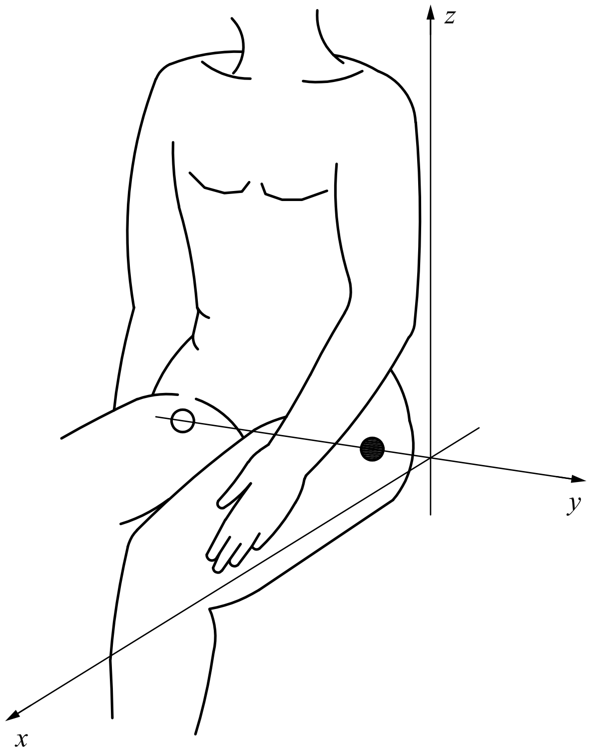
A suitable coordinate system resembles an external polar coordinate system. It consists of orthogonal unit vectors $\boldsymbol{x}$, $\boldsymbol{y}$, and $\boldsymbol{z}$. The vector $\boldsymbol{x}$ is fore-aft at the pelvis; $\boldsymbol{y}$ is lateral and left at the pelvis and $\boldsymbol{z}$ is vertical at the pelvis (Figure 4). For upright seated persons, the vector z opposes gravity. The y-axis of the coordinate system is parallel to the y-axis of the pelvis, given by the line that connects the greater trochanters. This coordinate system is the basis for all variables concerning the movements of the spine described in Clause 5.

NOTE 1 The line that connects the greater trochanters is not necessarily the rotational axis of the pelvis. Within the levels of accuracy of this Technical Report, this is acceptable.

If the pelvis orientation does not correspond to the seat orientation, the coordinate system rotates with the pelvis. This might be the case, e.g. when the driver is leaning out of the window or is driving backwards for a longer time. Then the coordinate system should be transformed in such a way that the transformed coordinate system's new y-axis is again parallel to the y-axis of the pelvis and the angle of old and new z-axis is minimal. If there is spinal axial rotation, the origin is defined at the pelvis.

NOTE 2 In this case, the transformed coordinate system does not correspond to the coordinate system of the seated person in the measurement standard for whole-body vibration (ISO 2631-1[1]). Both coordinate systems can be associated with each other by a unitary transformation.

NOTE 3 In many cases, additional transformations are necessary when the seat coordinate system is not in line with the vehicle coordinate system.



NOTE The y-axis is parallel to the line that connects the greater trochanters (circles).

Figure 4 — Cartesian coordinate system for a seated person

5 Characterization of postures

5.1 General

In order to characterize a posture, the quantities in this clause should be determined. For postural information, e.g. angles of body segments, see 5.2; for other information which should be collected in order to describe the ergonomic environment, e.g. whether arm- or backrests are present or not, see 5.3.

5.2 Postural information

5.2.1 Angles of body segments

This subclause describes 13 angles of body segments (see Table 2) with respect to the coordinate system defined in Clause 4. The sign of flexion angles is positive when the flexion resembles a clockwise movement.

Every body segment is represented by a line between two points on the body of the person as in ISO 11226.[4] These points are palpable landmarks on the skin or the surface of the clothing in accordance with ISO 8727.[3] Transducers or markers can be fixed at these points or alternative techniques can be applied such as goniometry, video or visual analysis to provide equivalent data.

These body segment angles might continuously or periodically change during a measurement. The nature of movement should be described.

Figure 1 presents a sketch of the human body together with a possible set of points for the description of the movement of the respective body segments. The latter are summarized in Table 2.

Table 2 — Body segments and their movements as described by the position of attributed points of the body according to Figure 1

Body segment	Movement/angle	Necessary points
Head/cervical spine	Sagittal flexion, extension	1 to 3
	Lateral flexion	1 to 3
	Axial rotation	1 to 5
Thoracic spine	Sagittal flexion, extension	6, 7
	Position of the backrest	6, 7
	Lateral flexion	6, 7
	Axial rotation	4 to 7
Lumbar spine	Sagittal flexion, extension	8, 10
	Position of the backrest	8, 10
	Lateral flexion	8, 10
	Curvature (kyphosis, lordosis)	8 to 10
Pelvis	Tilt	11, 12
	Axial rotation	11,12

Body angles that are listed in Table 2 are described in 5.2.2 to 5.2.10. In the case of simultaneous movements, the descriptions have to be adapted accordingly.

5.2.2 Sagittal flexion, extension of the head

For a person in an upright standing position, the angle between the tragus and canthus with respect to the x-axis should be indicated (Figure 5). Looking straight ahead is represented by 0°. Looking downward results in positive angles.

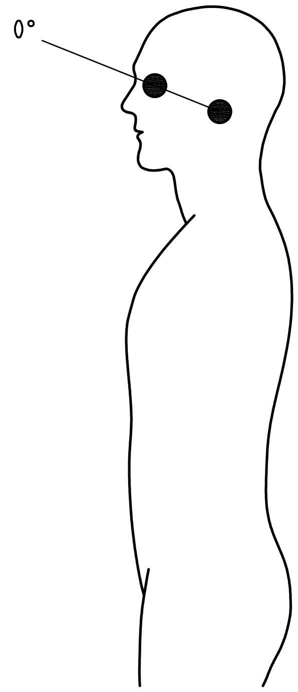


Figure 5 — Sagittal flexion, extension of the head

5.2.3 Lateral flexion of the head

For lateral flexion the angle between the z-axis and a line that is orthogonal to the line between the left and right tragus should be declared (Figure 6). Angles to the left are negative.

