International Journal of Industrial Ergonomics 53 (2016) 19–26

Contents lists available at ScienceDirect

International Journal of Industrial Ergonomics

journal homepage: www.elsevier.com/locate/ergon

Ergonomic analysis of the effects of a telehandler's active suspended cab on whole body vibration level and operator comfort

Federica Caffaro [a], Margherita Micheletti Cremasco [b], Christian Preti [a], Eugenio Cavallo [a, *]

[a] Institute for Agricultural and Earthmoving Machines (IMAMOTER), National Research Council (CNR) of Italy, Strada delle Cacce, 73, 10135, Torino, Italy
[b] Department of Life Sciences and Systems Biology, University of Turin, Via Accademia Albertina, 13, 10123, Torino, Italy

ARTICLE INFO

Article history:
Received 12 March 2015
Received in revised form
13 October 2015
Accepted 26 October 2015
Available online xxx

Keywords:
Active suspension
Anthropometric variability
Comfort
Telehandler
Whole-body vibration transmissibility

ABSTRACT

Introduction: Exposure to whole body vibration (WBV) is one of the most important risks for musculoskeletal disorders (MSDs). The objective of the study was to investigate whether an active cab suspension system fitted on a telehandler was effective in reducing WBV and in improving comfort.
Method: Sixteen male healthy professional operators drove a telehandler on a 100 m ISO 5008 smooth track at two different speeds (5 and 12 kph) with activated and deactivated cab suspension system. Adopting an ergonomic approach, different aspects of the human-machine interaction were analyzed: 1) vibration transmissibility, 2) subjective ratings of general comfort and local body discomfort, and 3) anthropometric characteristics of the users.
Results: A series of ANCOVAs showed that the suspension system was effective in reducing WBV at both speeds but did not affect the perception of comfort by the operators. Moreover, individuals with higher Body Mass Index (BMI) experienced more comfort. Some neck/shoulder and lumbar complaints and perceived hard jolts seemed to remain even when the system was activated. No correlations were found between objective and subjective measures.
Practical applications: Results suggest that the operators, given their wide range of physical variability, may need more adjustable or customizable WBV reduction systems.

1. Introduction

1.1. Background and motivation

Exposure to whole body vibration (WBV) has been identified as one of the most important risks for musculoskeletal disorders (MSDs) (Lyons, 2002; Osborne et al., 2012), having severe effects on low-back pain, neck-shoulder disorders, early degeneration of the spine and herniated discs (Bovenzi and Zadini, 1992; Griffin, 1990; Kittusamy and Buchholz, 2004). MSDs are a main issue of concern in agricultural industry: in the United States, a 2008 report showed that about 20 percent of farm workers suffer from musculoskeletal injuries (Kandel, 2008). In Europe, 2,070,000 out of over 40 millions occupational diseases among agricultural operators are MSDs (EU OSHA, 2010). Agricultural and earth-moving machinery operators are particularly at risk because they are usually exposed to vehicle vibrations for a long time (Mayton et al., 2008): indeed they typically spend many hours on the machine (Lin, 2011) and they have to accomplish many operations on different types of uneven terrain (Wikström, 1993), with the vehicle moving at various forward speeds (Lines et al., 1995; Scarlett et al., 2007).

The awareness of the risks related to WBV exposure led to the development of standards and requirements to maintain healthy working conditions. The development of WBV standards started in 1966 in Europe, resulting in the publication of ISO 2631 (Paschold and Sergeev, 2009). This standard is included into the European Commission Directive 2002/44/EC as a framework to measure, with the appropriate frequency weightings, the daily WBV exposure. The Directive imposes, on the European Union countries, duties on employers to protect employees who may be exposed to WBV vibration at work, and other persons who might be affected by the vibrations, whether they are at work or not. A partially different situation exists in the United States, where the WBV exposure limits are based upon the ISO 2631 standard but are voluntary (Paschold and Sergeev, 2009).

