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A REVIEW OF THE TRANSMISSION OF TRANSLATIONAL SEAT VIBRATION TO THE HEAD

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Published studies of the transmission of translational seat vibration to the heads of seated subjects are reviewed in order to determine the variations in transmissibility. The review is restricted to vibration having the same direction at the seat and the head: (a) transmission between fore-and-aft seat vibration and fore-and-aft head motion, (b) transmission between lateral seat vibration and lateral head motion, and (c) transmission between vertical seat vibration and vertical head motion. Only studies reporting transmissibilities from six or more subjects are included in the review. Transmissibilities are shown for all studies included: 10 studies with fore-and-aft seat vibration, 14 studies with lateral seat vibration and 46 studies with vertical seat vibration. The studies involved a wide range of experimental conditions, including different sitting postures, various types of subject and various locations for measuring vibration on the head. The conditions of each experiment are tabulated. The transmissibility data have been used to calculate the median, interquartile range and range of transmissibility for each axis of vibration.

1. INTRODUCTION

The development of an understanding of the adverse effects of whole-body vibration and shock on the human body involves study of the mechanical, psychological, physiological and pathological responses. Part of this process involves consideration of how vibration is transmitted through the body: the transmission of mechanical vibration through the human body has been studied for more than 50 years. Most early studies were concerned with only vertical vibration of a seat and vertical motion at the head. Few investigators reported the exposure of subjects to other axes of translational vibration or the transmission of rotational seat vibration to the head. More recently, several studies have reported the transmission of horizontal seat vibration to the head and a small number of studies have attempted to measure the transmission of vibration to specific locations on the spine.

The transmissibility of the human body reflects the various biodynamic responses of the body, particularly those between the point at which the vibration enters the body (e.g., on a seat) and the point at which the vibration is measured on the body (e.g., on the head). The transmissibility therefore gives some information on the biodynamic system. It has sometimes been assumed that the resonances reflected in, for example, the seat-to-head transmissibility indicate frequencies at which injury, discomfort or interference with activities is most likely. More recently, as techniques for measuring vibration of the spine have been developed, similar assumptions are being made about measures of transmissibility to the lumbar, thoracic or cervical spine.

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It has become clear that there are large differences in the transmissibility data presented in the published studies, and a few studies have investigated possible causes of these differences. However, International Standard 7962 [1] specified one average transmissibility of the seated body, based on data from only a few of the early published studies.

The purpose of this paper is to review available information on the transmission of translational vibration from the seat to the heads of seated subjects. The data are restricted to the transmissibilities between: (a) fore-and-aft vibration at the seat and fore-and-aft vibration at the head; (b) lateral vibration at the seat and lateral vibration at the head, and (c) vertical vibration at the seat and vertical vibration at the head. One purpose of such a review is to compile "grand average" transmissibility curves from the published average transmissibility data. However, the validity of this objective requires assumptions about the causes and extent of the variations in the transmissibilities reported within the studies, and the variations in transmissibility between the studies. The extent of the variability is therefore presented and the validity of an average transmissibility is considered. Similar considerations will apply to the interpretation of transmissibilities measured to other locations on the body.

2. PUBLISHED STUDIES

Experimental data obtained from studies of the transmission of fore-and-aft, lateral and vertical seat vibration to the heads of seated subjects are presented. The data from 10 studies with fore-and-aft seat vibration, 14 studies with lateral seat vibration and 46 studies with vertical seat vibration have been used. A tabulated summary of each study included in the review is shown in Appendix A.

The published studies have reported on experiments with variable numbers of human subjects (between 6 and 112). Studies presenting results based on fewer than six subjects were not included. The average (or median) transmissibility presented in the published reports of the studies were used for this review. Not all the studies listed in Appendix A were used in the calculation of the averages because some publications did not present mean or average transmissibility data.

The data were obtained from measurements of vibration occurring in the same axes at the input and output: between fore-and-aft seat vibration and fore-and-aft head motion, between lateral seat vibration and lateral head motion, and between vertical seat vibration and vertical head motion. In some studies the multiple axis head motion occurring as a result of single axis seat vibration has also been measured (e.g., by Rowlands [2], Bennett *et al*. [3], Johnston *et al*. [4] and Paddan and Griffin [5, 6]). However, the number of studies available is not sufficient to justify the presentation of average values for these data.

The studies included in the review had different objectives and therefore differed in many respects. The variables that differed can be considered in two categories: intrinsic variables (relating to the individual subjects) and extrinsic variables (relating to the experimental conditions). Table 1 lists some of the intrinsic and extrinsic variables, and the expressions that have been used to describe them in the studies. It is well known that some variables can have large effects on seat-to-head transmissibility; for example sitting posture [7], contact with the seat backrest [5, 6].

The ranges of the variables used in the studies included in this review are shown in Table 2. The effects of these variables on seat-to-head transmissibility cannot be identified in the averaged data.

Inter-subject variability has a large effect on transmissibility. Some studies have illustrated inter-subject variability and also shown average values. In these cases it is clear that while individuals often show transmissibilities which vary rapidly with small changes in frequency and may have several peaks, average transmissibilities show slower changes with frequency and have fewer peaks. The process of averaging the individual data to obtain a mean or median transmissibility curve for one condition loses the individual response and masks the large range of inter-subject variability. The process of averaging data across studies results in a further loss of the differences obtained with different subject groups or different experimental conditions. To some extent, these losses leave the final average transmissibility with few useful applications. Certainly, from a scientific point of view, the form and causes of variability are more interesting than the final average. Additionally, the variability may provide the information needed to understand the solution to any situation where head motion is required to be reduced. However, since an International Standard has been published showing the average transmissibility it seems interesting to consider how the available data compare with the standard.

