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The effect of vibration on human performance and health: A review of recent literature

Ann M. Nakashima

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Abstract

A literature review on the effects of vibration on the occupational performance and health of workers has been done in the interest of understanding how Canadian Forces (CF) personnel are affected by exposure to vibration in military vehicles. Effects such as annoyance, discomfort, hearing loss and back pain have been identified. The International Standard (ISO 2631) for evaluation of human exposure to whole-body vibration gives guidelines for how vibration should be measured and assessed, but there has been some criticism regarding the validity of the evaluation procedures that are defined, and the ambiguity in the wording of the standard. In terms of vibration control, advances in the ergonomic and mechanical design of vehicles and new technologies such as active vibration control have been developed to reduce the amount of vibration exposure in vehicle operators. It is concluded that the state of knowledge of the vibration characteristics of vehicles that are currently being used by the CF must be brought up-to-date so that work can begin on improving working environments.

Résumé

L'auteure a dépouillé la littérature traitant des effets des vibrations sur le rendement professionnel et la santé des travailleurs afin de comprendre les effets subis par les membres des Forces canadiennes (FC) qui sont exposés aux vibrations des véhicules militaires dans lesquels ils se déplacent. Des études ont mis en évidence différents effets comme la gêne, l'inconfort, les pertes auditives et les maux de dos. La Norme internationale (ISO 2631) qui porte sur l'évaluation de l'exposition à des vibrations globales du corps contient des lignes directrices sur la façon de mesurer et d'évaluer les vibrations, mais certains contestent la validité des méthodes d'évaluation décrites et soulignent l'ambiguïté du libellé de la norme. On a amélioré la conception ergonomique et mécanique des véhicules et mis au point de nouvelles technologies comme le contrôle actif des vibrations afin d'atténuer les vibrations auxquelles sont exposés les conducteurs de véhicules. L'auteure conclut qu'il faut actualiser nos connaissances sur les caractéristiques vibratoires des véhicules actuellement utilisés par les FC, de manière à pouvoir améliorer les milieux de travail.

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Executive summary

Mechanical vibration of military vehicles leading to increased noise levels and whole-body vibration causes adverse effects on the health of Canadian Forces (CF) personnel. Previous reports on the effects of mechanical vibration on humans written by Defence Research and Development Canada (DRDC) date back to the 1980s. This report is a review of the research that has been done in recent years with regard to human response to vibration, health risks associated with vibration and control of vibration, in preparation for a new research initiative.

Many effects of human exposure to vibration have been identified. Short-term effects include annoyance, temporary hearing threshold shift (temporary hearing loss), reduced motion control, impaired vision, discomfort and fatigue. Long-term and extended exposure to whole-body vibration has been linked to chronic back pain. The extent to which these effects are felt has been connected to the characteristics of the vibration such as the frequency, magnitude and duration of exposure. However, there are currently no widely accepted guidelines for vibration exposure limits with respect to human comfort and health risks.

The current International standard for evaluation of human exposure to whole-body vibration (ISO 2631-1:1997) outlines methods for quantifying vibration exposure. The standard suggests quantitative guidelines for human response to vibration in terms of comfort levels and health guidance caution zones. Although some national standards organizations have adopted ISO 2631, some researchers have questioned the validity of the guidelines and criticized the wording of the standard as being ambiguous.

Technological advances in recent years have allowed various methods of vibration control to be developed. The development of mathematical models and vibration dummies for simulation of vibration exposure can potentially eliminate the need for human test subjects. Research on the design of automobile and seat suspension systems has helped to reduce vibration transmission to the drivers, thereby increasing driver comfort. Computer-controlled adaptive algorithms for vibration control (active vibration control [AVC]) have the potential to improve vibration reduction for changing operating conditions (e.g. different terrain, driving speeds or environmental conditions).

Given the increased amount of knowledge and technological advances in the field of vibration, it is concluded that the state of knowledge of vibration exposure for CF personnel should be brought up-to-date, so that new research initiatives can be formed in the interest of improving working environments.

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Sommaire

Les vibrations mécaniques des véhicules militaires augmentent les niveaux de bruit et les vibrations transmises à l'ensemble du corps, ce qui a des effets délétères sur la santé du personnel des Forces canadiennes (FC). Les rapports antérieurs de Recherche et développement pour la défense Canada (RDDC) traitant des effets des vibrations mécaniques sur le corps humain remontent aux années 1980. Le rapport que voici présente une analyse des études récentes portant sur les réactions de sujets humains aux vibrations, sur les risques pour la santé qui y sont associés et sur la réduction des vibrations, en vue de la réalisation de nouveaux projets de recherche.

Beaucoup d'effets de l'exposition aux vibrations chez l'être humain ont été mis en évidence. Parmi les effets à court terme figurent la gêne, le déplacement temporaire du seuil d'audition (perte auditive temporaire), la détérioration du contrôle des mouvements, l'affaiblissement de la vue, de l'inconfort et de la fatigue. Il y a un rapport confirmé entre les maux de dos chroniques et l'exposition prolongée, à long terme, à des vibrations globales du corps. L'intensité des effets ressentis dépendrait des caractéristiques des vibrations, notamment la fréquence, l'amplitude et la durée d'exposition. Toutefois, il n'existe pas à l'heure actuelle de lignes de conduite universellement admises en ce qui concerne les limites d'exposition aux vibrations qui permettraient d'assurer le confort de sujets humains et d'éviter les risques pour la santé.

La Norme internationale actuelle relative à l'évaluation de l'exposition des individus à des vibrations globales du corps (ISO 2631-1 : 1997) décrit les méthodes utilisées pour quantifier l'exposition aux vibrations. Elle énonce des lignes directrices quantitatives à respecter pour préserver le confort et la santé des personnes exposées aux vibrations. Bien que des organismes normatifs nationaux aient adopté la norme ISO 2631, certains chercheurs l'ont critiquée, mettant en doute la validité de ses lignes directrices et jugeant son langage trop ambigu.

Les avancées technologiques des dernières années ont permis de mettre au point diverses méthodes de réduction des vibrations. L'élaboration de modèles mathématiques et l'utilisation de mannequins lors de simulations de l'exposition aux vibrations pourraient éliminer la nécessité de tests sur des sujets humains. Les recherches sur la conception des automobiles et les systèmes de suspension des sièges ont permis d'atténuer les vibrations transmises aux conducteurs, améliorant par le fait même le confort de ceux-ci. Des algorithmes adaptatifs commandés par ordinateur qui réduiraient les vibrations (contrôle actif des vibrations) pourraient contribuer à réduire les vibrations lorsque les conditions de conduite des véhicules changent (p. ex. terrain différent, changement de vitesse ou modification des conditions ambiantes).

Étant donné l'accumulation de nouvelles connaissances et les avancées technologiques dans le domaine des vibrations, l'auteure conclut à la nécessité de mettre à jour nos connaissances sur l'exposition du personnel des FC aux vibrations, de manière à pouvoir concevoir de nouveaux projets de recherche qui permettront d'améliorer les milieux de travail.

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Introduction

There has been an assumed link between the vibration levels experienced in military vehicles and adverse health effects on Canadian Forces (CF) personnel. These effects include but are not limited to: discomfort/fatigue, decreased performance level (i.e. reduced motion control, blurred vision), back disorders and hearing loss. The Human Factors Research and Engineering Section (HFRE) of Defence Research and Development Canada Toronto (DRDC Toronto) aims to support CF personnel through research and development that improves the quality of their working environments. In recent years, a great deal of research has been performed by various academic, industrial and government groups on the subject of human exposure to vibration. As this is a topic that is directly relevant to the CF, the need for a literature review was identified.

Whole-body vibration occurs when the body is supported by a vibrating surface. In the context of military vehicles, personnel are exposed to vibration when seated on a vibrating seat, are in contact with the backrest of a seat, or standing on a vibrating floor. The amount of vibration exposure depends on a number of factors, including the type and design of vehicle, the speed at which the vehicle is travelling, the environmental conditions and body posture. In addition, ground and maintenance crew can be exposed to whole-body vibration through the airborne transmission of sound pressure waves. Translation vibration, or linear vibration, is generally measured in the fore-to-aft (x-axis), lateral (right to left side, y-axis) and vertical (z-axis) directions. The defined positions of the axes relative to the human body depend on whether the person is seated, standing or recumbent, and may differ slightly between published standards. Rotational vibrations that occur about the three axes are referred to as roll (x-axis), pitch (y-axis) and yaw (z-axis). A sudden, high acceleration vibration event is called a shock. In the context of this review, only translation vibration will be discussed. The range of frequencies that is most often associated with whole-body vibration is approximately 0.5 to 100 Hz (Griffin, 1990). Vibration magnitude is generally measured in terms of the acceleration of the oscillations, rather than the velocity or displacement between peak-to-peak movements. The preferred International System (S.I.) unit for vibration acceleration magnitude is meters-per-second-per-second (m/s^2), and measurements are often expressed as root-mean-squared (rms) values rather than peak values.

The subject of human exposure to vibration encompasses a wide range of topics from different disciplines of research, including medicine, psychology and engineering. In this review, emphasis will be placed on studies that were performed after the latest version of the International standard for human exposure to vibration (ISO 2631-1:1997) was released, although the results of earlier studies will also be mentioned. The first section will describe guidelines that ISO 2631 gives for measuring, analyzing and interpreting human exposure to vibration. Evaluation of ISO 2631 and comparison to the British standard will be discussed in the second section. The third section will discuss human response to vibration, including short-term health effects such as discomfort and fatigue, and the long-term effect of chronic back pain. The fourth section summarizes research on possible solutions for vibration exposure, including methods of passive (mechanical design) and active vibration control, followed by a discussion and suggestions for future research.