* Corresponding author.
E-mail addresses: f.caffaro@ima.to.cnr.it (F. Caffaro), margherita.micheletti@unito.it (M.M. Cremasco), c.preti@imamoter.cnr.it (C. Preti), e.cavallo@imamoter.cnr.it (E. Cavallo).

http://dx.doi.org/10.1016/j.ergon.2015.10.009
0169-8141/

In order to comply with rules and standards and to promote operators' health, safety and comfort, many technological and design innovations have been introduced on vehicles by manufacturers during last decades (for a review, see Donati, 2002 and Tiemessen et al., 2007). Innovations range from suspended seats (Hostens et al., 2004) to correct ergonomic layout of vehicle interior (Pope et al., 1998) and to cab suspension systems (Velmurugan et al., 2012). Concerning cab suspension, different solutions have been developed, from passive systems to more recent semi-active and active ones (Fischer and Isermann, 2004): active systems in particular represent an important innovation, not only for WBV control but also for the improvement of ride quality, handling and performance under different operating conditions (Ikenaga et al., 2000; Wong, 2001).

The effects of passive and semi-active cab suspension systems on WBV exposure have been investigated on many vehicles: agricultural tractors (Scarlett et al., 2007), fork lift trucks (Lemerle et al., 2002) and harvesters (Deprez et al., 2005). Less is known about active systems, and in particular with regard to telescopic handlers (telehandlers). These vehicles are indeed little investigated (Mansfield et al., 2009; Strambi et al., 2012) and not typically involved in user trials assessing WBV exposure, despite the fact that the telehandler is a versatile and widespread vehicle used on different off-road applications (construction, agriculture, mining, etc.) on uneven terrains and for a large number of different operations (Bertani, 2014).

Studies evaluating the effectiveness of suspension systems typically adopt an objective/mechanical approach, focusing in particular on acceleration and frequency analysis to determine workers' exposure limit and action values stated by rules and standards (De Temmerman et al., 2005; Hansson, 1995). Nonetheless, current sales trends show that the operator's comfort is becoming more and more important in determining the market value of agricultural machines (Vink, 2005). Previously, customers wished that their basic needs would be fulfilled at an affordable cost, while, in recent years, customers' decision to purchase a machine has become increasingly influenced by comfort (Cavallo et al., 2014a; Krause and Bronkhorst, 2003). Furthermore, comfort is one of the technological trajectories adopted by off-road vehicle manufacturers to develop their products (Cavallo et al., 2014b, 2015).

Many previous studies showed that is not always possible to predict comfort from objective methods only (De Looze et al., 2003; Mehta and Tewari, 2000). Nonetheless, and even though comfort is a subjective phenomenon (De Looze et al., 2003), users' perceptions are often left in the background. Only recently, researchers have become more aware of the positive outcomes that could be achieved by involving final users in the evaluation of comfort (Blüthner et al., 2008).

The role played by some anthropometric characteristics, such as stature, body mass and Body Mass Index (BMI), of the users of different vehicles in affecting WBV exposure and MSDs development has been investigated in previous studies but contrasting results are reported (Blood et al., 2010; Costa and Arezes, 2009; Mani et al., 2011; Milosavljevic et al., 2011, 2012; Sadeghi et al., 2012). Among these characteristics, the BMI is used by the World Health Organization to classify underweight, overweight and obesity in adults (WHO, 2000). Thus, it is a relevant index to be considered, because of the increasing rate of overweight and obesity conditions in the developed countries (WHO, 2000, 2004). Moreover, as an index calculated as the body mass in kilograms divided by the square of the stature in meters (kg/m^2), it is a combination of measurements. It is therefore essential for the interpretation of measurements, since, as reported by WHO (1995), body mass alone has no meaning unless it is related to an individual's stature. However, the relation between BMI and exposure to vibration is controversial: some studies pointed out that MSDs related to WBV exposure increase when the BMI raises (Bovenzi et al., 2006). On the opposite, results from other studies showed that vibrational discomfort decreases (Leino et al., 2006) and energy absorption increases (Wang et al., 2006) when the BMI raises.

Little is known, however, about the influence of this anthropometric characteristic on the perception of comfort in field machinery operators, whose population is undergoing the same trend of increasing overweight and obesity conditions as the general population (WHO, 2004).