In some studies, variations in posture and muscle tension seem to be confused with each other, but they are different: posture reflects the geometry of the body while muscle tension reflects the muscle activity. A change in either posture or muscle tension may result in a change in the other variable. A change of posture will often be visible to an observer: a subject may be described as sitting "erect" (e.g., with the back held straight, upright, shoulders held back and vertically above the pelvis, head in a forward facing position), or "slouched" (e.g., with the back in a convex curve, kyphosis, with the shoulders held forward), or other variations, such as rotation of the whole body. A change of muscle tension does not necessarily involve visible changes in the subject. Changes in muscle tension may be described as "normal" or "tensed". Both body posture and muscle tension are reported to affect human transmissibility: see references [1, 7–9].

Various types of input motion have been used to study seat-to-head transmissibility (e.g., sinusoidal oscillation, sine sweeps, pseudo-random, random, transients, recorded vehicle vibration). The type of input motion and the level of the input motion (i.e., vibration magnitude) may affect the transmission of vibration to the head. A study of the effect on transmissibility of various factors (including input motion spectra, sine sweep duration, frequency resolution and analysis method) has been presented elsewhere [10].

The analysis methods used to determine seat-to-head transmissibilities have varied between studies. The methods include the ratio of peak accelerations at the head and the seat, and the ratio of root-mean-square (r.m.s.) accelerations at the head and the seat. These methods make assumptions about the waveform, usually that it is sinusoidal, but often at both the seat and the head this will not be the case. Other studies have calculated transmissibilities from the ratios of Fourier transforms or power spectral densities of the acceleration at the seat and the head. These methods assume that all motion occurring at the head at one frequency are caused by the same frequency of vibration at the seat. Although this will often be approximately valid, some studies have shown that vibration at one frequency on the seat can result in motion at other frequencies at the head [11, 12]. The above methods are also vulnerable to the effects of "noise" (e.g., motions at the head due to voluntary movements and not due to the seat vibration). Some investigators have determined transmissibilities from the ratio between the cross spectral densities and the power spectral densities so as to determine the head motion arising from the linear response between the seat and the head. This method yields the phase between the seat and the head motion and allows the calculation of coherency and confidence intervals. Few studies of seat-to-head transmissibility have reported the phase and so this review does not attempt to present average phase data.

TABLE 1

Variables that may affect transmissibility and expressions used to define the variables

Variable	Expressions							
body posture	erect	attention	alert	normal	slumped	slouched	back-on	back-off
muscle tension	stiff	tensed	normal	relaxed	slack			
waveform	discrete sinusoidal	sine swept	random	magnitude	frequency range	duration		
seating	hard, soft	backrest angle	harness	headrest				
subject characteristics	gender	age	weight	stature	build			
other parameters	measuring equipment	helmet	head angle	type of analysis	frequency resolution			

TABLE 2

The ranges of the variables used in the studies included in the analysis

Variable	Range
posture	slouched to erect
pelvic angle	95° to 105°
presence of backrest	"back-off" to "back-on"
backrest angle	0° to 20° with respect to vertical
harness	no harness to 5-point harness
head angle	pitch angle ±20°
upper back forward inclination	0° to 30° with respect to vertical
location of measurement	mouth to crown
vibration magnitude	0·2–4 ms^{-2} r.m.s.
vibration frequency	0–100 Hz
waveform	sinusoidal to random
muscle tension	relaxed to stiff
subject type	male and female
	age 8–70 y
	weight 26–95 kg
	height 1·30–1·89 m

3. AVERAGE TRANSMISSIBILITIES

The average transmissibility data from each investigation eligible for inclusion in this review were digitised at a frequency increment of 1 Hz. Where experimental data were not determined (or not presented) at 1 Hz intervals, the values shown graphically by interpolation were used.

The mean data obtained from the individual studies are presented in Figures 1–3 for transmissibilities obtained with seat vibration in the fore-and-aft, lateral and vertical axes, respectively. The two transmissibilities for lateral vibration showing unusually high values of about 1 at 10 Hz in Figure 2 correspond to a study in which a racing car type seat was used. The seat provided lateral support for the seated body at the shoulders; subjects wore a 4-point harness with shoulder straps. Figure 3 shows the range of transmissibilities in the 46 published studies for vertical head motion occurring during exposure to vertical seat

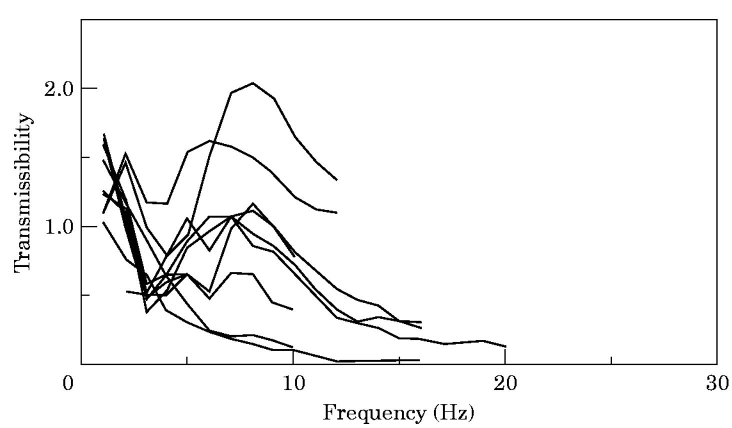

Figure 1. Average data from 10 studies of the transmission of fore-and-aft seat vibration to fore-and-aft head motion.