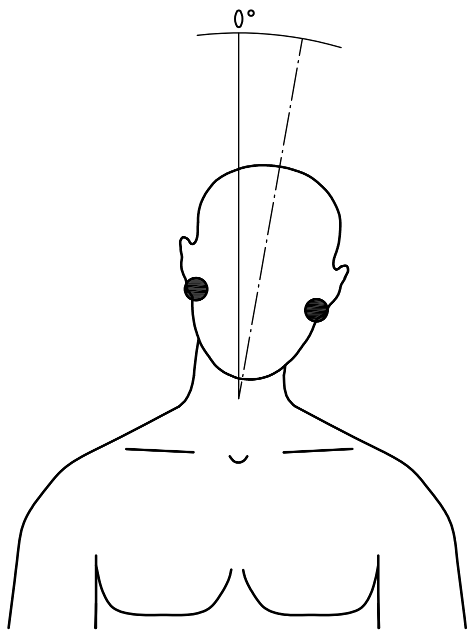


Figure 6 — Lateral flexion of the head

5.2.4 Axial rotation of the head

The axial rotation of the head is given by the angle between the shoulder line and the line between the left and right tragus for an unbent cervical spine (Figure 7). This leads to a torsion within the cervical spine. Angles to the right are negative.

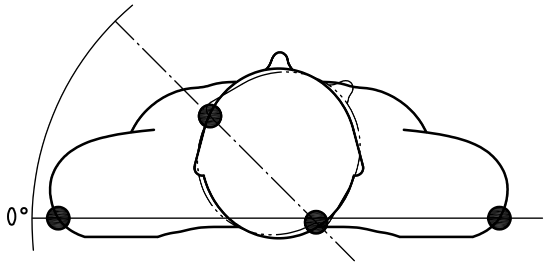


Figure 7 — Axial rotation of the head

5.2.5 Sagittal flexion/extension of the lumbar and thoracic spine

In the absence of lateral flexions and axial rotations, the sagittal movement of the lumbar (or thoracic) spine should be described by the angle between the z-axis and the line between L_1 and L_5 (T_3 and C_7), see Figure 8. Backward angles are negative. The position of the person while in contact with the backrest can be described by the sagittal extension of the lumbar and thoracic spine as seen in Figure 8.

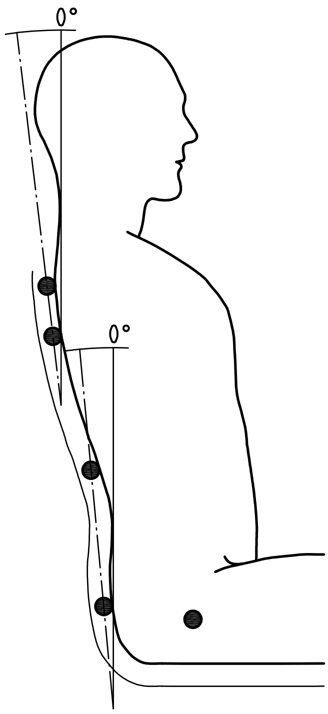


Figure 8 — Sagittal flexion/extension of the lumbar and thoracic spine

5.2.6 Lateral flexion of the lumbar and thoracic spine

In the absence of sagittal flexions and extensions or torsions, one can define the lateral flexion of the lumbar (thoracic) spine by the angle between the z-axis and the line between L_1 and L_5 (T_3 and C_7) (Figure 9). Angles to the left are negative.

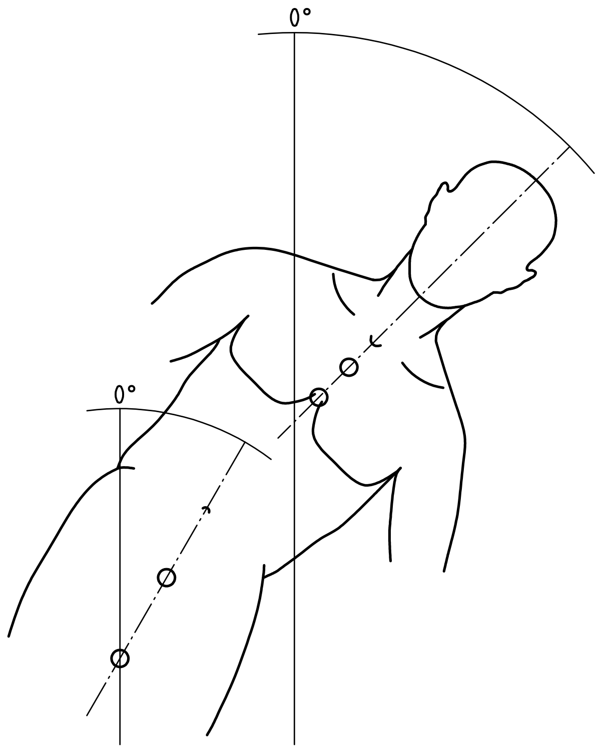


Figure 9 — Lateral flexion of the lumbar and thoracic spine

5.2.7 Axial rotation of the thoracic spine

The axial rotation of the thoracic spine in an upright posture is given by the angle between the left and right acromion and the y-axis of the coordinate system (Figure 10). This leads to a torsion within the thoracic and lumbar spine. Angles to the right are negative.

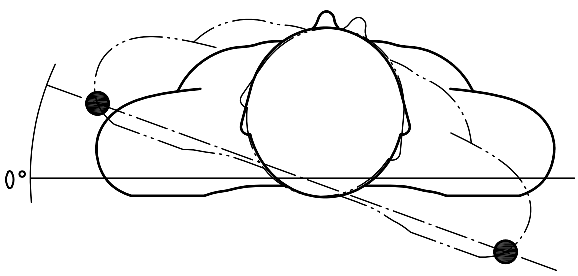


Figure 10 — Axial rotation of the thoracic spine

5.2.8 Curvature of the lumbar spine (kyphosis, lordosis)

The curvature of the lumbar spine is given by the angle between L_1, L_3 and L_5. The curvature is kyphosis, if the angle opens to the front of the person (Figure 11), and lordosis if the angle opens to the back of the person.