1.2. Aims of the study

The objective of the present study was to investigate whether an active cab suspension system fitted on a telehandler was effective in reducing WBV and in improving comfort for the operators. The study adopted an ergonomic approach "*concerned with the understanding of the interactions among humans and other elements of a system […]*", which considers users' involvement essential "*in order to optimize human well-being and overall system performance*" (International Ergonomics Association, 2015; see also Karwowski, 2006). The importance of this approach is highlighted also by the European Directive 42/2006 (European Commission, 2006), which states that "*Under the intended conditions of use, the discomfort, fatigue and physical and psychological stress faced by the operator must be reduced to the minimum possible, taking into account ergonomic principles such as: allowing for the variability of the operator's physical dimensions, strength and stamina; providing enough space for movements of the parts of the operator's body; avoiding a machine-determined work rate; avoiding monitoring that requires lengthy concentration; adapting the man/machinery interface to the foreseeable characteristics of the operators.*" (Annex 1, p.21). Thus, the study was addressed to assess not only the objective effects of the suspension system on vibration transmissibility but also the benefits perceived by the users, considered in their anthropometric variability.

To characterize the effects of the cab suspension system fitted on the telehandler the following aspects of the human-machine interaction were analyzed: 1) objective measures of vibration transmissibility, 2) subjective ratings of general comfort and local body discomfort, and 3) anthropometric characteristics of the users.

This study brings an additional contribution to the existing literature about WBV reduction and comfort improvement. First of all, the study investigates WBV exposure and vibrational comfort on an understudied type of field vehicle, the telescopic handler. Moreover, the vehicle was equipped with an active hydropneumatic suspension system. Additionally, the present research includes a subjective assessment of vibrational comfort and, finally, relations between objective measures, subjective evaluation and anthropometrics characteristics of the users are analyzed.

2. Materials and methods

2.1. Participants

Sixteen male healthy professional telehandler drivers took part in the study. Individuals with a minimum of 5 years of driving experience on telehandlers (driving-experience cut-off as in Kumar et al., 2001) were chosen to participate in the study. The mean age and experience operating telehandlers were 39.4 years (SD = 12.2; range 18–60) and 20.0 years (SD = 14.49; range 10–50), respectively. The participants completed a brief questionnaire about their work experience and musculoskeletal disorders history. All the participants did not report any musculoskeletal disorders and were suitable for the investigation trials. All the participants signed an informed consent to participate in the study.

2.2. The telehandler

The telescopic handler is a field vehicle equipped with a longitudinal telescopic and elevating arm, usually activated by hydraulic jacks, to orientate the load carrier (ISO 12934, 2013; ISO 5053, 1987). An example of the vehicle is shown in Fig. 1. Because of their versatility, telehandlers are widely used in agriculture and construction sector (Bertani, 2014). They show high sales numbers worldwide: the Association of Equipment Manufacturers (AEM) statistics estimates 30,000 units sold in 2011 (Cranes and Access, 2012).

The telehandler used in the study was a Merlo make, P55.9CS model. It is a 2 axles, 4 wheel drive vehicle equipped with 103 kW Diesel engine and hydrostatic transmission. The maximum forward speed is 40 kph (25 mph). The vehicle is representative of the typical telehandler architecture adopted by most of the manufacturers: the cab, with the driving station, is on the left and the engine on the right of the vehicle median plane. The telescopic boom, in 3 sections for a maximum length of 9 m, is on the median plane of vehicle. The maximum loading mass of the telescopic boom is 5500 kg. The telehandler was equipped with hydro-pneumatic active cab suspension system designed to reduce vibration magnitude along the vertical direction, from the buttock to the head (z-axis) of the driver. The cab is joined to the chassis of the vehicle by front and rear mechanical articulated connections. They make possible the cab to displace 120 mm vertically under the force of the active dumper, placed between the chassis and the floor of the cab. The system is covered by Merlo patent.

2.3. Whole-body vibration

Vibration level was measured using three ICP accelerometers mounted respectively on the driver's seat, on the floor of the cabin close to the base of the seat, and on the chassis of the telehandler. The accelerometer on the seat was a set pad. The vibration levels were measured along the three orthogonal directions (x, y and z) according to the coordinate system for a seated person (ISO 2631-1, 1997). However, since the vertical vibrations are usually dominant in vehicles (Basri and Griffin, 2013), they significantly contribute to vibration magnitude exposure of the driver (Cann et al., 2004), and the active suspended cab system has been designed to operate along this direction, only the vertical direction (z axis) was considered for the purposes of the present paper.