The International Standard: ISO 2631

ISO 2631 was first published in 1974, with the purpose of giving "numerical values for limits of exposure for vibrations transmitted from solid surfaces to the human body in the frequency range 1 to 80 Hz" (Griffin, 1990). The standard was republished in 1978, 1982, 1985 and 1997, having undergone major revisions along the way. The current version of ISO 2631, entitled "Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration" consists of four parts (labelled 2631-1, 2631-2, 2631-4 and 2631-5). The part that is relevant to the current review is 2631-1, which is called "General Requirements." ISO 2631-1:1997 provides a more quantitative guide on the effects of vibration on health and comfort than its predecessor, ISO 2631-1:1985. It is stated that the primary purpose of the standard is to "define methods of quantifying whole-body vibration in relation to:"

- human health and comfort;
- the probability of vibration perception;
- the incidence of motion sickness.

Human response to vibration is strongly frequency-dependent. The primary quantity of vibration magnitude is the acceleration, given by

$$a_w = \left[\frac{1}{T} \int_0^T a_w^2(t)dt \right]^{\frac{1}{2}} , \quad (1)$$

where $a_w(t)$ is the weighted acceleration as a function of time, t, in m/s^2 and T is the duration of the measurement, in seconds. There are 3 principal frequency weightings: W_k for the z-axis or vertical direction (except head), W_d for the x- and y-axes, or horizontal direction, and W_f for motion sickness. Additional frequency weightings defined for the special cases of seat-back measurements, rotational vibration and vibration under the head are denoted by W_c, W_e and W_j, respectively. The weightings are given in ISO 2631-1 in both graphical and tabular form; the graph is shown in Fig. 1. In general, for W_k, frequencies below about 2 Hz are weighted slightly less than frequencies of about 3 to 10 Hz, and above 10 Hz, the curve drops off rapidly. For W_d, the highest weighting is given to frequencies in the range of 0.5 to 2 Hz.
When evaluating comfort, it is recommended that the combined vibration of the three axes be used. The vibration total value, a_v, is calculated as

$$a_v = (k_x^2 a_{wx}^2 + k_y^2 a_{wy}^2 + k_z^2 a_{wz}^2)^{\frac{1}{2}} , \quad (2)$$

where a_{wx}, a_{wy} and a_{wz} are the weighted rms accelerations and k_x, k_y and k_z are the multiplying factors with respect to the x-, y-, and z-axes, respectively. The multiplying factors are given separately in the standard for seated and standing persons, and for recumbent persons when measuring under the pelvis. Different multiplying factors are defined for health, comfort and human perception of vibration.

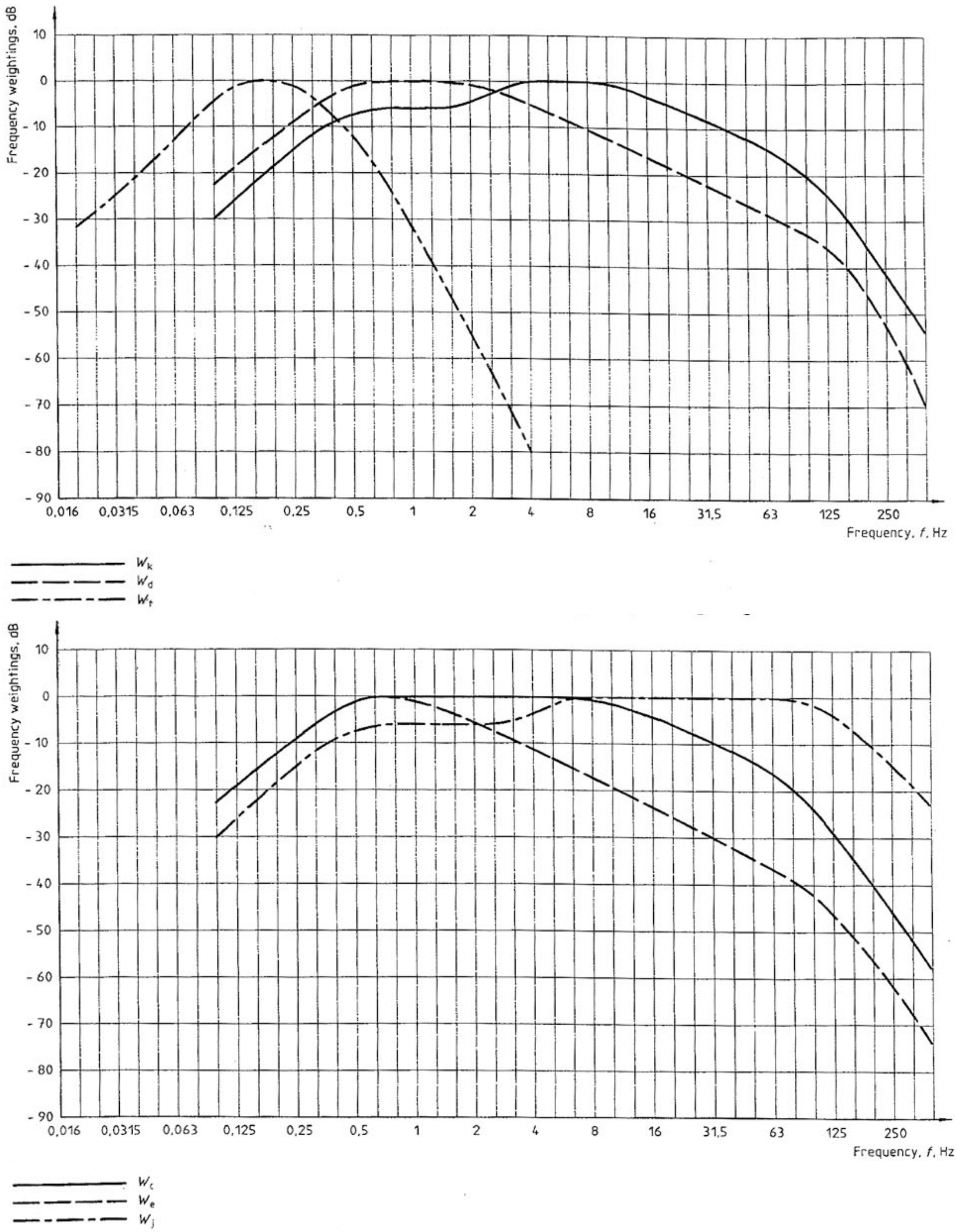

Figure 1. *ISO 2631-1:1997 frequency weighting curves for the principle weightings (top) and the additional weightings (bottom).*

Random or transient vibrations are accounted for by using the crest factor. The crest factor is defined as "the modulus of the ratio of the maximum instantaneous peak value of the frequency-weighted acceleration signal to its rms value." The peak value is determined over the duration of measurement. In the case that the vibration consists of various periods of different characteristics, the periods should be analyzed separately. A vibration signal can thus have multiple crest factors. For a signal that has high crest factors, it is stated that the vibration may be characterized by the running rms method, calculated approximately as

$$a_w(t_0) = \left\{ \frac{1}{\tau} \int_{-\infty}^{t_0} \left[a_w(t) \right]^2 \exp\left[\frac{t - t_0}{\tau} \right] dt \right\}^{\frac{1}{2}}, \tag{3}$$

where $a_w(t)$ is the instantaneous frequency-weighted acceleration as a function of time, t, τ is the integration time for running averaging and t_0 is the time of observation. The maximum transient vibration value, MTVV, is defined as