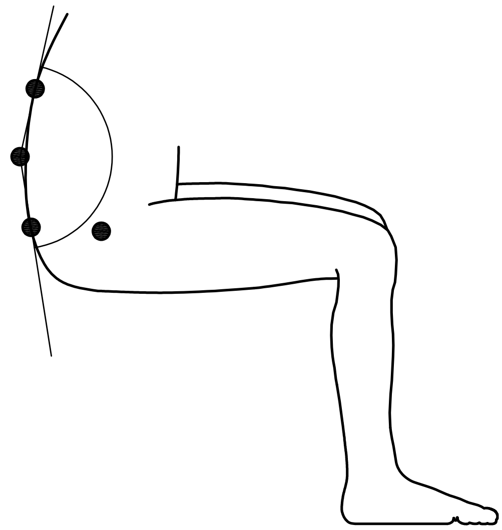


Figure 11 — Curvature of the lumbar spine (kyphosis)

5.2.9 Tilt of the pelvis

In most cases, the position of the pelvis is in the seat. When the driver is, for example, leaning out of the window, then the pelvis is tilted. The tilt angle is given by the line between the greater trochanters and the horizontal (Figure 12). Leaning to the left results in negative tilt angles.

In this case, the coordinate system (see Clause 4) changes.

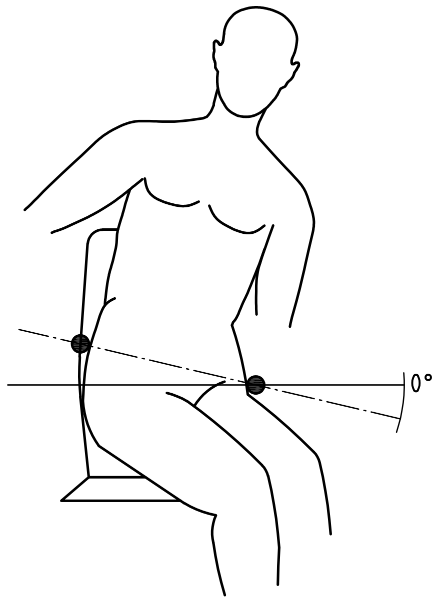


Figure 12 — Tilt of the pelvis

5.2.10 Axial rotation of the pelvis

If the pelvis is rotated on the seat surface, the coordinate system (see Clause 4) changes. The axial rotation angle is given by the line between the greater trochanters and the old y-axis (Figure 13). A clockwise axial rotation, as viewed from above, leads to negative axial rotation angles.

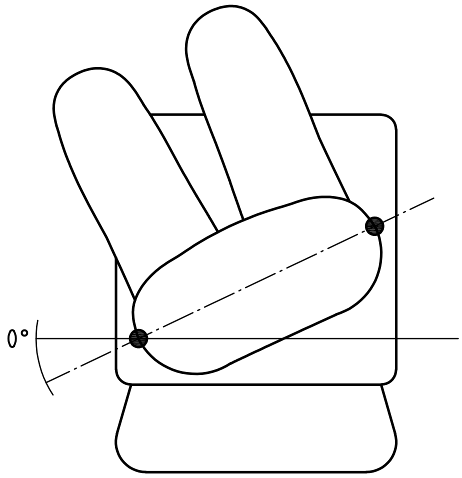


Figure 13 — Axial rotation of the pelvis

5.3 Other information

5.3.1 General

Other information should provide sufficient data to understand internal and external loading on the body. This can be split into body support, controls and external loading. For example, the angle of the legs can affect the pelvis and trunk posture. The consequences of this information on the posture of the upper and lower limbs should be described (see 3.3).

5.3.2 Body support

Each contact point supporting the body should be described.

- *Feet* flat on floor/on heels/free hanging/on pedals
- *Seat pan* angle and length of contact
- *Seat back* angle and height of contact
- *Headrest* contact/no contact
- *Armrest* no/yes (dimensions)
- *Grip* grab rail/steering wheel/joystick/other
- *Other*

5.3.3 Controls

Primary controls should be described. Primary controls can change during different phases of a work cycle. Foot controls are controlled by the feet; hand controls are controlled by motion of the arm or wrist; finger controls are controlled by motion of the fingers.

- *Foot controls* control type, continuous/intermittent operation, (legs stretched? no / yes)
- *Hand controls* control type, continuous/intermittent operation, (arms stretched? no / yes)
- *Finger controls* control type, continuous/intermittent operation, (arms stretched? no / yes)

— *Other*

It is recommended to record the position of the controls with respect to the seat.

5.3.4 External loading

External loading can come from items mounted on the body. Some of these items are designed to restrict body movement (e.g. harnesses, some protective equipment). Where appropriate, the masses of these items should be reported.

— *Harness* seatbelt/harness type

— *Protective equipment* helmet/body armour/buoyancy aid/other

— *Equipment* pack/weapon/tools/other

— *Other*

6 Methods for determination of posture quantities

6.1 General. The posture of persons can be determined in a variety of ways. Some of the most common methods are described here but this list is not comprehensive and should not impede innovation. Several methods described here require specialized measurement equipment.

6.2 Optical methods have been applied to assess posture simultaneously with whole-body vibration in the laboratory and in the field as shown e.g. in References [7][8]. Generally, they measure the position of markers on the surface of the skin or clothing of the test person. Dedicated cameras and software can be used to track these markers and determine the relevant angles. One problem with optical markers is that complex software is needed to evaluate results from multi-camera measurements. Some optical systems cannot be used outdoors during the day.

6.3 Ultrasonic sensors determine the propagation of ultrasound via the skin and deduce information on posture by comparing the actual signal to a set of reference positions (leaning in the backrest, forward inclination, etc.; for an example see Reference [9]). The choice of these reference positions determines the number of quantities that are accessible and the connection to the definitions of this Technical Report is more difficult.