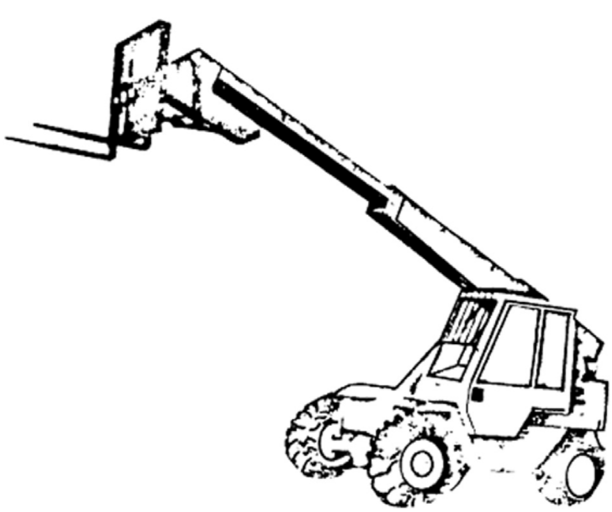

Fig. 1. Example of telehandler (from ISO 5053, 1987).

The signal from the three accelerometers was stored on the laptop using a National Instruments data acquisition card (NI9234). Later on the data were processed using a LabView software (National Instruments, 2012).

2.4. Subjective ratings

Subjective measures were collected by means of a questionnaire, developed considering the instrument by Bovenzi et al. (2006) and the scales typically used in the subjective measurements of comfort (for a review, De Looze et al., 2003; Mehta and Tewari, 2000). The questionnaire submitted to the participants was composed of 3 items, to assess their perception of comfort, the possible body discomfort, and the jolts perceived while driving. First, the participants were asked to rate the comfort perceived regarding vibrations during each trial on a 11-point rating scale, ranging from 0 (no comfort at all) to 10 (extreme comfort). Then, they were asked to identify body areas experiencing little/moderate/hard/very hard discomfort during the trial on a body map (Corlett and Bishop, 1976). Finally, the participants were asked to indicate how often (never, sometimes, often), they perceived, while driving the telehandler, so hard jolts to lose contact with the seat.

2.5. Anthropometric parameters

Stature and body mass were measured for each of the participants in the study, in accordance with ISO 7250-1 (2012) guidelines regarding variable descriptions, instruments and measurement conditions. These parameters were then used to calculate each participant's BMI.

The anthropometric characteristics of the participants in the study are reported in Table 1. The sample was a good representation of the anthropometric variability of the Italian population (ISO 7250-2, 2010; Masali, 2013), with participants from both the 5–10th and the 90–95th percentiles (some participants were even above the 99th percentile with regard to body mass).

2.6. Testing procedure

Objective measurements were carried out while the telehandler was driven over a 100 m ISO smooth track (ISO 5008, 2002). Previous studies confirmed that the use of ISO-5008 track provides a reasonable basis for comparison of the WBV to which the operator of a field wheeled-vehicle is exposed, due to the high repeatability of vibration data (Cavallo et al., 2005; Deboli et al., 2012; Scarlett et al., 2005; Zehsaz et al., 2011).

Each of the participants drove the telehandler on the ISO-smooth track in 4 different conditions:

1. Trial 1 (Low, OFF): speed of 5 kph, deactivated suspension
2. Trial 2 (Low, ON): speed of 5 kph, activated suspension

Table 1
Anthropometric characteristics of the 16 participants.

	Mean	SD	Range
Body mass (kg)	88.6	18.5	64–129
Stature (mm)	1751	72	1600–1860
Body Mass Index (kg/m^2)	28.9	5.8	22–42

3. Trial 3 (High, OFF): speed of 12 kph, deactivated suspension
4. Trial 4 (High, ON): speed of 12 kph, activated suspension

Participants were not informed that the telehandler cab was equipped with a suspension system to avoid any influence on their subjective ratings. Before the trials, each participant performed a training trial during which he had the possibility to adjust the seat, so, in any of the test conditions, the seat suspension travel was set with vertical adjustments for custom comfort. The fore/aft adjustment of the seat was set to fit the most comfort posture for each participant. After each trial a research assistant administered the questionnaire.