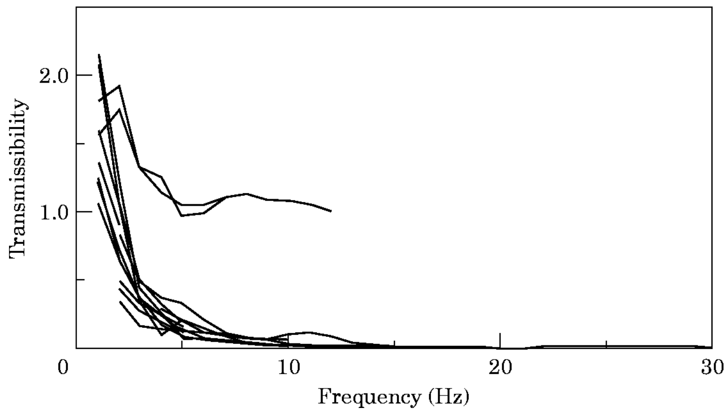

Figure 2. Average data from 14 studies of the transmission of lateral seat vibration to lateral head motion.

vibration. An example of the variability in transmissibility is seen at 4 Hz where one study showed a transmissibility value which was more than five times greater than the value presented in another study (minimum transmissibility of 0·48 and maximum transmissibility of 2·78). The variation in transmissibility may be greater at other frequencies (for example at about 15 Hz).

The median and interquartile ranges of the transmissibilities presented in Figures 1–3 are shown in Figures 4–6, respectively. (The median is a value which exactly divides a set of values arranged in ascending, or descending order; the median is sometimes referred to as the 50th percentile. The interquartile range is the range between the 25th and 75th percentile.) The highest frequencies included in Figures 4–6 are 16 Hz for fore-and-aft vibration, 14 Hz for lateral vibration and 30 Hz for vertical vibration, respectively. The frequency range was restricted according to the number of available studies (a minimum of 4). (The two curves for lateral seat vibration showing high transmissibility in Figure 2 have had a large effect on the upper quartile transmissibilities shown in Figure 5 and tabulated in Appendix B, but no effect on the median transmissibilities.)

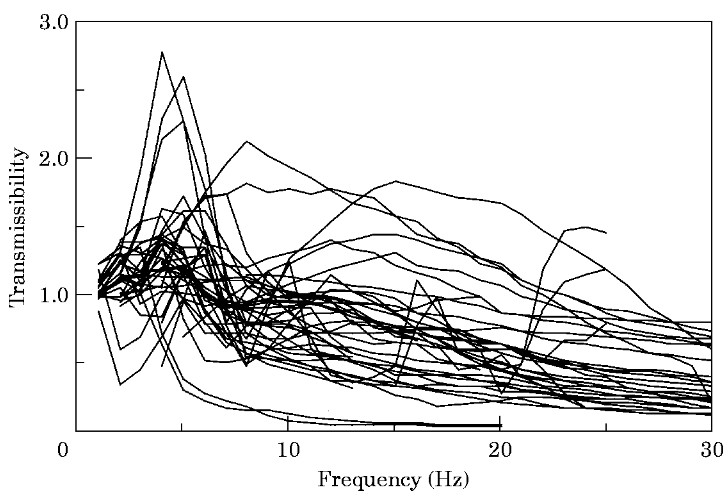

Figure 3. Average data from 46 studies of the transmission of vertical seat vibration to vertical head motion.

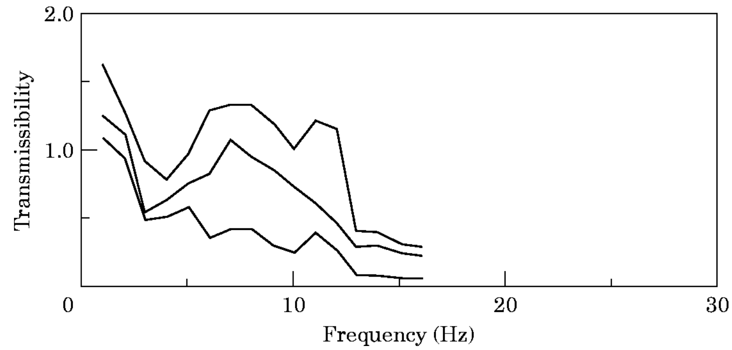

Figure 4. Median and interquartile ranges from 10 studies of the transmission of fore-and-aft seat vibration to fore-and-aft head motion (sufficient data only available up to 16 Hz).

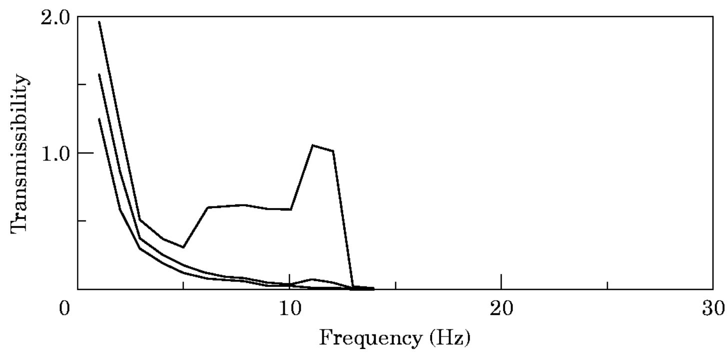

Figure 5. Median and interquartile ranges from 14 studies of the transmission of lateral seat vibration to lateral head motion (sufficient data only available up to 14 Hz).

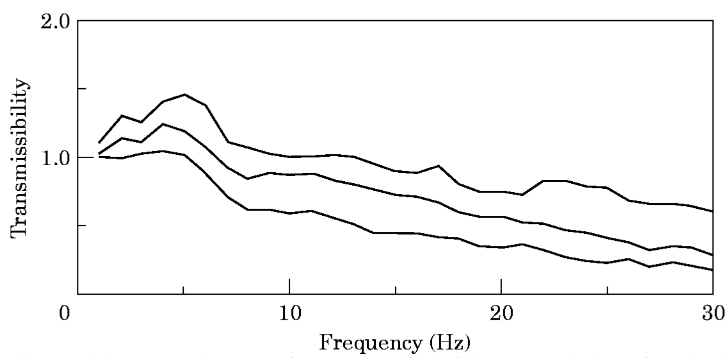

Figure 6. Median and interquartile range from 46 studies of the transmission of vertical seat vibration to vertical head motion.