$$\text{MTVV} = \max\left[a_w(t_0) \right]. \tag{4}$$

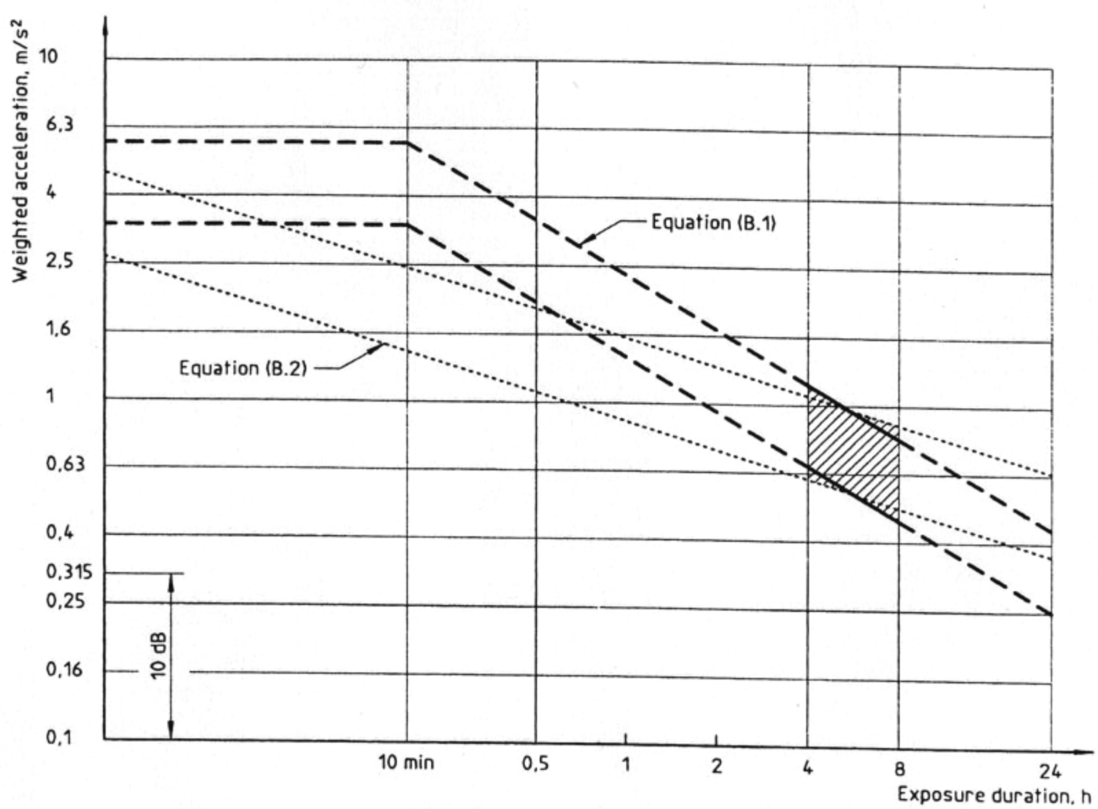

Figure 2. *ISO 2631-1:1997 health guidance caution zones.*

The recommended value for τ in measuring the MTVV is one second. Alternatively, the amount of vibration exposure can be calculated with the fourth power vibration dose method. The fourth power vibration dose value is given by

$$\mathrm{VDV} = \left\{ \int_0^T [a_w(t)]^4 \, dt \right\}^{\frac{1}{4}}, \tag{5}$$

in units of $\mathrm{ms}^{-1.75}$, where $a_w(t)$ is the instantaneous frequency-weighted acceleration as a function of the time, t, and T is the duration of measurement.

The standard acknowledges that long-term exposure to high-intensity whole-body vibration can lead to an increased risk of injury to the lumbar spine and connected nervous system. Effects on the digestive system, genital/urinary system and female reproductive organs have also been identified. Although no quantitative relationship between vibration dose and health effects has been identified, health guidance caution zones have been defined in terms of the weighted acceleration and exposure duration; they are shown in Fig. 2. Within the zone, caution with respect to potential health risks is advised, and above the zone, health risks are said to be likely.

Although exposure limits with regard to comfort are not defined, guidelines for the levels of comfort experienced for different magnitudes of vibration are included; these are listed in Table 1. The guidelines are intended to be approximate indications of likely reactions to vibration in public transport.

Many studies of whole-body vibration measurements in vehicles report their findings with reference to ISO 2631-1; some examples are given in the next section.

Table 1. *ISO 2631-1:1997 guidelines for levels of comfort for different vibration magnitudes.*

Less than 0.315 m/s^2	Not comfortable
0.315 to 0.63 m/s^2	A little uncomfortable
0.5 to 1 m/s^2	Fairly comfortable
0.8 to 1.6 m/s^2	Uncomfortable
1.25 to 2.5 m/s^2	Very uncomfortable
> 2 m/s^2	Extremely uncomfortable

Vibration Measurements

Studies have been conducted on specific types of vehicles to measure the levels of whole-body vibration exposure and assess the results according to ISO 2631-1. These studies have been performed either out of necessity because of the regulations imposed by the governing organization, or in response to the grievances of the affected employees.

Construction Vehicles

Cann *et al*. (2003) made vibration measurements in 14 different types of construction equipment. It was found that according to ISO 2631-1 standards, the mean weighted rms acceleration levels of 8 of the 14 types of equipment fell into the health guidance caution zone for a regular workday. The vehicles of concern were: bulldozers, scrapers, skid steer vehicles, backhoes, crawler loaders, wheel loaders, ride-on power trowels and off-road dump trucks. In terms of comfort, they would be classified at "Uncomfortable" according to Table 1, with only the scraper being classified as "Very uncomfortable." With respect to potential health risks, the vibration exposure levels fell into the health guidance caution zone shown in Fig. 2 for an 8-hour workday. There was, however, a large range in the vibration levels measured within a given category of vehicle. This indicated a great deal of variability within vehicles of the same type. For example, for the 14 excavators measured, the weighted rms acceleration ranged from 0.1 to 1.1 m/s^2, with a standard deviation of 0.28 m/s^2. The authors concluded their findings were, for the most part, consistent with those found in other studies.

Snowmobiles

An ergonomic evaluation of snowmobiles was reported by Habes *et al*. (2003). Rangers and maintenance workers of the National Park Service (NPS) ride snowmobiles for up to 10 hours per day during the winter months. On posted roads, the speed limit was 45 mph, and on the days that the measurements were taken, the roads were reported to have moguls approximately 18 inches apart and 8 to 12 inches high. Because the rough road conditions caused severe jolting of the riders, the measurements were analyzed in terms of peak acceleration levels. The median peak acceleration levels ranged from 3.13 to 4.71g (related to the acceleration due to gravity, g [9.81 m/s^2]). At the time of the case study, there was no specific method defined by ISO to deal with frequently occurring, high magnitude shocks; thus, the results could not be evaluated in terms of health risks. It was recommended that the roads in the park be groomed more frequently, and that the suspension system of the snowmobiles be improved to reduce the shocks sustained by the riders.

Truck Tractor

The United States Army Aeromedical Research Laboratory (USAARL) performed a whole-body vibration assessment of the M915A2 truck tractor (1994). Vibration measurements were taken for different terrain types, load configurations and vehicle speeds that covered the range of use of the tractor. The measurements were analyzed according to ISO 2631-1:1985, which defined health and safety exposure limits (HSEL). The HSEL were used to define duration of safe exposure (DSE) values. Since the M915A2 mission required 10 hours of operation, conditions in which the DSE was less than 10 hours were identified and flagged for assessment. Four of the measured conditions were found to have unacceptable DSE values: loaded configuration (44000 lbs load with a trailer attached) over asphalt driven at 55 mph, bobtail configuration (no load and no trailer attached) over asphalt driven at 45 mph, loaded configuration over Belgian block driven at 8 mph and bobtail configuration over cross-country (rough dirt road) driven at 12 mph. All four conditions were considered be encountered at least occasionally in the range of operations for which the vehicle is used.

The aforementioned case studies show that potentially hazardous levels of vibration are experienced in a range of occupational functions. It is essential that whole-body vibration exposure be assessed wherever possible and applicable so that action can be taken to reduce the impact on the health of workers. Whole-body vibration exposure can be measured and evaluated with reference to ISO 2631-1; however, as discussed in the next section, some have questioned certain aspects of the standard.

Evaluation of ISO 2631

The impact of published standards cannot be understated. Standards influence important decisions that can impact the success and credibility of manufacturers, and the safety and well-being of employees. Standards must be carefully formulated, reviewed and constantly assessed and revised if necessary in order to reflect the most current state of knowledge in a given field. Despite the revisions that have been made to ISO 2631 over the years, the current standard has been a target of criticism by some authors.

Comparison of ISO 2631-1:1997 and BS 6841 (1987)

Griffin published an extensive review and comparison of ISO 2631 to the British Standard, BS 6841 (Griffin, 1998). The paper compared previous versions of ISO 2631 (1974, 1978, 1982, 1985), BS 6841 (1987) and ISO 2631-1 (1997), although only the latter two standards will be discussed here. The main differences that were noted were in the context of 1) the axes of vibration, 2) the frequency weightings, 3) the magnitude and duration of vibration, and 4) the dependent variables.

In the assessment of the health effects of whole-body vibration, BS 6841 defines three translational axes on the supporting surface (seat for a seated person, floor for a standing person), and one axis (fore-to-aft) on the seat backrest. ISO 2631 identifies the same axes for evaluation of vibration for health, but uses frequency weighting curves and multiplying factors that are different from the British standard. The multiplying factors are listed in Table 2. It should be noted that the multiplying factors listed in Table 2 are with respect to health, since the International standard defines different values for assessment of vibration with respect to comfort and perception. Griffin argues that the multiplying factor of 1.4 for the horizontal axes defined by ISO 2631 creates ambiguity in the reporting of weighted values, as to whether they have been corrected or not.

Table 2. *Frequency weightings and multiplying factors as specified by the British standard BS 6841 (BS) and the International standard 2631-1 (ISO) (see study by Paddan and Griffin, 2002).*

LOCATION	AXIS	WEIGHTING		MULTIPLYING FACTOR	
		BS	***ISO***	***BS***	***ISO***
Seat	x	W_d	W_d	1.0	1.4
	y	W_d	W_d	1.0	1.4
	z	W_b	W_k	1.0	1.0
Backrest	x	W_c	W_c	0.8	0.8

There are also differences between the two standards with respect to how multi-axis vibration should be reported. In the British standard, the total vibration dose value, VDV_{total}, is given by

$$VDV_{total} = (VDV_{xs}^4 + VDV_{ys}^4 + VDV_{zs}^4 + VDV_{xb}^4)^{\frac{1}{4}} \qquad (6)$$

where VDV_{xs}, VDV_{ys} and VDV_{zs} are the VDV (Eq. 5) in the x-, y- and z-axes on the seat, respectively and VDV_{xb} is the VDV in the x-axis on the backrest. The ISO standard states that:

> The assessment of the effect of a vibration on health shall be made independently along each axis. The assessment of vibration shall be made with respect to the highest frequency-weighted acceleration determined in any axis on the seat pan. NOTE – When vibration in two or more axes is comparable, the vector sum is sometimes used to estimate health risk.