2.7. Data processing

Vibration data were processed to obtain root-mean-square (rms) accelerations in m/s^2 and the frequency spectra in one-third octave band ranging from .5 to 80 Hz. This range is indeed interesting from a hygienist's point of view as reported in the ISO standard 2631-1 (1997). The signals were therefore weighted using the weighting curve W_k for the z axis as described in the same standard. These aspects are developed in detail in a dedicated paper while the present paper focuses on vibration transmissibility (ISO 10326-1, 1992).

Vibration transmissibility was evaluated by computing the floor/chassis and the seat/chassis indexes. The indexes were calculated following the method used for the SEAT (Seat Effective Amplitude Transmissibility) factor, as stated by the EN 13490 (2001) and ISO 7096 (2000) standards. The floor/chassis index accounted for the effects of the cab suspension system, whereas the seat/chassis index accounted for the joint effects of seat and cab suspension systems. The indexes were calculated by a 2 steps process. The first step was the calculation of the floor/chassis and seat/chassis rms ratios for each participant, at each of the third octave frequency bands taken into consideration, and in any of the 4 testing conditions. Then, in the second step, the ratios in the frequency range 2–8 Hz were summed up for any of the participants in each of the testing conditions. In the 2–8 Hz range the human vibration sensitivity is the highest (Griffin, 1990).

2.8. Statistical analyses

Descriptive statistics were computed for the vibration indexes, the comfort ratings, the body discomfort areas and perceived jolts.

Then, Pearson correlations were calculated, to investigate the associations between vibration indexes and between vibration indexes and comfort ratings, within each trial and across the trials. Finally, to test for differences in vibration indexes and comfort ratings with activated and deactivated system at each forward speed, a series of repeated measures Analysis of Covariance (ANCOVA) were carried out on each variable, at low and high forward speed, while controlling for the BMI of the participants. Vibration indexes and the comfort ratings were within-subject factors and the BMI was a covariate.

Prior to analysis, diagnostic and normality tests were conducted. Scatter plots and histograms were generated and Shapiro–Wilk tests performed for the vibration indexes and the comfort ratings. Floor/chassis indexes at 5 kph and 12 kph with deactivated system, and comfort ratings at 5 kph with activated and deactivated system showed a negative skew. Transformations were unsuccessful in achieving normality for floor/chassis indexes at 12 kph with deactivated system and comfort ratings at 5 kph with deactivated system. However, adopting the same approach as reported by Govindu and Babski-Reeves (2014) and since the analyses used for the study are known to be robust with regard to normality assumptions (Howell, 2010), the data were used in their raw format.

Statistical analyses were performed using Statistical Package for Social Science 21 (SPSS software).

3. Results

Table 2 reports descriptive statistics of the seat/chassis and floor/chassis vibration indexes and comfort ratings with activated and deactivated suspension system at the two speeds. As can be seen, when the suspension system was activated, vibration transmissibility decreases, in particular when considering the floor/chassis index at high speed. Higher ratings of comfort were reported with activated system, in particular at high speed.

Considering then the data coming from the body map, 5 participants reported body discomfort after the trials with deactivated system (Trials 1 and 3) and 4 after the trials with activated system (Trials 2 and 4). Discomfort was reported mainly arising along the lumbar and neck/shoulders regions (see Fig. 2) and it was particularly reported for Trial 3. This was the condition with high forward speed and deactivated suspension. A qualitative analysis of Fig. 2 shows that, at low speed, there was a slight difference in reported discomfort with activated and deactivated system (Trials 1 and 2), whereas some more consistent differences can be observed at high speed (Trials 3 and 4). In particular at high-speed with activated system (Trial 4) there was not any discomfort reported for knees and ankles. Similarly, in the same trial, discomfort at neck/shoulders and lumbar area decreases.

Overall, when the cab suspension system was activated, there was a slightly reduced number of participants complaining about body discomfort (from 5 to 4 participants) and a reduced intensity of reported discomfort (from moderate to little), with some exceptions in the lumbar area (two participants still reported little or moderate discomfort with activated system).