4. DISCUSSION

4.1. EFFECT OF EXPERIMENTAL CONDITIONS ON MEASURES OF SEAT-TO-HEAD TRANSMISSIBILITY

The studies used in the above analyses vary in experimental conditions: for example, the location of measurement of vibration at the head, the type of input motion used, and the postures adopted by the subjects. In calculating the average transmissibilities for the different axes, the effects of such factors have been ignored. There are insufficient published data to determine average curves for all the different factors that affect the transmission

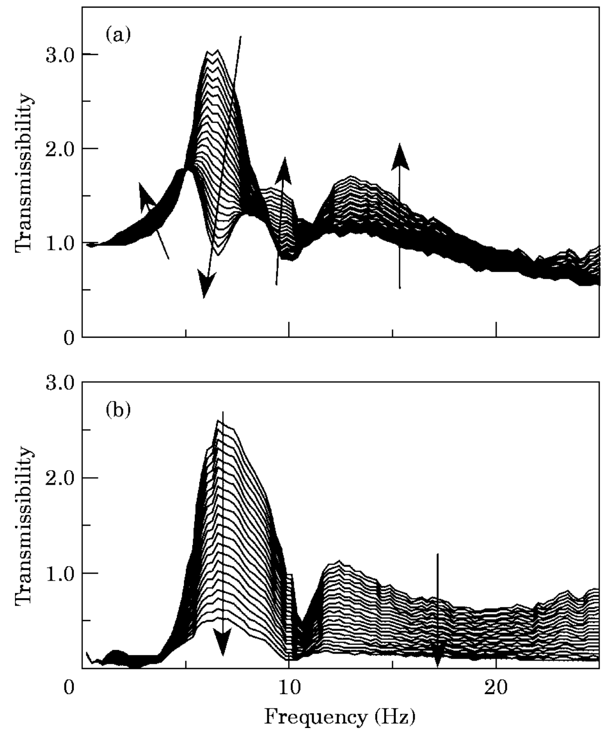

Figure 7. The variation in translational head motion with position of the transducer on the head for one person exposed to vertical seat vibration. (a) Vertical motion, vary fore-and-aft position from front of head to back of head; (b) fore-and-aft motion, vary vertical position from crown to chin.

of seat vibration to the heads of seated subjects. However, these effects can be seen in the results of individual experimental studies.

4.1.1. *Measurement position on the head*

The location of measurement of vibration on the head varied between studies: from the mouth, to the top of the head and to a point near to the ears. Assuming the human head

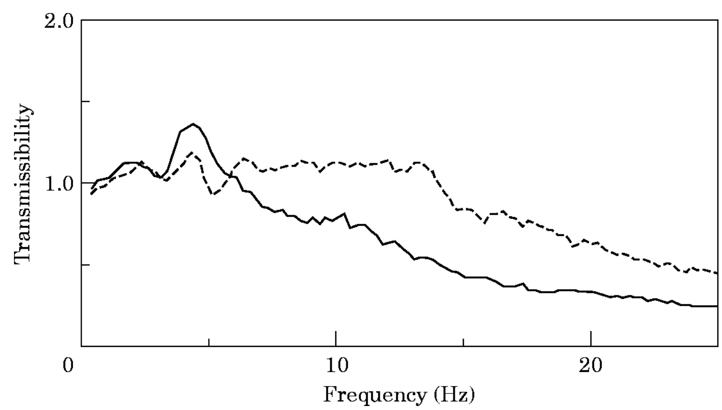

Figure 8. Median transmissibilities between vertical seat and vertical head vibration for subjects seated in a "back-off" posture and between vertical floor and vertical head vibration for subjects standing in a legs locked posture (adapted from references [19, 20]). Key: —, seated subjects; - - - , standing subjects.

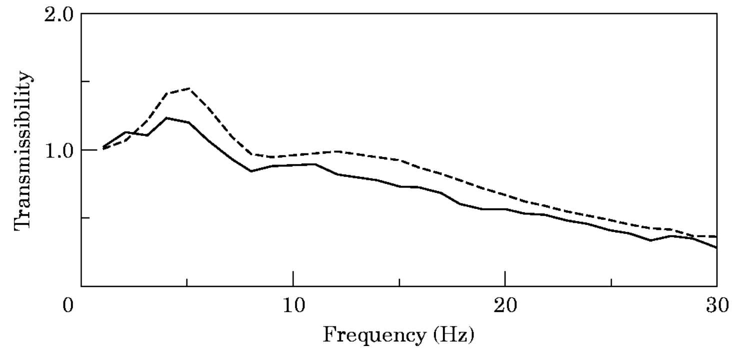

Figure 9. A comparison of the average transmissibility curve presented in ISO 7962 [1] and the median seat-to-head transmissibility curve calculated from this study. Key: ——, present study; – – –, ISO 7962 [1].

to be a rigid body, and assuming the head moved only in the translational axes (i.e., fore-and-aft, lateral and vertical), motion measured on the head would not be affected by the location of measurement. The first assumption is usually appropriate since it is believed that the lowest natural frequency of the human skull is at higher frequencies than considered here [13]. However, the second assumption is not valid since numerous studies have shown that rotational motion of the head occurs during exposure to whole-body vibration, see, e.g., references [4–6, 14]. The effect of the measurement position on the motion of the head has been demonstrated by Paddan and Griffin [15] with the subjects exposed to whole-body vertical vibration (see also reference [9]). Figure 7 shows, as an example, the effect of the location of the transducer at the head on the seat-to-head transmissibility in the vertical and fore-and-aft direction for 1 seated subject exposed to vertical vibration. Fore-and-aft head motion was affected by the vertical position on the head, and vertical head motion was affected by the fore-and-aft position on the head. The main factor causing this variation was the pitch motion of the head (see reference [15]). The potentially large effect of the differing locations used to measure head motion in the different studies inhibits comparison between studies.