It is not clear how close the vibration magnitudes in two or more axes must be in order to constitute using the vector sum. The standard goes on to "encourage" measurements in the x-axis on the backrest, but does not state that the measurements are to be included in the calculation of the vibration magnitude or VDV.

BS 6841 states that the VDV procedure should be used when 1) the crest factors exceed 6.0, 2) the vibration has variable magnitude, 3) the motion contains occasional peaks, or 4) the motion is intermittent. ISO 2631-1 states that the "basic evaluation method" (rms acceleration), is normally sufficient for vibration with crest factors less than or equal to 9. It goes on to state in a note:

> For certain types of vibrations, especially those containing occasional shocks, the basic evaluation method may underestimate the severity with respect to discomfort even when the crest factor in not greater than 9. In cases of doubt it is therefore recommended to use and report additional evaluations also for crest factors less than or equal to 9 according to [Section] 6.3 [the running rms or fourth power vibration dose value].

Both standards are ambiguous in their statements as to which evaluation method should be used, but what is clear is their disagreement on the value of the threshold crest factor. Donati (2002) comments on the differences between quantifying vibration exposure in terms of weighted rms values and fourth power vibration dose, stating that "it is remarkable and confusing that the standard [ISO 2631-1] does not provide clues as to which methods should be selected, as they are not equivalent and give different results."

The International standard suggests that one of the VDV (Eq. 5) or the MTVV (Eq. 4) should be used to describe the vibration magnitude, "in the case where the basic evaluation method [rms acceleration] may underestimate the effects of vibration." However, it does not specify when to use which method. Since the recommended integration time for the MTVV is 1 s, Griffin criticizes that the quantity will be determined completely by the worst one second of vibration during an exposure, meaning that exposure to a single shock will be rated as the same as exposure to multiple shocks.

With regard to relating health risks to vibration exposure, the British standard makes the following statement:

> …there is currently no consensus of opinion on the precise relation between vibration dose values and the risk of injury. It is known that the vibration magnitudes and durations which produce vibration dose values in the region of $15ms^{-1.75}$ will usually cause severe discomfort. It is reasonable to assume that increased exposure to vibration will be accompanied by increased risk of injury.

ISO 2631-1 defines “health guidance caution zones” in terms of the rms acceleration and exposure duration as shown in Fig. 2. In terms of the VDV, it is stated that the upper and lower boundaries of the health guidance caution zone are approximately 17 and 8.5 $ms^{-1.75}$. Dose values that fall within the zone should be regarded with caution with respect to potential health risks, and above the zone, health risks are said to be likely. Griffin notes that the 17 $ms^{-1.75}$ upper boundary of the zone and the 15 $ms^{-1.75}$ VDV value mentioned by the British standard are similar for horizontal vibration with the use of the 1.4 multiplying factor in ISO 2631-1.

In a study by Paddan and Griffin (2002), vibration measurements were taken in a variety of passenger, construction and military vehicles and analyzed according to both the British and ISO standards. The rms accelerations were calculated according to the vector sum of the four vibration axes as defined by BS 6841, and the most severe axis as implied by ISO 2631-1. It was found that while the median values obtained by the two methods were similar, the vibration severity was underestimated by the ISO method. Over the 461 measurements taken in 100 vehicles, the median rms values for the BS and ISO methods were 0.74 m/s^2 and 0.66 m/s^2, respectively. The results of the study indicate that caution should be used when interpreting results that have been calculated in accordance with ISO 2631-1. If only the most severe vibration axis is included, the rms acceleration may be underestimated, consequently leading to an underestimated health risk assessment.

Other Evaluations of ISO 2631-1

Nakashima and Maeda (2004) noted that although the International standard gives general instructions for vibration measurements for seated persons, there are no requirements to show the exact measuring points and no description of the measurement differences that may result from different measurement positions. Experiments were performed to study the differences between vibration measurements made at different positions on the seat back of a sports utility vehicle at different seat-back angles. Measurements were made with the accelerometer placed 2.5 cm higher, 2.5 cm lower and 5.0 cm lower on the seat back than the reference position of 38 cm above the seat cushion surface. The seat-back angle was varied ±4 degrees from the reference position of 24 degrees from the vertical. It was found that the difference in seat-back angle caused rms acceleration measurements as much as 0.07 m/s^2 larger than the reference measurements. The measurement differences for the different accelerometer heights were as large as 0.05 m/s^2. It was therefore recommended by the researchers that exact accelerometer placement on the seat back and seat-back angles should be included in the standard.

Despite the apparent criticisms that have been expressed by various researchers, other standards organizations have adopted ISO 2631. The most recent versions of the American, Australian and Japanese standards for whole-body vibration (ANSI S3.18-2002, AS 2670.1-2001 and JIS B 7760-2:2004, respectively) are identical to ISO 2631-1:1997. The Japan Society for Occupational Health (JSOH) also recommends the occupational exposure limits that were a part of ISO 2631-3:1985, but were excluded in ISO 2631-1:1997.

The development of a clear and internally consistent standard for the assessment of human response to vibration is difficult because of the many aspects of human performance and health that can be affected. Commonly reported human responses to vibration are discussed in the next section.

Human Response to Whole-body Vibration

People are exposed to whole-body vibration mainly during transport and while operating heavy machinery. The level of tolerance will depend greatly on the environment and the type of activity that is being performed. For example, higher magnitudes of vibration would likely be tolerated in a railroad train than in a luxury passenger automobile. Human response to whole-body vibration exposure can be psychological or physiological, temporary or chronic. As discussed in this section, these effects can be difficult to characterize.

Annoyance

Short-term or low-amplitude vibration can be described as a source of annoyance for humans. It is well known that noise, or unwanted sound, can interfere with speech communication, affect concentration and cause sleep disturbance. When the noise is low frequency, vibration of the body and the surrounding area also result, which may influence the human perception of low-frequency noise. The presence of rattle and vibration can increase the human body's reaction to noise, increasing the level of annoyance (Berglund and Hassmén, 1996; Howarth and Griffin, 1990). Field surveys on the effects of noise and vibration from railway traffic found that residents who were exposed to combined noise and vibration expressed a higher degree of annoyance than those exposed to noise alone (Öhrström and Skånberg, 1996; Öhrström, 1997).

The reaction to combined noise and vibration inside an aircraft has been studied (Västfjall, Kleiner and Gärling, 2003). Twenty test subjects rated their affective reactions to 18 combinations of noise and vibration while seated in an aircraft seat in a laboratory setting. A shaker exciter was used to vibrate a foot plate that was used in conjunction with the aircraft seat. Two different vibration frequencies (16 and 95 Hz) in the lateral direction were used. The noise signals used were binaural recordings of interior turboprop aircraft sounds, presented to the subject over headphones. The subjects' responses were evaluated in terms of activation (arousal), valence (unpleasantness-pleasantness) and preference. Valence was measured by the subjects' responses using three scales whose extremes were defined by the adjective pairs pleased-displeased, happy-depressed and glad-sad. Activation was determined by the adjective pairs sleepy-awake, dull-peppy and active-passive, and preference was assessed with the words attractive-unattractive, likeable-dislikeable and preferred-not preferred. Each scale ranged from 10 to 90, with 10 corresponding to the left adjective, 90 corresponding to the right adjective and 50 being neutral. The ratings were averaged for each noise and vibration combination to determine the activation, valence and preference levels. A general summary of activation-valence combinations and their affective reactions is shown in Table 3. It was found that the strongest negative reactions occurred when an unpleasant sound was combined with the 16 Hz vibration. However, pleasant sounds received unfavourable reactions when combined with the 95 Hz vibration. It was suggested that a single scale for rating annoyance or comfort is insufficient, and that the combinations of valence and activation induced by the aircraft might give a better assessment of ride quality.

Table 3. *Affective reactions corresponding to various activation-valence combinations (Västfjall, Kleiner and Gärling, 2003).*

ACTIVATION	VALENCE	AFFECTIVE REACTION
Low	Unpleasant	Boredom
High	Unpleasant	Distress
High	Pleasant	Excitement
Low	Pleasant	Calmness
Moderate	Unpleasant	Annoyance
Moderate	Pleasant	Comfort

Decreased Performance Levels

Noise and vibration are known to affect the cognitive performance, hearing, motor control and vision of humans. The motion that is induced by vibration can also affect an individual's ability to perform certain tasks. In a military vehicle environment, sharp performance and clear communication between crewmembers are essential. Thus, it is important to understand how mechanical vibrations affect the ability of humans to perform their duties on the job.

Cognitive Performance

Harris and Shoenberger (1980) studied individual and combined effects of noise and vibration on cognition by monitoring the ability of human test subjects to perform a complex counting task. Twelve male Air Force military personnel were exposed to 65 or 100 dBA broadband noise, with and without 0.36 rms G_z vibration. The vibration was a quasi-random sum-of-sines signal composed of five frequencies: 2.6, 4.1, 6.3, 10 and 16 Hz. The complex counting task involved keeping a simultaneous count of the number of flashes of three lights that flashed at different rates. The subjects performed best on the counting task under the 65 dBA noise-only condition, followed by the 100 dBA noise plus vibration condition, the 100 dBA noise-only condition and the 65 dBA noise plus vibration condition. The results showed that exposure to broadband noise in combination with a complex vibration signal had a negative effect on the cognitive performance of the subjects, compared to exposure to noise alone.