Concerning hard jolts while driving, all the participants reported no jolting during low speed trials (Trial 1 and 2). In Trial 3, 7 out of the 16 participants reported having experienced some hard jolts while driving, whereas 9 participants reported no jolts. In Trial 4, 3 participants reported some jolts while 13 reported no jolts.

Pearson's r correlation coefficients were calculated between WBV measurements, comfort ratings and the BMI for each of the 4 trials. The analysis showed significant correlations between the BMI and the comfort ratings in Trials 1, 2 and 4. Overall, objective indexes and comfort ratings significantly correlated with themselves across the testing conditions. No significant correlations were found either between vibration transmissibility indexes or between comfort ratings and objective measures (see Table 3).

At low forward speed, the ANCOVA showed a significant main effect of the Trial on the seat/chassis index ($F_{(1,14)} = 7.95$; $p = .014$; $\eta^2 = .362$), with a lower transmissibility with activated system ($EMM = 4.57$, $ESD = .21$), as compared to deactivated system ($EMM = 5.32$, $ESD = .26$). The BMI reported a main effect on the comfort rating ($F_{(1,14)} = 7.48$; $p = .016$; $\eta^2 = .348$), with an increased perception of comfort at higher levels of BMI, with both deactivated and activated suspension system ($\beta = .185$, $t(14) = 2.48$, $p = .027$ and $\beta = .214$, $t(14) = 2.83$, $p = .013$, respectively).

No significant interaction effects between Trial and the BMI on any of the objective indexes (seat/chassis: $F_{(1,14)} = 4.05$; $p = .064$; floor/chassis: $F_{(1,14)} = 3.28$; $p = .091$) and comfort ratings ($F_{(1,14)} = .64$; $p = .436$) were found.

At high forward speed, the ANCOVA showed a significant main effect of the Trial on the seat/chassis index ($F_{(1,14)} = 4.85$; $p = .045$; $\eta^2 = .257$) and on the floor/chassis index ($F_{(1,14)} = 93.23$; $p = .000$; $\eta^2 = .869$). The transmissibility for the seat/chassis index was lower with activated system ($EMM = 3.85$, $ESD = .21$) than with

Table 2
Descriptive statistics of the seat/chassis and floor/chassis vibration indexes and comfort ratings in the four trials.

Parameter	Cab suspension system	N	Speed					
			Low (5 kph)			High (12 kph)		
			Mean	SD	Range	Mean	SD	Range
Seat/chassis index (m/s^2)	OFF	16	5.32	1.05	3.92–7.54	5.55	.75	4.26–6.95
	ON	16	4.57	.82	3.66–6.50	3.85	.81	2.76–5.72
Floor/chassis index (m/s^2)	OFF	16	6.81	.14	6.41–6.96	7.29	.30	6.60–7.55
	ON	16	5.47	.38	4.53–5.96	4.05	.14	3.83–4.28
Comfort rating	OFF	16	7.13	1.93	3–9	5.19	2.37	1–10
	ON	16	7.81	2.04	3–10	7.44	1.99	4–10