6.4 Electro-goniometers measure segment angles directly using devices which are mounted across a joint. They can be obscured from view and do not require cameras. Some problems with electro-goniometers include the bulk and routing of cables for multiple measurement sites and potentially erroneous measurements if the device is unable to bend freely.

6.5 Other transducer-based methods include: gyrometers, magnetometers and accelerometers which can be fixed on the surface of the skin or clothing. For examples see References [10][11]. Usually, the exact position in space is not accessible, but a relative one, e.g. the angle of a transducer with respect to gravity, which gives access to the relevant angles. A combination of transducers can provide a full measurement of posture.

6.6 Visual methods determine the posture by predefined categories, e.g. as described in References [12]–[14]. They can be used for postures which do not require continual monitoring (e.g. a driver who alternates between several postural positions such as driving, loading, reversing) by using goniometers to measure segment angles for example postures. Video recording can then be used to measure the time in each posture and to synchronize these with vibration events.

7 Measurement errors

Measurement errors should be considered for any selected measurement system. Systems should be calibrated and validated for systematic and random errors as well as calibration drift for measurements in the environment of interest. Marker-based systems might have a high precision under laboratory conditions which cannot be replicated under field conditions. In many cases, a precision of ±10° might be sufficient in order to understand the movements of the person.

Even under the most ideal conditions, the complex movement of the human spine by the measurement of a limited number of external landmarks has the following restrictions.

- The resolution of a single vertebra is not possible.
- The effect of muscles and connective tissues is not described. Therefore, the actual load on the spine can be different for the same measured posture.
- The ball and stick model of the spine on the basis of the considerations in 5.2 cannot represent all degrees of freedom (e.g. curvature of the cervical spine).
- Consequently, some of the assumptions made in Clause 5 might not be valid (e.g. the coplanarity of the shoulders, C_7 and T_3).

In particular for measurements of body angles, it is necessary for the external transducers to be:

- fixed at palpable landmarks (ISO 8727[3]);
- closely related to the body segment in focus (ISO 11226[4]);
- not too close together to avoid measurement errors (ISO 11226[4]).

Annex A
(informative)

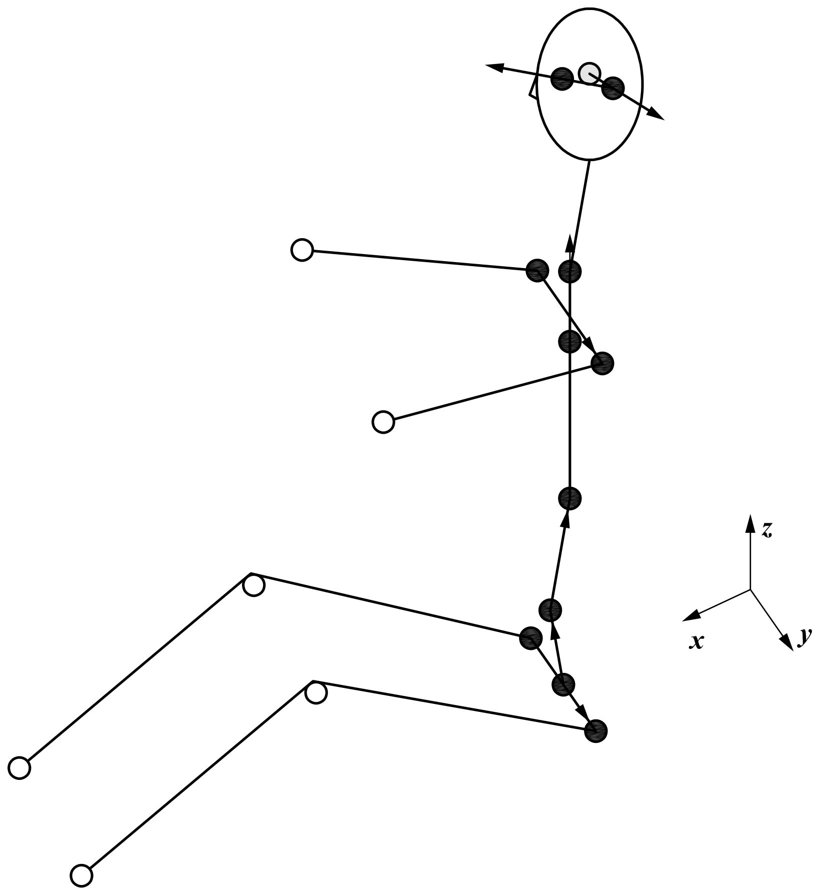
Examples for the application to different body segments

A.1 General

This annex shows the application of the descriptive posture quantities to different body segments. In Table A.1, the movements that should be monitored for each body segment are summarized, together with the definitions of their respective angles.

All quantities are defined by the angles of a vector within an appropriate coordinate system (see Clause 4). In the examples, the seven vectors defined are needed for a minimal description of the quantities in Table A.1.

Figure A.1 provides a sketch of these vectors and the 12 points from Figure 1 that are used in their definition.



NOTE Correlated vectors are represented by arrows. Details are given in A.2 to A.5.