More recently, Ljungberg *et al*. (2004) investigated the effect of combined exposure to whole-body vibration and noise on the short-term memory performance of human test subjects. The 54 test subjects (27 men and 27 women) were randomly assigned to low (77 dBA noise and 1.0 m/s^2 vibration), medium (81 dBA noise and 1.6 m/s^2 vibration) or high (86 dBA noise and 2.5 m/s^2 vibration) levels of exposure for a duration of 20 min. The noise signal was helicopter noise with a dominant 21 Hz component. The memory task involved observing 2, 4 or 6 letters on a screen for a period of 1, 2 or 3 seconds, after which a probe letter appeared. The subject had to indicate as quickly as possible if the probe was present in the previous list of letters. The subjects stated that it was more difficult to perform the task when exposed to combined noise and vibration, and the high exposure group indicated the highest levels of annoyance. However, no support was found for the hypothesis that combined noise and vibration worsened the cognitive performance of the subjects compared to one stimulus on its own. The authors stated that the results were inconsistent with a similar study that had been performed previously.

The inconsistencies among the results of experimental studies on the effect of combined noise and vibration on cognitive performance are indicative of the complexity of interaction between the two stimuli. There is currently no concrete evidence to support that whole-body vibration exposure has a negative effect on cognition.

Temporary Threshold Shift

The effects of vibration on temporary hearing loss, or temporary threshold shift, have been researched in early studies. Studies performed by Temkin in 1927, Pintér in 1973, and Pyykko *et al*. in 1981 suggested that low-frequency hearing loss was exacerbated in workers who were exposed to both noise and vibration (see review by Hamernik *et al*., 1989). Okada *et al*. (1972) studied the effect of noise and vibration, separately and in combination, on hearing using five male test subjects. It was found that 5 Hz vibration with an acceleration of $5 m/s^2$ caused a threshold shift of more than 7 dB at 1 and 4 kHz after an exposure duration of 60 min. The 5 Hz vibration is significant because it is approximately equal to the resonance frequency of the human body. Other vibration frequencies (2, 10 and 20 Hz) caused smaller amounts of threshold shift. Exposure to vibration in combination with noise caused a greater degree of threshold shift than exposure to noise alone. Other studies have also reported temporary threshold shift after prolonged exposure to 5 Hz vibration (see review by Griffin, 1990). It is now well-known that the resonance frequency of the human body is about 4 to 5 Hz, and modern vehicles are thus designed to avoid the transmission of these frequencies to the operators and passengers. However, the possibility that vibrations at other frequencies (particularly when experienced in combination with noise) cause temporary threshold shift in humans should be acknowledged.

There is now a standard for the safety of vibration tests on humans (ISO 13090-1:1998), whish requires that proposed vibration experiments involving humans must be reviewed by an ethics committee. In addition, it states that a medical doctor or physician must be present if the amount of vibration exposure is above the upper limits of the health guidance caution zones defined in ISO 2631-1 (Fig. 2). Thus, studies that expose human subjects to the vibration levels used by Okada *et al*. would almost certainly not be allowed today. It is therefore difficult to isolate and quantify the effects of vibration on hearing experimentally.

Reduced Motion Control

Limb movements that are essential to the operation of vehicles can be affected by vibration. For example, vertical whole-body vibration has an effect on the difficulty, speed and legibility of writing. The greatest effect occurs when the vibration frequency is in the range of 4 to 8 Hz (Griffin, 1990). Falou *et al*. (2003) studied the ability of test subjects to perform a tracking task in the presence and absence of vibration. The tracking task required the subjects to follow a moving circle on a computer screen using a cursor. Two different car seats, labelled as comfortable (C) and uncomfortable (U), mounted on a vibrating platform, were used. The magnitude of vibration was fixed at 0.6 m/s^2, but the frequency was not mentioned. While the tracking performance of the subjects did not decrease over a 150 min period for a given seat type, it was found that in the presence of vibration, the subjects performed significantly worse when seated in seat U than in seat C. It can be suggested that the better ergonomic design of seat C reduced the magnitude of vibration that was transmitted to the subject, resulting in better tracking performance.

Impaired Vision

If an observer and visual display are exposed to vibration such that they oscillate out-of-phase with respect to each other, the observer will see a blurred image. Thresholds for an effect on vision according to the vibration magnitude and frequency have been calculated. In general, the threshold acceleration increases in proportion to the viewing distance and the square of the frequency. The problem frequency range for display vibration is about 2 to 20 Hz. Above 20 Hz, the threshold accelerations for blur are rarely encountered (Griffin, 1990).

In aircraft, head-up displays and helmet-mounted displays are collimated by a lens to reduce the image distortion caused by translational vibration. Stabilization systems that move the image on the display can counteract the rotational motion of the head, resulting in greater legibility (Griffin, 1990).

Discomfort and Fatigue

Whole-body vibration can be a source of discomfort and fatigue. Duration of exposure, magnitude of vibration and frequency of vibration have been identified as influential factors on the degree of discomfort and fatigue that is experienced, but it is difficult to quantify their effects.

Effect of Duration

Continuous exposure to vibration can lead to increased fatigue or drowsiness, while intermittent and random vibration can have a wakening effect. In a review on vibration and heavy vehicle driver fatigue, Mabbott *et al*. (2001) reported that during an 8-hour shift, the average vibration exposure for a truck driver falls into the likely health risk zone of ISO 2631-1. There are some studies that have shown a possible link between prolonged exposure to low-frequency (3 Hz) vibration and fatigue, but not enough evidence to establish meaningful exposure limits. ISO 2631-1 states "There is no conclusive evidence to support a universal time dependence of vibration effects on comfort."

In addition to studying manual tracking performance, Falou et al. (2003) also evaluated the discomfort felt by subjects in car seats U and C by way of a questionnaire. The subjects were asked to rate their overall discomfort throughout the 150-minute exposure period on a scale from 0 to 10, 0 being "no discomfort", 4 being "real pain" and 10 being "unbearable". The subjects reported increasing discomfort during the testing period; however, the trend was the same for both seats, with and without vibration. Although the greatest increase in discomfort occurred with seat U with vibration, the subjects only rated the discomfort level as being just over 2 ("noticeable discomfort") at the end of the testing period. The surface electromyography (SEMG) signals that were recorded from the cervical erector spine and external oblique muscles showed no significant changes throughout the experiment. The study provides further evidence of the difficulties that exist with respect to linking duration of vibration exposure to discomfort and fatigue.

Effect of Magnitude and Frequency

It is intuitive that an increase in vibration magnitude will lead to increased discomfort. ISO 2631-1 lists the likely reactions to different magnitudes of overall vibration total values; these are listed in Table 1. However, the same magnitude of vibration will not produce the same level of discomfort at all frequencies. The combined effects of vibration magnitude and frequency on discomfort have thus been studied by many researchers. The growth in sensation, ψ, with increasing vibration magnitude, φ, has been found to agree approximately with Stevens' Power Law, given by

$$\psi = k\varphi^n \tag{7}$$

where k is a constant that depends on the system of units used and n is a frequency-dependent growth function.

For whole-body vibration, the growth function, n, has been reported to be 1.04 to 1.47 in the frequency range of 4 to 60 Hz, suggesting that the sensation magnitude increases approximately linearly with acceleration magnitude (Griffin, 1990; Morioka and Griffin, 2000). Frequencies below 2 Hz have not been studied extensively. Ruffel and Griffin (1995) studied the discomfort caused by different vibration magnitudes and durations for 1 and 2 Hz vertical sinusoidal vibration. Twenty test subjects were asked to rate their discomfort to a given vibration setting compared to a reference motion. The vibration magnitudes ranged from 0.63 to 1.6 m/s^2 and the exposure durations ranged from 1 to 60 s. For both frequencies and all vibration magnitudes, the level of discomfort generally increased with duration. With the exception of one magnitude-duration combination (0.63 m/s^2 and 1 s), there were no significant differences between the subject responses to 1 and 2 Hz vibration. For the mentioned exceptional case, the 1 Hz vibration was judged to be more uncomfortable. Although the results cannot be compared directly to the levels of discomfort experienced at higher frequencies, it has been suggested that vibration frequencies below 2 Hz are less disruptive because they are not high enough to induce the various body resonances (Griffin, 1990).

Discomfort Due to Airborne Vibration

Whole-body vibration can also occur when humans are exposed to very high noise levels via airborne transmission of sound waves. Aircraft ground and maintenance crew, for example, are exposed to noise levels that are sufficient to induce whole-body vibration. For frequencies between 100 and 1000 Hz, a 120 dB noise signal will cause tissue vibration. Below 100 Hz, the airborne vibration can cause movement in the body cavities and air-filled or gas-filled spaces. This can induce symptoms such as nausea, coughing, headache and fatigue (cited in Smith, 2002).

In a study by Smith (2002), vibration measurements were taken at different positions of a single subject's body during ground-based aircraft engine run-up tests. The accelerometers were placed on the subject's head, chest, lower thoracic spine, lower leg, and beneath the feet. The largest magnitudes of vibration were found to be in the for-to-aft direction at the chest. Based on subject-reported low-tolerance levels for acceleration and noise, an approach for developing airborne vibration exposure criteria was proposed. It was suggested that airborne noise of 137 dB (total 5 to 250 Hz) that induces a vibration acceleration of at least 0.428 g_{rms} (related to the acceleration due to gravity, g [9.81 m/s^2]) should be avoided. It is not known if these limiting values have been readily accepted.