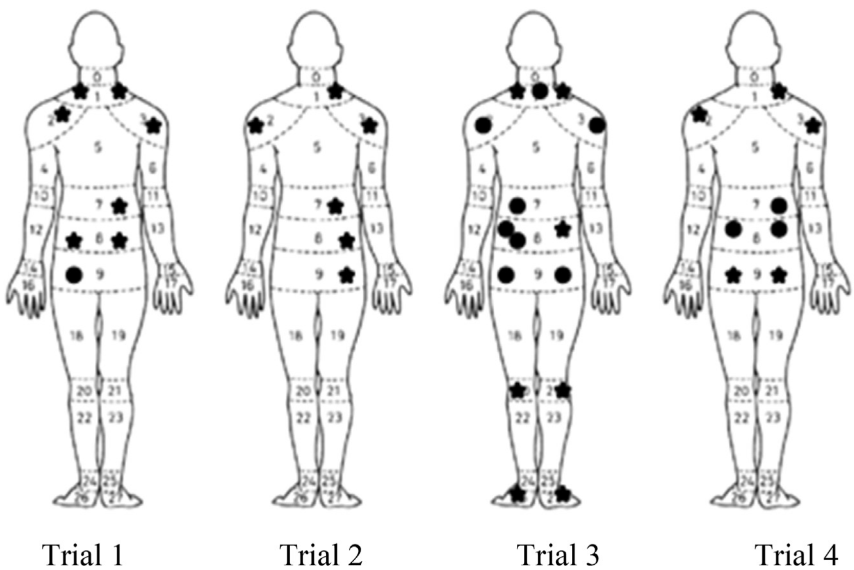

Fig. 2. Body maps (Corlett and Bishop, 1976) with levels of discomfort reported by the participants for different body parts during the four trials (star = little discomfort; small circle = moderate discomfort).

Table 3
Pearson's correlations between vibration indexes, comfort ratings, and BMI in the four trials.

	BMI	Seat/ chassis Low,OFF	Seat/ chassis Low,ON	Seat/ chassis High,OFF	Seat/ chassis High,ON	Floor/ chassis Low,OFF	Floor/ chassis Low,ON	Floor/ chassis High,OFF	Floor/ chassis High,ON	Comfort Low,OFF	Comfort Low,ON	Comfort High,OFF	Comfort High,ON
BMI	–	–,309	,035	–,227	–,126	,097	–,303	,010	,296	,552*	,603*	,261	,720**
Seat/chassis Low,OFF		–	,708**	,748**	,538*	,258	,388	,111	–,399	,006	–,076	,084	,140
Seat/chassis Low,ON			–	,556*	,168	,271	,440	,263	–,223	,171	,183	–,002	,388
Seat/chassis High,OFF				–	,621*	,435	,459	,448	–,101	–,139	–,154	–,019	,151
Seat/chassis High,ON					–	,347	,215	,191	–,209	–,388	–,454	,064	–,035
Floor/chassis Low,OFF						–	,738**	,870**	,364	,156	,255	,065	,083
Floor/chassis Low,ON							–	,801**	,238	–,058	–,009	–,319	–,094
Floor/chassis High,OFF								–	,480	,144	,255	–,058	,117
Floor/chassis High,ON									–	,074	,291	–,175	,003
Comfort Low,OFF										–	,922**	,490	,729**
Comfort Low,ON											–	,435	,724**
Comfort High,OFF												–	,459
Comfort High,ON													–

Note. *p < .05; **p < .01.

deactivated system (*EMM* = 5.56, *ESD* = .19). Similarly, the transmissibility for the floor/chassis index (*EMM* = 4.05, *ESD* = .03) was lower compared to deactivated system (*EMM* = 7.29, *ESD* = .08). The BMI showed a main effect on the comfort rating ($F_{(1,14)} = 6.09$; $p = .027$; $\eta^2 = .303$), with an increased perception of comfort at higher levels of the covariate, when the suspension system was activated (β = .250, t(14) = 3.88, p = .002).

No significant interaction effects between Trial and the BMI on any of the objective indexes (seat/chassis: $F_{(1,14)} = .14$; $p = .717$; floor/chassis: $F_{(1,14)} = .29$; $p = .600$) and comfort ratings ($F_{(1,14)} = 2.04$; $p = .175$) were found.

4. Discussion

The aim of the study was to investigate the effects of an active cab suspension system fitted on a telehandler on WBV and operators' comfort, accounting for their anthropometric variability. Adopting an ergonomic approach, both the vehicle and the operator were taken into account, considering both objective and subjective parameters.

From a mechanical point of view, the activation of the cab suspension system proved to be effective in reducing the vibration transmissibility to the driver. At both low (5 kph) and high (12 kph) forward speed the activation of the system reduced the vibration transmissibility from the chassis to the seat. Moreover, at high speed, it led to a significant reduction of vibration transmissibility also at the floor/chassis level. Thus, the system was effective *per se*, independently from the effect of the seat suspension. Considering urgent safety issues related to WBV in field machinery (Mayton et al., 2008), this result stresses the importance of adopting such systems and encourages further studies in the area.