The measuring position on the head may also influence the coupling between the accelerometers and the head. Many measurements are made at the mouth, where it is assumed that the use of a bite-bar results in the transducers moving with the head. However, measurements at other locations may have sometimes involved relative motion between the transducers and the skull due to the soft tissue.

4.1.2. *Numbers of subjects*

In this review, a minimum of six subjects was required before a study was included. However, studies with only six subjects then carried as much weight as much larger studies when forming the average transmissibilities. Several studies could not be included in the calculation of the average curves due to the small number of subjects, although they may contain relevant information (e.g., those of Woods [16], 4 subjects; of Johnston *et al.* [4], 5 subjects; and of Sandover [17], two subjects). In some studies head motion was measured but no data were presented.

4.1.3. *Number of studies and number of subjects*

A large number of studies (46) were used to determine the transmission of vertical seat vibration to the head. However, only 10 studies in the fore-and-aft axis and 14 studies in the lateral axis were included.

The data from approximately 50 subjects were used to compile the curves in ISO 7962 [1]. The total number of subjects that took part in the studies used to compile the median and interquartile transmissibility curves shown in Figures 4–6 for fore-and-aft, lateral and vertical vibration were 133, 157 and 644, respectively. (Only a small number of subjects was used to compile "average curves" for the mechanical driving point impedance of the human body that appears in International Standard ISO 5982 [18]: mean data from 39 seated subjects and only five standing subjects were used to determine the recommended values.)

4.1.4. *Standing versus seated subjects*

International Standard 7962 [1] suggests the same transmissibility from the seat (for seated subjects) and from the floor (for standing subjects) to the head. The standard does not differentiate between the two postures: the data were combined to form one curve for both seated and standing persons. A comparison between transmissibilities for sitting and standing positions has been presented by Paddan and Griffin [19, 20] and the median values obtained from 12 subjects are shown in Figure 8. It is clear that the transmissibilities for the two body postures are different: for frequencies greater than about 6 Hz, significantly more vibration was transmitted to the head when standing (with straight legs) compared to when seated. However, bending the legs was found to greatly reduce the transmission of vibration to the head at frequencies above about 4 Hz so that, with bent legs, the transmissibility was less than when seated.

From the references included in ISO 7962 [1] it appears that only four studies included standing subjects: about 19 of the 50 subjects used to compile the curves in ISO 7962 were standing. Average transmissibility curves could be calculated from the published data for standing subjects, but only rather limited data are available at present see, e.g., references [19, 21, 22].

4.1.5. *Other axes of vibration*

A similar review to the one presented here could be carried out for the transmission of rotational seat vibration to the head but, as with standing subjects, only a few studies are available (e.g., roll and pitch seat vibration [11, 23]; yaw seat vibration [12, 24]). Some of these studies have attempted to investigate the effects of different postures of the body on the vibration transmitted to the head; but useful comparisons between the data cannot be made as the different experiments have used varying and "non-standard" postures.

4.2. COMPARISON WITH ISO 7962 (1987)

Figure 9 compares the average transmissibility presented in ISO 7962 [1] with the median transmissibility between vertical seat vibration and vertical head motion (the median curve included in Figure 6). The two curves are remarkably similar, although the curve from ISO 7962 [1] is consistently higher and "smoother" than the median curve from the present study. The differences between the two transmissibility curves may be related to the number of studies and the number of subjects used in determining the different curves. A total of approximately 50 subjects were used to calculate the curve included in ISO 7962 [1] whereas, data from 644 subjects were taken to compile the average curve determined in this study. Also, studies involving only seated subjects were used for the average curve whereas, data from both seated and standing subjects were used for the curve in the standard. Figure 8 shows that the transmissibilities for vertical head motion occurring during exposure to vertical vibration are not the same for the two postures (seated and standing subjects).

4.3. TABULATED DATA

Numerical values for the median, lower quartile and upper quartile transmissibilities determined from this review, together with the range of the data, are presented in Appendix B.

5. CONCLUSIONS

The overall median transmissibility data determined from this and other studies should be used with caution. The variability obtained within studies (e.g., due to intra-subject variability and inter-subject variability) and the variability between studies (e.g., due to different experimental conditions or measurement locations) suggest that factors other than the vibration frequency have large effects on seat-to-head transmissibility. The standard deviations (and interquartiles and ranges) of transmissibilities should be considered when using the presented median values.

The results reported within individual experimental studies show that the effect of vibration frequency is only one of several factors which influence the transmission of vibration to the head. It is misleading to report an average transmissibility without identifying the conditions to which it applies and the variability to be expected in the biodynamic responses. This conclusion may be expected to be applicable to reports of transmissibilities to other locations of the body as more data for other sites become available.

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39. M. E. Johnston 1979 *Royal Aircraft Establishment*, *Farnborough*, *Technical Memorandum FS* 292. The effect of reclined seating on the transmission of linear vibration to the head.
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41. T. A. Furness 1981 [*Ph.D. thesis*] *Institute of Sound and Vibration Research*, *University of Southampton*, *Hampshire*. The effects of whole-body vibration on the perception of the helmet-mounted display.
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43. M. J. Griffin, E. M. Whitham and K. C. Parsons 1982 *Ergonomics* **25**, 603–630. Vibration and comfort. I. Translational seat vibration.
44. K. C. Parsons, M. J. Griffin and E. M. Whitham 1982 *Ergonomics* **25**, 705–719. Vibration and comfort. III. Translational vibration of the feet and back.
45. B. K. N. Rao 1982 *Shock and Vibration Bulletin* **52**, 89–99. Bio-dynamic response of human head during whole-body vibration conditions.
46. D. G. Wilder, B. B. Woodworth, J. W. Frymoyer and M. H. Pope 1982 *Spine* **7**, 243–254. Vibration and the human spine.
47. F.-W. Hagena, J. Piehler, C.-J. Wirth, G. O. Hofmann and Th. Zwingers 1986 *Neuro-Orthopedics* **2**, 29–33. The dynamic response of the human spine to sinusoidal G_z-vibration. In-vivo-experiments.
48. M. H. Pope, D. G. Wilder, L. Jorneus, H. Broman, M. Svensson and G. Andersson 1987 *Transactions of the ASME*. *Journal of Biomechanical Engineering* **109**, 279–284. The response of the seated human to sinusoidal vibration and impact.
49. M. W. Brett 1989 *United Kingdom Informal Group Meeting on Human Response to Vibration*, *AFRC*, *Institute of Engineering Research*, *Silsoe*, *Bedfordshire*. Effects of seating conditions on the transmission of horizontal vibration to the head.
50. M. W. Brett 1990 *United Kingdom Informal Group Meeting on Human Response to Vibration*, *Rheumatology and Rehabilitation Unit*, *University of Leeds*. Effect of seat shape on head motion during exposure to low frequency horizontal vibration.
51. G. S. Paddan 1991 [*Ph.D. thesis*] *Institute of Sound and Vibration Research*, *University of Southampton*, *Hampshire*. Transmission of vibration through the human body to the head.
52. P. D. Woodman and M. J. Griffin 1993 *Paper presented at a Seminar entitled* '*New Developments in Mechanics*, *Biomechanics and Design Aspects of Military Helmets*' *held at DRA*, *Farnborough* 1–3 December. The effect of helmet mass on the transmission of seat vibration to the head and helmet.