Long-Term Effects on Health: Back Pain

One of the most commonly reported pathological effects of whole-body vibration is back pain. Back pain is a common complaint for heavy vehicle operators, motor vehicle passengers, armoured vehicle drivers and helicopter pilots. Although there are a number of confounding factors such as age, physical condition and working posture, many studies have reported that driving and heavy equipment-operating occupations show an elevated risk for back disorders (Teschke *et al.*, 1999).

It has been suggested that repeated and prolonged exposure to vibration can lead to serious back problems such as herniated discs or premature degeneration of the spinal vertebrae. The resonance frequency of the human spine has been found to be approximately 5 Hz, and the greatest magnitude of vibration is transmitted to the spine at frequencies of 4.5 to 5.5 Hz and 9.4 to 13.1 Hz. Bending and rotating postures, which are often necessary depending on the nature of work that the operator is performing, tend to increase vibration transmission (see reviews by Griffin, 1990 and Teschke *et al.*, 1999). ISO 2631-1 has defined health guidance caution zones according to the frequency-weighted acceleration and the exposure duration (see Fig. 2). Many studies have attempted to evaluate specific vehicles to determine if the health of the operators is at risk according to the ISO standard.

Table 4. *M113 and Centurion Tank cross-country vertical axis vibration exposure limits according to ISO 2631 1978/Ammendment 1 1982 (Beevis and Forshaw, 1985).*

VEHICLE	SPEED	RC	FDP	EL
M113 APC	20 km/h	< 1 min	1 hr	4 hr
Centurion Tank	12 km/h	1 hr	8 hr	24 hr

There has been a history of complaints of back pain in CF personnel. Beevis and Forshaw (1985) investigated the problem for a pool of drivers who were required to drive M113 armoured personnel carriers (APC) for long periods of time. Two other groups were investigated for comparison: those drove the APC for fewer average hours per week and those who drove Centurion tanks (a slower, heavier vehicle). The ride characteristics of the two vehicles were determined through acceleration measurements at the driver's buttocks as the vehicle was driven at representative speeds over different types of road and terrain. Each vehicle was assessed according to ISO 2631 1978/Ammendment 1 1982, which listed values for the Exposure Limit (EL), Fatigue Decreased Proficiency Boundary (FDP) and Reduced Comfort Boundary (RC). These limits are not part of the current version of ISO 2631. The results over cross-country terrain for vertical axis vibration are summarized in Table 4. The APC was found to reach the EL after 4 hours. Some of the APC drivers reported to driving between 50 and 70 hours a week. While the actual duration of daily continuous driving was unclear, it seems that the drivers were being exposed to unacceptable vibration conditions. The authors concluded that it was not unreasonable to say that the high incidence of back pain in the pool of APC drivers was a result of exposure to intense levels of vibration and shock in the vehicle, which was worsened by the poor posture of the operators.

Back pain is also frequently reported by helicopter aircrew. The pain is most likely to be felt by the pilot in-flight, and has been attributed to both the vibration of the seat and poor posture. However, pilots often must assume a forward-bending posture in order to achieve maximum visibility and precise control, which places increased pressure on the intervertebral disc. It has been suggested that temporary pain can also be caused by fatigue from increased muscular activity. De Oliveira *et al*. (2001) studied the lumbar back muscle activity of helicopter pilots before and during flight by recording the SEMG of the erector spine muscle. Only one of the 10 test subjects showed a significant correlation between the vibration and the EMG activity, leading to the conclusion that the erector spine muscle is not an important causative factor in the lower back pain experienced by helicopter pilots. The experiment may have been limited by the short flight duration that was used. The EMG was recorded for a 15 min flight; however, it has been suggested that the amount of time that must be spent in the air before back pain is experienced is between 2 and 4 hours. Other studies investigating the activity of the erector spine muscle and back pain have also been inconclusive (see review by Bowden, 1987).

Bowden (1987) suggests that in the interest of reducing back pain in helicopter pilots, it would be more effective to improve the ergonomic design of the cockpit and controls to promote better posture, than to reduce the vibration itself. However, he does acknowledge that vibration reduction may be beneficial in other ways, as it could help to increase the visual ability and motor control of the operator. Methods of vibration control are described in the next section.

Control of Vibration

There is an evident need for vibration control in vehicles. In recent years, research of vibration control by means of modeling, mechanical and ergonomic design and active control has helped manufacturers to reduce the amount of vibration exposure in many vehicles.

Vibration Perception Thresholds

To better understand how much reduction in vibration is required for the motion to be perceived as less uncomfortable, studies of vibration difference thresholds have been performed. Since mechanical vibrations contain multiple frequencies with different magnitudes, the frequency and magnitude dependence of difference thresholds must be studied. Morioka and Griffin (2000) tested the difference thresholds of 12 seated subjects for 5 and 20 Hz vibrations using reference magnitudes of 0.1 and 0.5 m/s^2 rms. It was concluded that there was no significant difference in difference thresholds for the two frequencies. To determine the percentage change in magnitude that was required for detection by the subjects, Weber fractions (the absolute difference threshold divided by the reference magnitude) were calculated. For the two frequencies, the median thresholds were found to be 11.6% and 9.2% for the 0.1 and 0.5 m/s^2 magnitudes, respectively. The range of thresholds for the 12 subjects was quite large (3.2% to 23.2%). It was suggested that reductions in vibration magnitude of more than 10% are required for a change to be detected.

Matsumoto, Maeda and Oji (2002) studied difference thresholds on 16 subjects using a reference magnitude of 0.7 m/s^2 at six different frequencies: 4, 8, 16, 31.5, 63 and 80 Hz. The median Weber's ratios were found to vary from 5.2% to 6.5% for the various frequencies. The results were presented graphically, so it is not possible for the reader to discern exact values for each frequency. It was reported that the difference thresholds tended to be the lowest at 4 Hz and highest at 31.5 Hz. Although the results cannot be compared directly to those of Morioka and Griffin (2000) because different frequencies were used, it was hypothesized that the difference in the results could be attributed to the differences in the psychophysical methods used by the two studies.

It is difficult to form conclusions on how much vibration reduction is necessary for perception when there is little documented research. Design of such studies and interpretation of the results are confounded by the fact that the difference thresholds vary greatly among individuals. There appears to be a need for further studies with larger numbers of test subjects in order to obtain more statistically significant results, which would be very expensive. As this is the case with many types of whole-body vibration experiments, it is of interest to develop mathematical and mechanical models; this is discussed in the next section.

Modeling of Whole-body Vibration

Performing experiments using mathematical or mechanical models can potentially eliminate the cost and ethical problems that are associated with using human test subjects. Mathematical models of whole-body vibration and resonance can help researchers understand how much vibration will be transmitted to the body through the supporting surface, and what the critical frequencies are. Understanding the dynamic response of the supporting surface and the vibration response of the human body requires knowledge of the mechanical impedance of the human body. The impedance of the human body has been found to change with different vibration magnitudes and frequencies, and is thus often called the apparent mass (see review by Griffin, 1990). Mathematical models for the apparent mass of seated and standing subjects have been developed by Griffin and others (see for example, Matsumoto and Griffin, 2003). Yue and Mester (2004) studied the resonance behaviour of a mathematical model for whole-body vibration. It was found that the resonance frequencies increase with increasing muscle stiffness and decreasing body mass. The phase differences between different parts of the system (i.e. different parts of the body) tend to be small at the lowest resonance frequency, but increase dramatically at vibration frequencies beyond resonance. It was concluded that internal loads might be maximized at frequencies above the range for major body resonance, thus explaining the higher frequency ranges for symptoms such as abdominal pain.

The use of a vibration dummy can possibly eliminate the need for human subjects for tasks such as vehicle seat testing. Mansfield and Griffin (1996) developed a passive vibration dummy using a simple mass-spring-damper system. While the dummy gave similar results to real test subjects for the seat effective amplitude transmissibility (the ratio of the VDV at the seat surface to the VDV at the floor) for vertical motion, discrepancies were seen in the lateral direction. An active vibration dummy has been designed by Cullmann and Wölfel (2001) to determine vibration transmission through vehicle seats. The dummy was said to be adjustable to different body masses and different prescribed vibration characteristics, and usable at low excitation levels which are relevant to the judgement of comfort. The prototype was comprised of a single-degree-of-freedom mass-spring-damper system using a fixed base mass of 8 kg and a moving mass that was varied between 28 and 52 kg. A real-time control loop was used to adjust the apparent mass of the dummy to a targeted frequency response that was obtained using human test subjects. The targeted frequency responses were categorized according to percentile male and female groups. The results using the dummy appeared to be in good agreement with the targeted response for frequencies below about 15 to 20 Hz. It was recommended that further research should focus on creating a more realistic form of the dummy such that correct pressure distribution between the buttocks and back with the seat, as well as correct longitudinal positioning, could be attained.

Vehicle Design

The amount of vibration that one is exposed to in vehicles depends greatly on the design on the vehicle. Donati (2002) suggested that there are three areas of engineering solutions that minimize the effects of vibrating mobile machinery on operators:

- Reduction of vibration at source by improvement of the quality of terrain, careful selection of vehicle or machine, correct loading, proper maintenance, etc.;
- Reduction of vibration transmission by incorporating suspension systems (tires, vehicle suspensions, suspension cab and seat) between the operator and the source of vibration;
- Improvement of cab ergonomics and seat profiles to optimize operator posture.