Figure A.1 — Overview of measured points on the body from Figure 1 which are represented by filled circles

Table A.1 — Quantities of parts of the body that are described in 5.2

Body part	Quantity		
	Designation	Definition	Prerequisites
Lumbar spine	Sagittal flexion (extension)	$\theta_{\mathrm{ls}}^{xz} = \arctan\frac{v_{\mathrm{ls}}^{x}}{v_{\mathrm{ls}}^{z}}$	$\boldsymbol{v}_{\mathrm{ls}} = \frac{1}{N}\overrightarrow{\mathrm{L}_5\mathrm{L}_1}$ (extension $v_{\mathrm{ls}}^{x} < 0$) [Equations (1), (A.2)]
Lumbar spine	Lateral flexion	$\theta_{\mathrm{ls}}^{yz} = \arctan\frac{-v_{\mathrm{ls}}^{y}}{v_{\mathrm{ls}}^{z}}$	$\boldsymbol{v}_{\mathrm{ls}} = \frac{1}{N}\overrightarrow{\mathrm{L}_5\mathrm{L}_1}$ [Equations (2), (A.2)]
Lumbar spine	Support by backrest	$\theta_{\mathrm{ls,backrest}}^{xz} = \arctan\frac{v_{\mathrm{ls,backrest}}^{x}}{v_{\mathrm{ls}}^{z}}$	$\boldsymbol{v}_{\mathrm{ls}} = \frac{1}{N}\overrightarrow{\mathrm{L}_5\mathrm{L}_1}$ [Equations (A.2), (A.3)]
Lumbar spine	Lordosis	$\chi_{\mathrm{ls,curv}} = \arccos\left(\boldsymbol{v}_{\mathrm{ls},1} \cdot \boldsymbol{v}_{\mathrm{ls},2}\right)$ lordosis: $v_{\mathrm{ls},1}^{x} > 0$ kyphosis: $v_{\mathrm{ls},1}^{x} < 0$	$\boldsymbol{v}_{\mathrm{ls},1} = \frac{1}{N}\overrightarrow{\mathrm{L}_5\mathrm{L}_3}$; $\boldsymbol{v}_{\mathrm{ls},2} = \frac{1}{N}\overrightarrow{\mathrm{L}_3\mathrm{L}_1}$ or projections on to sagittal plane [Equations (A.1), (A.4)]
Pelvis	Tilt	$\frac{\pi}{2} - \theta_{\mathrm{pelvis}}$	$\boldsymbol{v}_{\mathrm{pelvis}} = \frac{1}{N}\overrightarrow{\mathrm{tr\ tl}} = \left(1, \theta_{\mathrm{pelvis}}, \phi_{\mathrm{pelvis}}\right)$ [Equation (A.5)]
Pelvis	Axial rotation	$\frac{\pi}{2} - \phi_{\mathrm{pelvis}}$	$\boldsymbol{v}_{\mathrm{pelvis}} = \left(1, \theta_{\mathrm{pelvis}}, \phi_{\mathrm{pelvis}}\right)$ [Equation (A.5)]
Thoracic spine	Sagittal flexion (extension)	$\theta_{\mathrm{th}}^{xz} = \arctan\frac{v_{\mathrm{th}}^{x}}{v_{\mathrm{th}}^{z}}$	$\boldsymbol{v}_{\mathrm{th}} = \frac{1}{N}\overrightarrow{\mathrm{T}_3\mathrm{C}_7}$ (extension $v_{\mathrm{th}}^{x} < 0$) [Equations (1), (A.6)]
Thoracic spine	Lateral flexion	$\theta_{\mathrm{th}}^{yz} = \arctan\frac{-v_{\mathrm{th}}^{y}}{v_{\mathrm{th}}^{z}}$	$\boldsymbol{v}_{\mathrm{th}} = \frac{1}{N}\overrightarrow{\mathrm{T}_3\mathrm{C}_7}$ [Equations (2), (A.6)]
Thoracic spine	Support by backrest	$\theta_{\mathrm{th,backrest}}^{xz} = \arctan\frac{v_{\mathrm{th,min}}^{x}}{v_{\mathrm{th}}^{z}}$	$\boldsymbol{v}_{\mathrm{th}} = \frac{1}{N}\overrightarrow{\mathrm{T}_3\mathrm{C}_7}$ [Equations (A.3), (A.6)]
Thoracic spine	Axial rotation	$\chi_{\mathrm{th}} = \arccos\left(\boldsymbol{v}_{\mathrm{sh}}' \cdot \boldsymbol{y}\right)$	$\boldsymbol{v}_{\mathrm{th}} = \left(1, \theta_{\mathrm{th}}, \phi_{\mathrm{th}}\right)$; $\boldsymbol{v}_{\mathrm{sh}} = \frac{1}{N}\overrightarrow{\mathrm{sr\,sl}}$ $\boldsymbol{D}\left(\theta_{\mathrm{th}}, \phi_{\mathrm{th}}\right)\boldsymbol{v}_{\mathrm{sh}} = \boldsymbol{v}_{\mathrm{sh}}'$ [Equations (A.6) to (A.9)]
Head	Sagittal flexion (extension)	$\theta_{\mathrm{head}}^{xz} = \arctan\frac{v_{\mathrm{head}}^{x}}{v_{\mathrm{head}}^{z}} - \theta_{\mathrm{head}}^{xz}(0)$	$\boldsymbol{v}_{\mathrm{jj}} = \frac{1}{N}\overrightarrow{\mathrm{jr\ jl}}$; $\boldsymbol{v}_{\mathrm{base}} = \frac{1}{N}\overrightarrow{\mathrm{jl\ eye}}$ $\boldsymbol{v}_{\mathrm{head}} = \boldsymbol{v}_{\mathrm{base}} \otimes \boldsymbol{v}_{\mathrm{jj}}$ $\theta_{\mathrm{head}}^{xz}(0) = \theta_{\mathrm{head}}^{xz}$ for the upright standing person looking straight ahead [Equations (1), (A.10), (A.11), (A.12)]
Head	Lateral flexion	$\theta_{\mathrm{head}}^{yz} = \arctan\frac{-v_{\mathrm{head}}^{y}}{v_{\mathrm{head}}^{z}}$	$\boldsymbol{v}_{\mathrm{head}} = \boldsymbol{v}_{\mathrm{base}} \otimes \boldsymbol{v}_{\mathrm{jj}}$ [Equations (2), (A.10), (A.11)]
Head	Axial rotation	$\chi_{\mathrm{head}} = \arccos\left(\boldsymbol{v}_{\mathrm{jj}}' \cdot \boldsymbol{v}_{\mathrm{sh}}'\right)$	$\boldsymbol{D}\left(\theta_{\mathrm{th}}, \phi_{\mathrm{th}}\right)\boldsymbol{v}_{\mathrm{sh}} = \boldsymbol{v}_{\mathrm{sh}}'$ $\boldsymbol{v}_{\mathrm{head}} = \left(1, \theta_{\mathrm{head}}, \phi_{\mathrm{head}}\right)$ $\boldsymbol{v}_{\mathrm{jj}} = \frac{1}{N}\overrightarrow{\mathrm{jr\ jl}}$ $\boldsymbol{D}\left(\theta_{\mathrm{head}}, \phi_{\mathrm{head}}\right)\boldsymbol{v}_{\mathrm{jj}} = \boldsymbol{v}_{\mathrm{jj}}'$ [Equations (A.6) to (A.8), (A.10) to (A.14)]