APPENDIX A: TABULAR SUMMARY OF EXPERIMENTAL STUDIES

This appendix summarises the experimental studies used to calculate the median and interquartile transmissibilities. Only studies in which the input and the output motions were measured in the same axes are included.

*See Table A*1 *overleaf*

TABLE A1

Summary of experimental studies concerned with the transmission of seat vibration to the head

Author(s) date and reference	Axes of input	Location of output	Axes of output	Vibration used	Frequency range (Hz)	Vibration magnitude	Seating condition	Backrest	Harness	Posture	No. of subjects and sex	Helmet
Bennett, M.D. Farmilo, B., Cole, S. H., Page, S. J., Withey, W. R. Webb, R. D. G. (1978) [3]	z	top of scalp	x y z	random superimposed with 125 ms pulses at 3 per 10 s	0–5	three levels: 0·21g, 0·28g and 0·35g r.m.s.	soft cushion	soft cushion	none	two: upright and semi-reclined	12 male	inner of safety helmet for accelerometers
Brett, M. W. (1989) [49]	x y	mouth using a bite bar	x y	random	0·4–12·5	1·0 ms^{-2} r.m.s.	two types: rigid hard seat and a cushioned tank seat	two types: hard flat and cushioned	4-point harness used in one condition	various: "back-on" "back-off"	10 male	none
Brett, M. W. (1990) [50]	x y	mouth using a bite bar	x y	random	0–12·5	1·0 ms^{-2} r.m.s.	racing car type seat, soft and cushioned	soft cushioned	4-point harness used in one condition	"back-on" and harnessed	8 male	none
Coermann, R. R. (1940) [25]	z	mouth using a bite plate	z	sinusoidal	15–140 at irregular intervals	constant amplitude of 50 mm	hard flat, wooden	none	none	not stated	10	none
Coermann, R. R. (1962) [30]	z	top of head using accelero-meters attached with elastic bandages	z	sinusoidal	1–20	not stated	hard flat	none	none	two postures: erect and relaxed	8 male	none
Cohen, H. H. Wasserman, D. E. Hornung, R. W. (1977) [35]	z	mouth using a bite bar	z	sinusoidal	2·5–5	0·69 ms^{-2} r.m.s.	tractor seat non-cushioned	none	seat belt	comfort-able neutral	6 male	none
Dennis, J. P. (1965) [27]	z	top of helmet	z	sinusoidal	5–37	$\pm 1/4g$ and $\pm 1/2g$	foam padded tank seat	foam padded	none	not stated	12 male	leather flying helmet to mount accelerometer

Dennis, J. P. (1965) [31]	z	top of helmet	z	sinusoidal	5–37	0·5 g and 1·0 g peak-to-peak	foam padded tank seat	foam padded	none	comfort-able	6 male	leather flying helmet to mount accelerometer
Furness, T. A. (1981) [41]	z	mouth using a bite bar	z	sine sweep	0–40	1·0 ms^{-2} r.m.s.	hard flat	hard flat inclined backwards at 13°	5 point harness	"back-on" and harnessed	10 male	USAF HGU 2A/P helmet with helmet-mounted display
Griffin, M. J. (1975) [7]	z	mouth using a bite bar	z	sinusoidal	7–75	six levels 0·2–4·0 ms^{-2} r.m.s.	flat wooden	none	none	for maximum head vibration and for minimum head vibration	12 male	none
Griffin, M. J., Lewis, C. H. Parsons, K. C. Whitham, E. M. (1979) [10]	z	mouth using a bite bar	z	sinusoidal	1–100 at 21 third-octave centre frequencies	not stated	hard flat	none	none	various: comfort-able upright, relaxed, stiff	various sets: 18 men and 18 women; 18 men and 12 boys	none
Griffin, M. J. Whitham, E. M. (1978) [37]	z	mouth using a bite bar	z	sinusoidal	4 and 16	1 ms^{-2} r.m.s.	flat wooden	none	none	upright	56 men 28 women 28 children	none
Griffin, M. J. Whitham, E. M. Parsons, K. C. (1982) [43]	z	mouth using a bite bar	z	sinusoidal	third-octave from 1–100	1·0 ms^{-2} r.m.s.	hard flat	none	none	comfort-able upright	18 male 18 female	none
Guignard, J. C. (1959) [26]	z	near right ear using a bite bar	z	sinusoidal	8–60 at 15 irregularly spaced frequencies	1 g peak	Martin Baker Mk3 ejection seat	no backrest contact	lap belts	two postures: slack and 'attention'	10 male	none
Guignard, J. C. Irving, A. (1960) [8]	z	top of head	z	sinusoidal	2·0–13·5	$\pm$0·25 g	hard flat	none	none	normal	10 male (5 'large' and 5 'small')	rubber bathing cap