Generally, a suspension system must have a cut-off frequency that is lower than the dominant frequency of the vehicle. The suspension travel (referring to the distance that the suspension moves between its compressed and extended states) must be large enough to prevent shocks at full compression and extension, which are referred to as bottoming and topping. However, the amount of travel is space-limited, and there is a risk of impact for high levels of vibration input. Damping the suspension can help to prevent bottoming and topping, but the performance of the suspension system suffers as a result (Donati, 2002).

In some types of vehicles, the only stage of suspension is the seat itself (e.g., for lift-trucks fitted with solid tires). Seat suspensions must have a maximum cut-off frequency (calculated for the lightest driver) that is lower than the dominant frequency of the cab floor in order to avoid amplifying vibration. Seat suspensions are designed to decrease the stiffness of the seat, thus decreasing the natural frequency of the seat to less than the dominant frequency of the vehicle (Griffin, 1990). The dynamic response of a seat can be expressed in terms of vibration transmission (the ratio of the acceleration at the seat surface to the acceleration at the base of the seat). Passive vertical suspension seats contain a damper and a spring, which can be placed compactly inside the seat cushion or backrest, or non-compactly below the seat cushion or behind the backrest. Pneumatic suspensions, in which the spring is replaced by an air pressure chamber, can be more efficient in reducing vibration transmission because the stiffness can be adjusted for occupant weight. In general, passive suspension seats are only effective at reducing the vibration transmission for frequencies above 2 Hz (Griffin, 1990; Donati, 2002).

In a review of structural properties of automobile seats and their contribution to lumbar strains, Johnson and Nève (2001) considered the ergonomic advantages of a seat with a moving backrest. With a backrest that is bolted to the seat base, and therefore the vehicle floor, the upper back of the passenger is pressed heavily to the backrest. The upper back is thus coupled to the upward and downward motion of the chassis. Meanwhile, the seat cushion is typically designed to lower the amplitude of shocks that reach the body, but the benefits are reduced by the coupling of the upper back to the backrest. It has been suggested that the resulting strain on the lower back can be reduced by decoupling the seat backrest from the frame by placing it on rollers. The passenger's back can then follow the vertical oscillations of the pelvis. Testimonies from private car drivers who used prototype seats with the vertically moving backrest indicated unanimously that the seat provided relief from chronic lower back pain.

Mansfield *et al*. (2002) investigated the shock and vibration isolation performance of a standard suspension seat and a saddle-type suspension seat fitted on a forestry machine. The authors observed that since drivers can anticipate when a shock will occur from observing the ground ahead of them, they can help to reduce the impact of the shock on their bodies by partially standing up out of the seat. Although the experimental results showed that there were fewer instances of bottoming and topping impacts (also called end-stop impacts) with the saddle seat, the results did not show conclusively that the seat reduced the amount of vibration exposure when calculated according to ISO 2631-1.

For vehicles such as lorries and agricultural tractors, the vibration of the cab can be efficiently isolated from vibrations due to the road by means of low-frequency suspension cabs. The suspension cab has the advantage over the suspension seat in that the whole body is isolated from vibration (Donati, 2002).

Regardless of how well the vehicle suspension system is designed, the amount of vibration exposure at various frequencies will depend greatly on the speed at which the vehicle is driven, the terrain that the vehicle is driven on other environmental factors. It is thus of interest to investigate adaptive methods for vibration control as discussed in the next section.

Active Vibration Control

In recent years, the concept of vibration cancellation has been researched as a potential method for overcoming the shortcomings of conventional (passive) vibration control methods. In active vibration control (AVC), the primary vibration is cancelled with a vibration signal that is of the same magnitude, but opposite in phase. The primary vibration signal is detected by means of a sensor, and the cancelling signal is generated with a force actuator. Smart materials such as piezoelectrics can be bonded onto a vibrating structure and used as both sensors and actuators. The best known such material is lead-zirconate-titanate, or PZT. A PZT transducer converts mechanical vibrations to an electrical signal. When a voltage signal from a PZT transducer is being monitored, it is acting as a sensor. In the actuator mode, a voltage signal is supplied to the PZT transducer in response to feedback (Stelzer *et al*., 2003). AVC using PZT materials has been researched for structures such as aircraft cabins in the interest of noise reduction (Li *et al*., 2004(a); Li *et al*., 2004(b)).

Active control of vibration has been researched in the context of reducing noise and increasing operator comfort in passenger vehicles. Passive designs are typically used for vibration isolation in automobiles because of their low cost; however, they are not particularly durable. Stelzer *et al*. (2003) investigated the performance of passive, semi-active and active isolator designs for use in passenger automobiles. A passive isolator can be a simple rubber mount, which acts only to remove energy from the system. A semi-active isolation system is capable of changing one or more properties (e.g. damping coefficient), while an active isolation system is controlled by a computer through input signals from the sensors. It was found that increased durability and isolation performance could be achieved with a semi-active isolator design using a magneto-rheological fluid (a fluid whose yield strength changes in response to a magnetic field) as a sensor-actuator in combination with an electronic control system. While the details of the design are beyond the scope of this paper, use of smart materials and electronic control systems can improve the vibration isolation over simple passive systems.

Discussion and Recommendations

Links between vibration exposure and health risks in humans have been clearly identified, although the mechanisms are not well understood in many cases. Because vibration exposure is complex (composed of many different frequencies of varying amplitudes), it is very difficult to define specific standards for vibration measurements and exposure limits. While a great deal of work has been done with regard to the understanding and quantifying of the effects of whole-body vibration on humans, it is clear that there are many members of the research community who are confused by and disagree with the current International standard. The finding by Paddan and Griffin (2002) that the methods defined by ISO 2631 may underestimate vibration severity further questions its validity. Given the strong criticism that has been expressed with regard to ISO 2631-1, it may be of interest to measure and analyze vibration according the British standard.

Although early studies suggested that combined noise and vibration exposure promotes low-frequency hearing loss, little attention has been paid to the effects of vibration on the auditory system in recent years. Experimental studies are difficult to perform on real test subjects due to ethical issues. One possibility would be to compare the audiograms of workers who are regularly exposed to noise but no or little vibration, to those of workers who are typically exposed to a combination of noise and vibration. In doing so, the finding of the early studies that combined noise and vibration exposure aggravates low-frequency hearing loss can be confirmed or questioned. More involved research projects could involve mathematical modeling of the auditory system response to vibration, or development of an active noise and vibration dummy. The use of such models would eliminate the need for human test subjects for vibration studies.

The ergonomic and mechanical design of vehicles with respect to the reduction of vibration transmission has improved greatly over the years. Improvements in the ergonomic design of the cab can encourage better posture in vehicle operators so as to minimize the amount of vibration exposure. In automobiles, improvements that are made to the suspensions and isolators for vibration reduction are often in the interest of improving vehicle handling. As a result, the reduction of vibration transmission of the body could be ruined by the tendency of the driver to drive faster or for longer durations. Implementation of adaptive vibration control methods, or active vibration control, might help to remedy this problem.

With regard to the CF, it is of interest to understand how the vibration of military vehicles affects the performance and health of personnel. Effective performance requires sharp situational awareness and clear communication between crew members, and the possibility that vibration affects these factors cannot be ignored. Given the increased amount of knowledge and technological advances in the field of vibration, it is essential that the state of knowledge of vibration exposure for CF personnel be brought up-to-date. Vibration measurements should be taken in all relevant vehicles, and analyzed according to BS 6841. Questionnaires should be prepared and distributed to personnel to gain a better understanding of the following points:

- The duration and frequency of vehicle use;

- The subjective level of discomfort and fatigue felt by the driver/passengers as a result of vibration;

- The incidences of back pain or other injuries experienced by the driver/passengers as a result of vibration;

- The subjective rating of cab ergonomics (e.g. ease of use of the controls) for evaluation of driver posture;

- The subjective rating of communication difficulties experienced in the presence of combined noise and vibration.

The combined knowledge of the measurement and questionnaire results will help to identify which vehicles are the most problematic in terms of vibration exposure. From there, possible measures to improve the working environments of CF personnel can be investigated and implemented.

Conclusion

Exposure to vibration has been found to have numerous effects on human performance and health. The effects range from short-term consequences such as annoyance and discomfort, to long-term problems such as chronic back pain. ISO 2631 gives guidelines for the evaluation of human exposure to vibration, but there are currently no widely accepted vibration exposure limits with respect to human comfort and health risks. With regard to vibration control, improvements in the ergonomic and mechanical design of vehicles over the years has helped to reduce vibration transmission to the passengers. New technologies such as active vibration control can help to reduce structure-borne vibrations and improve the performance of vibration isolators so as to decrease noise levels in vehicle cabins and increase passenger comfort. In the interest of improving the working conditions for CF personnel, steps must be taken to better understand the vibration characteristics of CF vehicles that are currently in use. Once the vibration exposure levels and specific performance and health problems have been determined, possible measures to improve the working environments can be investigated and implemented.

References

1. Beevis, D., Forshaw, S.E., 1985. Back pain and discomfort resulting from exposure to vibration in tracked armoured vehicles. Defence and Civil Institute of Environmental Medicine Report No. 85-R-28.

2. Berglund, B., Hassmén, P., 1996. Sources and effects of low-frequency noise. J. Acoust. Soc. Am., 99(5), 2985-3002.

3. Bowden, T., 1987. Back pain in helicopter aircrew: A literature review. Aviation, Space and Environmental Medicine, May, 1987, 461-467.