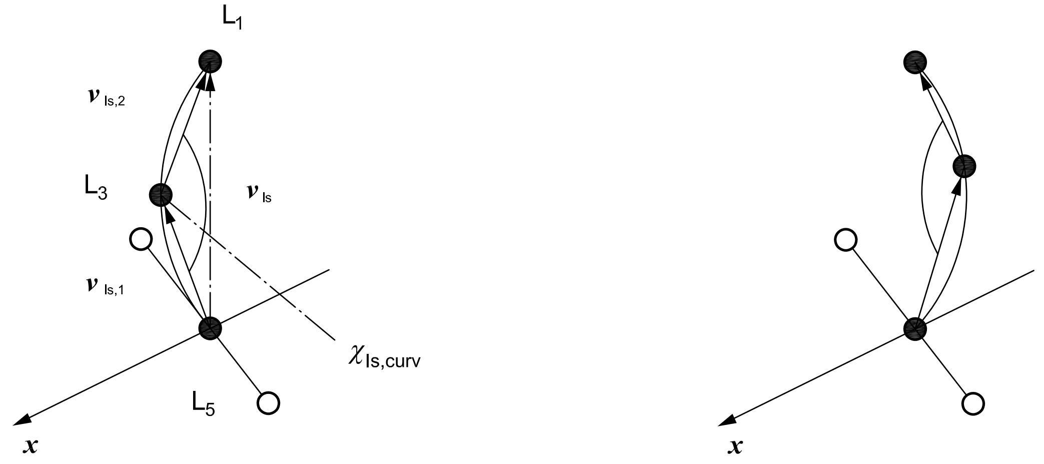
A.2 Lumbar spine

For the lumbar spine, the positions of L_1, L_3 and L_5 should be monitored which gives rise to the following vectors (Figure A.2):

$$\boldsymbol{v}_{\text{ls},1} = \frac{1}{N}\overrightarrow{\text{L}_5\text{L}_3}\,,\ \boldsymbol{v}_{\text{ls},2} = \frac{1}{N}\overrightarrow{\text{L}_3\text{L}_1} \tag{A.1}$$

$$\boldsymbol{v}_{\text{ls}} = \frac{1}{N}\left(\boldsymbol{v}_{\text{ls},1} + \boldsymbol{v}_{\text{ls},2}\right) = \frac{1}{N}\overrightarrow{\text{L}_5\text{L}_1} \tag{A.2}$$

where N is the relevant normalization constant.



a) Lordosis **b) Kyphosis**

NOTE Measured vertebrae (L_1, L_3 and L_5) are represented as filled circles that define two vectors (black arrows for $\boldsymbol{v}_{\text{ls},1}$ and $\boldsymbol{v}_{\text{ls},2}$). Their sum $\boldsymbol{v}_{\text{ls}}$ is a derived quantity and therefore printed as a dashed arrow. The sufficient criterion for a lordosis $v^x_{\text{ls},1} > 0$ [see a)] and kyphosis $v^x_{\text{ls},1} < 0$ [see b)] is illustrated (origin of coordinate system shifted to L_5).

Figure A.2 — Representation of the lumbar spine (black circles) resting on the pelvis (empty circles)

The sagittal flexion/extension and lateral flexion of the lumbar spine are defined with the help of $\boldsymbol{v}_{\text{ls}}$ and Equations (1) and (2), see Figure 3 a) and Table A.1. The angle of the maximal sagittal extension, $\theta^{xz}_{\text{ls,backrest}}$, is given by $v^x_{\text{ls,backrest}}$ when the lumbar spine is supported by the backrest:

$$\theta^{xz}_{\text{ls,backrest}} = \arctan\frac{v^x_{\text{ls,backrest}}}{v^z_{\text{ls}}} \tag{A.3}$$

where $v^x_{\text{ls,backrest}} < 0$ (see Table A.1).

In order to resolve the lordosis, however, the following angle has to be determined:

$$\chi_{\text{ls,curv}} = \arccos\left(\boldsymbol{v}_{\text{ls},1} \cdot \boldsymbol{v}_{\text{ls},2}\right) \tag{A.4}$$

between $\boldsymbol{v}_{\text{ls},1}$ and $\boldsymbol{v}_{\text{ls},2}$ as well as the sign of $\boldsymbol{v}^{x}_{\text{ls},1}$ (Figure A.2). A finite value of $\chi_{\text{ls,curv}}$ is a lordosis for $v^{x}_{\text{ls},1} > 0$ and a kyphosis for $v^{x}_{\text{ls},1} < 0$. This definition assumes that $\boldsymbol{v}_{\text{ls},1}$ and $\boldsymbol{v}_{\text{ls},2}$ lie in the sagittal plane. Otherwise, the projections on to the sagittal plane should be used.

A.3 Pelvis

The y-axis of the pelvis determines the y-axis of the coordinate system (see Clause 4) and is the reference for the axial rotation angle of the thoracic spine (5.2 and Clause A.4). Therefore, it is necessary to measure the y-axis of the pelvis in all cases when it is not parallel with the side-to-side direction of the vehicle, e.g. when the driver is leaning out of the window.