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Author(s) date and reference	Axes of input	Location of output	Axes of output	Vibration used	Frequency range (Hz)	Vibration magnitude	Seating condition	Backrest	Harness	Posture	No. of subjects and sex	Helmet
Hagena, F.-W. Piehler, J. Wirth, C.-J. Hofmann, G. O. Zwingers, Th. (1986) [47]	z	top of head	z	sinusoidal	3–40	0·2 g	not stated	none	none	erect	9 male and 2 female	none
Hornick, R. J. Boettcher, C. A. Simons, A. K. (1961) [29]	x y	on head	x y	sinusoidal	1·5–5·5 at 1 Hz intervals	various: peak of 0·15 g, 0·25 g, 0·30 g for x-axis; 0·15 g, 0·25 g 0·35 g for y-axis	rigid, wooden	rigid, wooden	lap-strap used for x-axis only	not stated	20 male	none, accelerometer tied to the head via a belt
Johnston, M. E. (1979) [39]	y z	mouth using a bite bar	x y z	sine sweep	2–25	1·5 ms^{-2} r.m.s. and 3·0 ms^{-2} r.m.s.	Martin Baker Mk 10B ejection seat	soft padded, angles used were 20° 30°, 45° and 60° to the vertical, also used headrest	seat harness used	'alert' posture	10 male	Mk 2/3 flying helmet without a mask
Lewis, C. H. Griffin, M. J. (1980) [40]	y z	mouth using a bite bar	y z r_x r_y	sine sweep	2–64	1·6 ms^{-2} r.m.s.	hard flat hard flat	none hard flat	none five point	upright comfort-able	10 male	RAF Mk1 for some conditions
Mertens, H. (1978) [38]	z	head	z	not stated constant acceleration amplitude	2–20	3·7 ms^{-2} r.m.s. plus static acceleration of up to 4 G_z	not stated	not stated	waist and shoulders	upright	6 male 3 female	none
Messenger, A. J. Griffin, M. J. (1989) [9]	z	mouth using a bite bar	x z r_y	random	various: 1–30, 0·5–40	various: 1, 2 ms^{-2} r.m.s.	two types: hard flat and soft foam	soft foam used in one condition	none	various: erect, different pelvic angles, normal upright, different back angles	various studies; 14 male, 8 male, 12 male, 20 male	none
Moseley, M. J. Lewis, C. H., Griffin, M. J. (1981) [42]	z	mouth using a bite bar	z r_y	sine sweep	0–65	1·5 ms^{-2} r.m.s.	two seats: one hard and one soft	one hard and one soft	five-point harness	comfort-able normal	12 male	used in one condition

Paddan, G. S. (1991) [51]	x	mouth using a bite bar	x z r_y	random	0–16	1·0 ms^{-2} r.m.s.	hard flat	hard flat	none	"back-on" comfort-able upright	31 male, female and children	none
Paddan, G. S. Griffin, M. J. (1988) [5]	z	mouth using a bite bar	x y z r_x r_y r_z	random	0·2–25	1·75 ms^{-2} r.m.s.	hard flat	two conditions: with hard flat and with none	loose lap strap	comfort-able upright	12 male	none
Paddan, G. S. Griffin, M. J. (1988) [6]	x y	mouth using a bite bar	x y z r_x r_y r_z	random	0·2–16	1·75 ms^{-2} r.m.s.	hard flat	two conditions: with hard flat and with none	loose lap strap	comfort-able upright	12 male	none
Parsons, K. C. Griffin, M. J. Whitham, E. M. (1982) [44]	z	mouth using a bite bar	z	sinusoidal	approx. 2·5, 4, 8, 16, 32, 50	not stated	various: hard flat; semi-rigid	hard flat inclined used in some conditions	five-point harness used in some conditions	various: normal, erect, no backrest with backrest contact	12 male	none
Pope, M. H. Wilder, D. G. Jorneus, L. Broman, H. Svensson, M. Andersson, G. (1987) [48]	z	mouth using a bite bar	z	sinusoidal	2–14	1·0 ms^{-2} r.m.s.	hard flat	none	none	two postures: erect and relaxed	5 male and 5 female	none
Pradko, F. Orr, T. R. Lee, R. A. (1965) [32]	z	top of the head	z	sinusoidal and random	1–60	0·35 g to 2·24 g	soft	soft	none	erect	10 male	thin rubber cap for mounting accelerometer
Rao, B. K. N. (1982) [45]	z	mouth using a bite bar	z	sinusoidal	2·5–30	3 magnitudes: 0·64, 1·32 and 2·0 ms^{-2} r.m.s.	not stated	used in some conditions	car seat belt used in one condition	various	8 male	none
Rowlands, G. F. (1972) [2]	y z	on head via head harness	x y z	sinusoidal	1–4	0·2 g and 0·4 g r.m.s.	Martin Baker Mk8 ejection seat	soft padded	two conditions: with three-point harness and without harness	normal	7 male	head harness for accelerometers