4. British Standards Institution. British Standard Guide to Measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock. BS 6841:1987.

5. Cann, A.P., Salmoni, A.W., Vi, P., Eger, T.R., 2003. An exploratory study of whole-body vibration exposure and dose while operating heavy equipment in the construction industry. Applied Occupational and Environmental Hygiene, 18, 999-1005.

6. Cullmann, A., Wolfel, H.P., 2001. Design of an active vibration dummy of sitting man. Clinical Biomechanics 16 Supplement No. 1 S64-S72.

7. de Oliveira, C.G., Simpson, D.M., Nadal, J., 2001. Lumbar back muscle activity of helicopter pilots and whole-body vibration. Journal of Biomechanics 34, 1309-1315.

8. Donati, P., 2002. Survey of technical preventative measures to reduce whole-body vibration effects when designing mobile machinery. Journal of Sound and Vibration, 253(1), 169-183.

9. Falou, W.E., Duchene, J., Grabisch, M., Hewson, D., Langeron, Y., Lino, F., 2003. Evaluation of driver discomfort during long-duration car driving. Applied Ergonomics 34, 249-255.

10. Griffin, M.J., 1990. Handbook of Human Vibration. London: Academic Press.

11. Griffin, M.J., 1998. A comparison of standardization methods for predicting the hazards of whole-body vibration and repeated shocks. Journal of Sound and Vibration, 215(4), 883-914.

12. Habes, D.J., Dick, R., Tubbs, R., Biggs, F., Burt, S., 2003. An ergonomic evaluation of snowmobiles. Applied Occupational and Environmental Hygiene, 19(4), 213-225.

13. Hamernik R.P., Ahroon, W.A., Davis, R.I., 1989. Noise and vibration interactions: Effects on hearing. J. Acoust. Soc. Am., 86(6), 2129-2137.

14. Harris, C.S. and Shoenberger, 1980. Combined effects of broadband noise and complex waveform vibration on cognitive performance. Aviat. Spp. Environ. Med 51(100):1-5.

15. Howarth, H.V.C. and Griffin, M.J., 1990. Subjective response to combined noise and vibration: summation and interaction effects. Journal of Sound and Vibration, 143(3):443-454.

16. International Organization for Standardization, 1997. Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration, Part 1: General requirements. ISO 2631-1:1997.

17. International Organization for Standardization, 1998. Mechanical vibration and shock – Guidance on safety aspects of tests and experiments with people, Part 1: Exposure to whole-body mechanical vibration and repeated shock. ISO 13090-1:1998.

18. The Japanese Society for Occupational Health, 2003. Recommendation of occupational exposure limits. Journal of Occupational Health, 45, 254-269.

19. Johnson, D.A., Nève, M., 2001. Analysis of possible lower lumbar strains caused by the structural properties of automobile seats: A review of some recent technical literature. Journal of Manipulative and Physiological Therapeutics, Vol. 24, No. 9, 582-588.

20. Li, D.S., Cheng, L., Gosselin, C.M., 2004(a). Optimal design of PZT actuators in active structural acoustic control of a cylindrical shell with a floor partition. Journal of Sound and Vibration, 269, 569-588.

21. Li, D.S., Cheng, L., Gosselin, C.M., 2004(b). The design of structural acoustic sensors for active control of sound radiation into enclosures. Smart Materials and Structures, 13, No. 2, 371-383.

22. Ljungberg, J., Neely, G. and Lundstrom, R., 2004. Cognitive performance and subjective experience during combined exposures to whole-body vibration and noise. Int Arch Occup Environ Health 77:217-211.

23. Mabbott, N., Foster, G., McPhee, B., 2001. Heavy vehicle seat vibration and driver fatigue. Report to the Department of Transport and Regional Services, Australian Transport Safety Bureau.

24. Mansfield, N.J., Griffin, M.J., 1996. Vehicle seat dynamics measured with an anthropodynamic dummy and human subjects. Proceedings of Internoise 96, 1725-1730.

25. Mansfield, N.J., Holmlund, P., Lundström, R., Nordfjell, T., Staal-Wästerlund, D., (2002). Vibration exposure in a forestry machine fitted with a saddle type suspension seat. Int. J. of Vehicle Design, Vol. 30, No. 3, 223-237.

26. Matsumoto, Y., Griffin, M.J., 2003. Mathematical models for the apparent masses of standing subjects exposed to vertical whole-body vibration. Journal of Sound and Vibration, 260, 431-451.

27. Matsumoto, Y., Maeda, S., Oji, Y., 2002. Influence of frequency on difference thresholds for magnitude of vertical sinusoidal whole-body vibration. Industrial Health, 40, 313-319.

28. Moran, A.W., Simmons, T.L., Erickson, B.S., Butler, B.P., 1994. Whole-body vibration assessment of the M915A2 truck tractor. United States Army Aeromedical Research Laboratory Report N. 94-5.

29. Morioka, M., Griffin, M.J., 2000. Difference thresholds for intensity perception of whole-body vertical vibration: Effect of frequency and magnitude. J. Acoust. Soc. Am., 107(1), 620-624.

30. Nakashima, Y., Maeda, S., 2004. Effects of seat-back angle and accelerometer height at the seat-back on the seat-back X axis r.m.s. acceleration in filed experiments according to the ISO2631-1 standard. Industrial Health, 42, 65-74.

31. Öhrström, E., 1997. Effects of exposure to railway noise – a comparison between areas with and without vibration. Journal of Sound and Vibration, 205(4), 550-560.

32. Öhrström, E. and Skånberg, A.-B., 1996 A field survey on effects of exposure to noise and vibration from railway traffic, part I: annoyance and disturbance effects. Journal of sound and vibration 193(1):39-47.

33. Okada, A., Miyake, H., Yamamura, K., Minami, M., 1972. Temporary hearing loss induced by noise and vibration. J. Acoust. Soc. Am., 51(4), 1240-1248.

34. Paddan, G.S., Griffin, M.J., 2002. Evaluation of whole-body vibration in vehicles. Journal of Sound and Vibration, 253(1), 195-213.

35. Ruffell, C.M., Griffin, M.J., 1995. Effects of 1-Hz and 2-Hz transient vertical vibration on discomfort. J. Acoust. Soc. Am., 98(4), 2157-2164.

36. Smith, S.D., 2002. Characterizing the effects of airborne vibration on human body vibration response. Aviation, Space and Environmental Medicine, Vol. 73, No. 1, 36-45.

37. Stelzer, G.J., Schulz, M.J., Kim, J., Allemang, R.J., 2003. A magnetorheological semi-active isolator to reduce noise and vibration transmissibility in automobiles. Journal of Intelligent Material Systems and Structures, Vol. 14, 743-765.

38. Teschke, K., Nichol, A.-M., Davies, H., Ju, S., 1999. Whole body vibration and back disorders among motor vehicle drivers and heavy equipment operators: A review of the scientific evidence. Report to the Workers' Compensation Board of British Columbia.

39. Västfjall, D., Kleiner, M., Gärling, T., 2003. Affective reactions to and preference for combinations of interior aircraft sound vibration. The International Journal of Aviation Psychology, 13(1), 33-47.

40. Yue, Z., Mester, J., 2004. A modal analysis of resonance during the whole-body vibration. Studies in Applied Mathematics, 112, 293-314.

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14. ABSTRACT

(U) A literature review on the effects of vibration on the occupational performance and health of workers has been done in the interest of understanding how Canadian Forces (CF) personnel are affected by exposure to vibration in military vehicles. Effects such as annoyance, discomfort, hearing loss and back pain have been identified. The International Standard (ISO 2631) for evaluation of human exposure to whole-body vibration gives guidelines for how vibration should be measured and assessed, but there has been some criticism regarding the validity of the evaluation procedures that are defined, and the ambiguity in the wording of the standard. In terms of vibration control, advances in the ergonomic and mechanical design of vehicles and new technologies such as active vibration control have been developed to reduce the amount of vibration exposure in vehicle operators. It is concluded that the state of knowledge of the vibration characteristics of vehicles that are currently being used by the CF must be brought up-to-date so that work can begin on improving working environments.

(U) L'auteure a dépouillé la littérature traitant des effets des vibrations sur le rendement professionnel et la santé des travailleurs afin de comprendre les effets subis par les membres des Forces canadiennes (FC) qui sont exposés aux vibrations des véhicules militaires dans lesquels ils se déplacent. Des études ont mis en évidence différents effets comme la gêne, l'inconfort, les pertes auditives et les maux de dos. La Norme internationale (ISO 2631) qui porte sur l'évaluation de l'exposition à des vibrations globales du corps contient des lignes directrices sur la façon de mesurer et d'évaluer les vibrations, mais certains contestent la validité des méthodes d'évaluation décrites et soulignent l'ambiguïté du libellé de la norme. On a amélioré la conception ergonomique et mécanique des véhicules et mis au point de nouvelles technologies comme le contrôle actif des vibrations afin d'atténuer les vibrations auxquelles sont exposés les conducteurs de véhicules. L'auteure conclut qu'il faut actualiser nos connaissances sur les caractéristiques vibratoires des véhicules actuellement utilisés par les FC, de manière à pouvoir améliorer les milieux de travail.

15. KEYWORDS, DESCRIPTORS or IDENTIFIERS

(U) whole-body vibration; vibration; noise; hearing; human performance; vibration control; ISO 2631

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