The normalized vector of the pelvis line in y-direction, between the left and right greater trochanters, tl, tr, is

$$\boldsymbol{v}_{\text{pelvis}} = \frac{1}{N}\overrightarrow{\text{tr tl}} = \left(1, \theta_{\text{pelvis}}, \phi_{\text{pelvis}}\right) \tag{A.5}$$

The side-tilt θ_{pelvis} and axial rotation angle ϕ_{pelvis} of the pelvis are derived from the polar angles of the pelvis line, when z defines the polar axis. When these two angles deviate from $\pi/2$, then the pelvis is tilted to the side or rotated and the coordinate system has to be transformed (Table A.1, Clause 4).

Since the lower part of the lumbar spine is closely connected to the pelvis (Clause 3), the forward and side tilt of the pelvis can be monitored also by the sagittal lateral flexion of $\boldsymbol{v}_{\text{ls},1}$ in Equation (A.1).

A.4 Thoracic spine

The sagittal and lateral movements as well as the position of the backrest for the thoracic spine are determined by means of Equations (1), (2), and (A.3) in the same way as for the lumbar spine (Table A.1). The reference vector is now defined by the upper part of the thoracic spine, Figure A.3 a):

$$\boldsymbol{v}_{\text{th}} = \frac{1}{N}\overrightarrow{\text{T}_3\text{C}_7} \tag{A.6}$$

In addition, the axial rotation of the thoracic spine is determined by the rotation angle χ_{th} of the plane pl_{th} defined by the shoulders and T_3 around $\boldsymbol{v}_{\text{th}}$. It is assumed, that all four points (shoulders, T_3, C_7) lie within this plane. The shoulder line is defined by the normalized vector between the right shoulder, sr, and the left shoulder, sl:

$$\boldsymbol{v}_{\text{sh}} = \frac{1}{N}\overrightarrow{\text{sr sl}} \tag{A.7}$$

One way to determine χ_{th} is to turn all vectors in pl_{th} by means of the rotary matrix $\boldsymbol{D}(\theta_{\text{th}},\phi_{\text{th}})$. The angles θ_{th} and ϕ_{th} are the polar angles of $\boldsymbol{v}_{\text{th}}$ and illustrated in Figure A.3 b) with z being the polar axis.

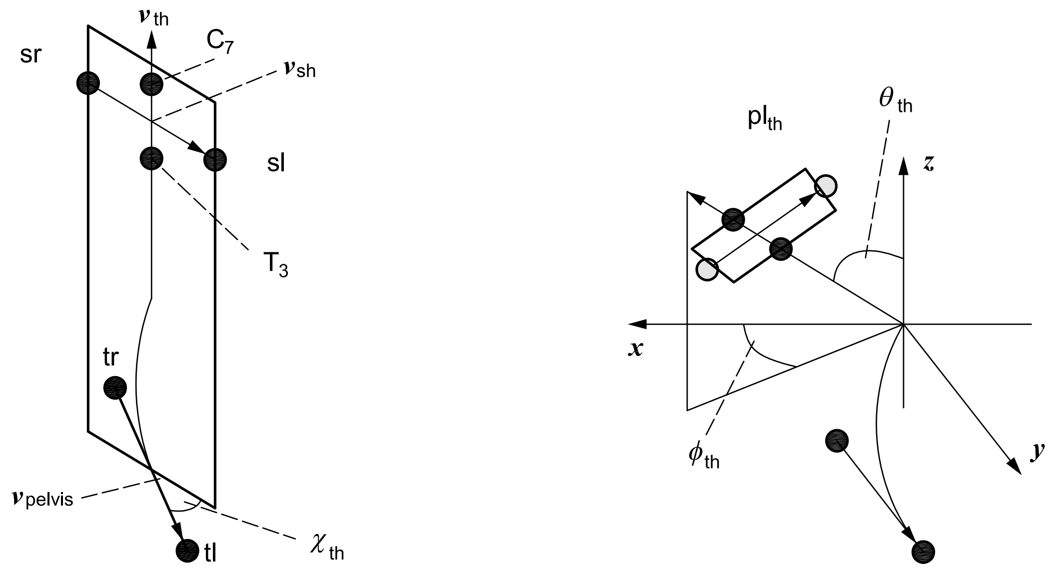
Applying $\boldsymbol{D}(\theta_{\text{th}},\phi_{\text{th}})$ to $\boldsymbol{v}_{\text{th}}$ leads to a transformed vector that lies parallel to z as described in 2.3:

$$\begin{aligned} \boldsymbol{D}\left(\theta_{\text{th}},\phi_{\text{th}}\right)\boldsymbol{v}_{\text{sh}} &= \boldsymbol{v}'_{\text{sh}} \\ \boldsymbol{D}\left(\theta_{\text{th}},\phi_{\text{th}}\right)\boldsymbol{v}_{\text{th}} \cdot \boldsymbol{z} &= 1 \end{aligned} \tag{A.8}$$

The same transformation leads to a transformed vector of the shoulder line that is parallel to the xy-plane and

$$\chi_{\text{th}} = \arccos\left(\boldsymbol{v}'_{\text{sh}} \cdot \boldsymbol{y}\right) \tag{A.9}$$

is the rotation angle of the thoracic spine [see Figure 3 b), Figure A.3 a), and Table A.1].



a) Correlated vectors

b) Polar angles

NOTE The filled circles in a) are the measured vertebrae, C_7, T_3, the left and right shoulder, sl, sr, and the left and right greater trochanters, tl, tr. Black arrows indicate the correlated vectors $\boldsymbol{v}_{th}$, $\boldsymbol{v}_{sh}$, and $\boldsymbol{v}_{pelvis}$. The plane pl_{th} is defined by (sl, sr, T_3); b) highlights the polar angles ϕ_{th}, θ_{th} of a given $\boldsymbol{v}_{th}$ (z-axis is the polar axis).

Figure A.3 — Representation of the thoracic spine and of the pelvis

A.5 Cervical spine

The load and posture of the cervical spine is mainly determined by the position of the head which is described by a plane of the base of the skull pl_{head} or any other parallel plane. This work refers to the left and right tragus, jl, jr, and to the corner of the left eye (eye) to define

$$\boldsymbol{v}_{jj} = \frac{1}{N}\overrightarrow{\text{jr jl}}, \; \boldsymbol{v}_{base} = \frac{1}{N}\overrightarrow{\text{jl eye}} \tag{A.10}$$

which in turn give rise to

$$\boldsymbol{v}_{head} = \boldsymbol{v}_{base} \otimes \boldsymbol{v}_{jj} = \left(1, \theta_{head}, \phi_{head}\right) \tag{A.11}$$

where θ_{head} and ϕ_{head} are the polar angles of $\boldsymbol{v}_{head}$ when z is the polar axis, Figure A.4 a).