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Author(s) date and reference	Axes of input	Location of output	Axes of output	Vibration used	Frequency range (Hz)	Vibration magnitude	Seating condition	Backrest	Harness	Posture	No. of subjects and sex	Helmet
Rowlands, G. F. (1977) [36]	z	top of head	z	sine sweep	2–25	2, 2·8 and 4 ms^{-2} peak-to-peak	hard flat	hard flat	lap strap	various: slumped, normal, erect, "back-off"	6 male	safety helmet for accelerometer mount
Sandover, J. Soames, R. W. (1975) [33]	z	mouth and crown	x z	sinusoidal	1–5 at 1 Hz intervals	2 ms^{-2} r.m.s.	not stated	not stated	not stated	not stated	6	not stated
Schmitz, M. A. Simons, A. K. (1960) [28]	z	top of the head	z	sinusoidal	2·5 and 3·5	various: 0·15 g, 0·18 g, 0·30 g and 0·35 g	contoured wooden seat	contoured wooden backrest	none	relaxed	18 male	none
Vogt, L. Schwartz, E. Mertens, H. (1979) [14]	z	temporal region on head	x (un-clear) z	sinusoidal	2–19 at 1 Hz intervals	0·35 g r.m.s.	not stated	two conditions: contact with backrest, no backrest contact	not stated	relaxed	11 male	none
Wilder, D. G. Woodworth, B. B. Frymoyer, J. W. Pope, M. H. (1982) [46]	z	on helmet	z	sine sweep	1–20	not stated	not stated	not stated	not stated	various: relaxed, backward and forward bend, left and right bend, axial rotation Valsalva	30 males 15 females	hockey helmet for accelerometer
Woodman, P. D. Griffin, M. J. (1993) [52]	x	mouth using a bite bar	x z r_y	random	0·25–20	1·0 ms^{-2} r.m.s.	hard flat	hard flat	none	normal upright, "back-on"	12 male	skull cap used in some runs, masses were 0, 1·4, 2·8 and 4·2 kg
Zagórski, J. Jakubowski, R. Solecki, L. Sadło, A. Kasperek, W. (1976) [34]	z	head	z	sinusoidal	2–20 at 1 Hz intervals	2·3 ms^{-2} and 1·15 ms^{-2}	hard flat	not stated	none	not stated	20 male	none

APPENDIX B: TABULATION OF TRANSMISSIBILITY DATA

This appendix presents numerical values of the medians, interquartiles (25% and 75%), and the lower and upper ranges of the reported transmissibilities for fore-and-aft, lateral and vertical seat vibration.

TABLE B1

Medians, interquartiles and ranges of transmissibilities between fore-and-aft seat vibration and fore-and-aft head motion; data from 10 *studies at frequencies up to* 16 Hz

Frequency (Hz)	Median	25%	75%	lower range	upper range
0	–	–	–	–	–
1	1·260	1·100	1·630	1·040	1·680
2	1·120	0·943	1·275	0·530	1·540
3	0·550	0·488	0·925	0·390	1·180
4	0·645	0·525	0·793	0·400	1·170
5	0·755	0·593	0·970	0·310	1·560
6	0·830	0·360	1·290	0·240	1·620
7	1·080	0·430	1·330	0·180	1·980
8	0·960	0·430	1·335	0·150	2·040
9	0·870	0·310	1·205	0·110	1·940
10	0·730	0·260	1·020	0·100	1·660
11	0·610	0·400	1·217	0·070	1·480
12	0·475	0·263	1·160	0·030	1·340
13	0·295	0·095	0·420	0·030	0·460
14	0·310	0·083	0·402	0·020	0·420
15	0·260	0·073	0·320	0·030	0·320
16	0·225	0·068	0·293	0·030	0·300

TABLE B2

Medians, interquartiles and ranges of transmissibilities between lateral seat vibration and lateral head motion; data from 14 *studies at frequencies up to* 14 Hz

Frequency (Hz)	Median	25%	75%	lower range	upper range
0	–	–	–	–	–
1	1·570	1·235	1·960	1·070	2·170
2	0·840	0·570	1·140	0·350	1·930
3	0·375	0·293	0·508	0·170	1·340
4	0·255	0·193	0·370	0·100	1·250
5	0·180	0·123	0·303	0·080	1·050
6	0·120	0·080	0·605	0·060	1·050
7	0·100	0·065	0·615	0·050	1·110
8	0·080	0·050	0·615	0·040	1·140
9	0·060	0·035	0·585	0·020	1·100
10	0·040	0·030	0·590	0·020	1·080
11	0·075	0·018	1·060	0·010	1·060
12	0·055	0·018	1·010	0·010	1·010
13	0·015	0·003	0·035	0·000	0·040
14	0·015	0·003	0·020	0·000	0·020

TABLE B3

Medians, interquartiles and ranges of transmissibilities between vertical seat vibration and vertical head motion; data from 46 *studies at frequencies up to* 30 Hz

Frequency (Hz)	Median	25%	75%	lower range	upper range
0	–	–	–	–	–
1	1·035	1·010	1·115	0·890	1·240
2	1·140	1·000	1·305	0·350	1·410
3	1·115	1·038	1·263	0·240	1·920
4	1·250	1·060	1·420	0·480	2·780
5	1·205	1·028	1·465	0·305	2·600
6	1·080	0·898	1·390	0·225	2·040
7	0·935	0·720	1·123	0·177	1·980
8	0·850	0·630	1·078	0·163	2·140
9	0·890	0·623	1·045	0·125	2·030
10	0·885	0·603	1·020	0·080	1·950
11	0·895	0·613	1·008	0·070	1·860
12	0·840	0·555	1·030	0·060	1·780
13	0·810	0·520	1·013	0·055	1·750
14	0·780	0·450	0·960	0·050	1·790
15	0·740	0·460	0·910	0·050	1·840
16	0·720	0·455	0·890	0·050	1·800
17	0·680	0·425	0·953	0·040	1·760
18	0·610	0·413	0·818	0·040	1·720
19	0·570	0·363	0·765	0·040	1·700
20	0·570	0·345	0·765	0·040	1·680
21	0·540	0·370	0·740	0·200	1·600
22	0·520	0·340	0·840	0·190	1·480
23	0·480	0·280	0·840	0·180	1·480
24	0·450	0·260	0·800	0·170	1·500
25	0·420	0·240	0·790	0·160	1·460
26	0·390	0·265	0·700	0·150	1·080
27	0·340	0·220	0·670	0·140	0·910
28	0·360	0·240	0·665	0·140	0·820
29	0·350	0·220	0·650	0·130	0·800
30	0·300	0·195	0·615	0·120	0·800