The vector $\boldsymbol{v}_{head}$ is the reference vector for the head and defines the lateral flexions by means of Equation (2), see Table A.1 for the definition of the sign. For the sagittal flexion (positive sign) and extension (negative sign), the reference angle $\theta_{head}^{xz}(0)$ [i.e. the value of Equation (2) for an upright standing person looking straight ahead] has to be subtracted from Equation (1):

$$\theta_{head}^{xz} = \arctan\frac{v_{head}^{x}}{v_{head}^{z}} - \theta_{head}^{xz}(0) \tag{A.12}$$

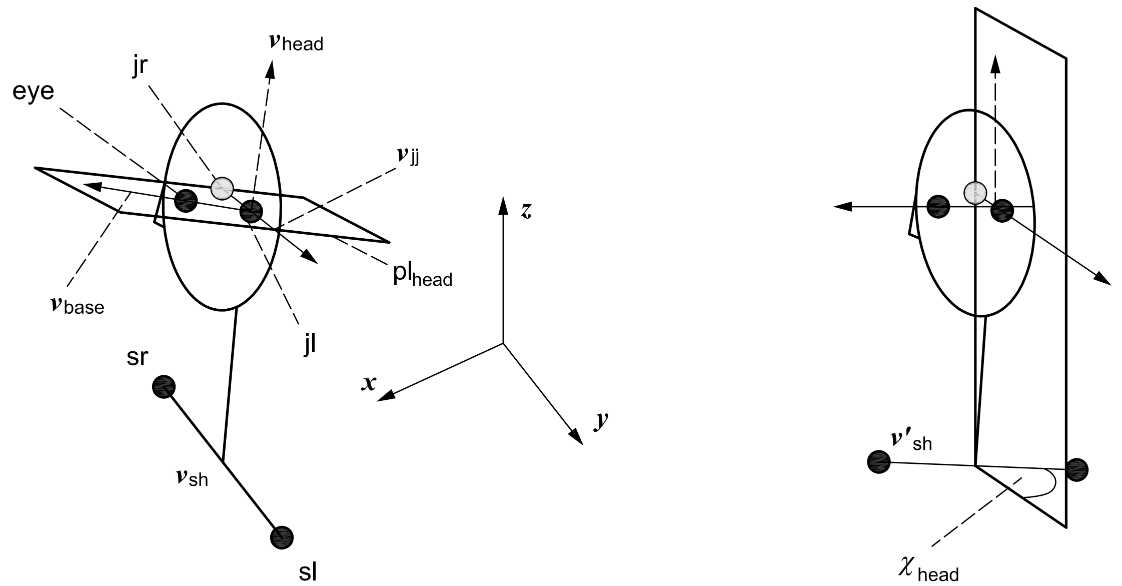
The axial rotation of the head is determined in a similar way to the axial rotation of the thoracic spine. Here, the angle between $\boldsymbol{v}_{\mathrm{jj}}$ and the shoulder line $\boldsymbol{v}_{\mathrm{sh}}$ is calculated. In order to eliminate the effects of flexion and extension, $\boldsymbol{v}_{\mathrm{jj}}$ and $\boldsymbol{v}_{\mathrm{sh}}$ are transformed into $\boldsymbol{v}_{\mathrm{jj}}^{'}$ and $\boldsymbol{v}_{\mathrm{sh}}^{'}$ which are orthogonal to $\boldsymbol{z}$. For $\boldsymbol{v}_{\mathrm{sh}}$, this is defined in Equation (A.8). For $\boldsymbol{v}_{\mathrm{jj}}$, the same rotary matrix $\boldsymbol{D}(\theta_{\mathrm{head}},\phi_{\mathrm{head}})$ has to be used that transforms $\boldsymbol{v}_{\mathrm{head}}$ to lie parallel to $\boldsymbol{z}$:

$$\begin{aligned} \boldsymbol{D}\left(\theta_{\mathrm{head}},\phi_{\mathrm{head}}\right)\boldsymbol{v}_{\mathrm{jj}} &= \boldsymbol{v}_{\mathrm{jj}}^{'} \\ \boldsymbol{D}\left(\theta_{\mathrm{head}},\phi_{\mathrm{head}}\right)\boldsymbol{v}_{\mathrm{head}}\cdot\boldsymbol{z} &= 1 \end{aligned} \tag{A.13}$$

The vector $\boldsymbol{v}_{\mathrm{jj}}^{'}$ is parallel to the xy-plane and the rotation angle of the head is

$$\chi_{\mathrm{head}} = \arccos\left(\boldsymbol{v}_{\mathrm{jj}}^{'}\cdot\boldsymbol{v}_{\mathrm{sh}}^{'}\right) \tag{A.14}$$

i.e. the angle of the head with the transformed shoulder line, Figure A.4 b).



a) Position of the head **b) Angle of the head**

NOTE The filled circles in a) are the corner of the left eye, eye, the left and right joints of the jaw, jl, jr, and the left and right shoulder, sl, sr. Black arrows indicate the correlated vectors $\boldsymbol{v}_{\mathrm{jj}}$, $\boldsymbol{v}_{\mathrm{base}}$ from which $\boldsymbol{v}_{\mathrm{head}}$ is derived (dashed arrow). The plane $\mathrm{pl}_{\mathrm{head}}$ is defined by (jl, jr, eye); b) shows $\boldsymbol{v}_{\mathrm{head}}$ parallel to the z-axis and the rotation angle χ_{head}. The vector triple in the middle between a) and b) depicts the external coordinate system for both figures.

Figure A.4 — Representation of the head and the shoulder line

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