As concerns the subjective assessment, results showed that the activation of the suspension system did not affect the perception of comfort by the participants, whereas the Body Mass Index had a significant effect on the increase of comfort ratings at both low and high speed. The positive effect of BMI on comfort improvement is consistent with previous evidences reporting a decreased vibrational exposure for people with higher BMI (Mani et al., 2011; Leino et al., 2006). This is an important result if we consider that people with BMI values of overweight and over actually represent the major part of agricultural and also earth-moving operators (WHO, 2000, 2004). However, the analysis did not show any interaction effect between the trial and the BMI, suggesting that the activation of the suspension system did not play any role in enhancing the effects of the higher BMI in improving the comfort perceived by the operators. The ongoing changes in agricultural population (more women, elderly and migrant workers) may ask for deeper investigation of the relation between objective, subjective and anthropometric parameters, by involving participants representing the lower ends of the BMI variability (underweight and normal weight conditions). In this way, more data will be available to design suspension systems that can be effective in reducing WBV and promoting comfort for these specific categories of users, in accordance with the ergonomic perspective of the universal design (Kroemer, 2005).

Although there was a small number of observations about perceived jolts, the analysis of jolting indicated that, at high speed, the activation of the suspension system did not wholly eliminate perceived jolting. This issue should be further investigated in larger samples, since jarring and jolting exposure is an important risk for musculoskeletal symptoms among farm workers (Mayton et al., 2008).

Data about body discomfort suggested that some complaints remained, even when the cab suspension system was activated, in the neck/shoulder area and lumbar area. This is an interesting result if we consider that avoiding operator discomfort is as important as improving the efficiency and the performances of the machinery (Cavallo et al., 2014a; Krause and Bronkhorst, 2003) and it should be examined more in depth by adopting the technique applied by Yoshimura et al. (2005) in their laboratory experiment about biodynamic responses to vertical vibration.

The study did not show any correlations between vibration indexes and subjective ratings of comfort confirming the result from previous studies on vibrational comfort, which reported weak or no relations between these two types of data (De Looze et al., 2003; Kuijt-Evers et al., 2003). In a future development of the research it will be useful to measure also the vibration transmissibility of the human body from the seat surface to the spinal column and to the head, following the method adopted by Yoshimura et al. (2005), to better comprehend and examine these issues. Moreover, other factors are reported in the literature as having an influence on the perception of vibration and comfort: for example, some behaviors and postures (Demić et al., 2002) can play an important role in reducing vibration magnitude. Thus, this issue should be further investigated by increasing the range of individual variables considered.

Beyond its strengths, some limitations of the present study should be taken into account. The participants in the study were limited to 16 individuals, due to practical difficulties in gathering people from field machinery population in an experimental setting. Indeed, they are spread across the country and have different paces of work. In future research it would be useful to increase the sample size to obtain more generalizable results. Given the results of this study, it would be useful also to stratify the sample for underweight, overweight and obesity conditions, to better explore the role played by human body in affecting technical measurements and subjective ratings. Finally, data were collected on one telehandler only. When the investigation was carried out, to the knowledge of the authors, Merlo was the only manufacturer having such active cab suspension system available on its vehicles. Nevertheless, different models, with different characteristics, such as mass, mass distribution, wheelbase, maximum dimension of the telescopic boom are available. Such different vehicles may be considered in a future investigation.

5. Conclusion

WBV exposure is a well-known risk for developing MSDs and it is an important source of discomfort, which can affect performance and lead to injuries. For these reasons, WBV has to be constantly taken into account and monitored, by means of different preventive measures and solutions (Tiemessen et al., 2007). This is particularly true for field vehicles users, given the work they had to perform and the time spent on the machine (Mayton et al., 2008). The present study showed that an active cab suspension system mounted on a telehandler was effective in reducing vibration transmissibility but it did not affect the perception of comfort in a group of professional users.

An ergonomic approach was adopted in the study to highlight consistencies and discrepancies between different sources of data about WBV exposure and comfort, coming from both the vehicle and the users. Anthropometric characteristics of the users have been considered to investigate which range of physical variability was better protected by the suspension system. At both low and high speed, individuals with higher BMI reported higher comfort levels, but this was not affected by the activation of the cab suspension. In addition, the cab suspension system did not eliminate discomfort: some neck/shoulder and lumbar complaints seems to remain.

The results of the study are not conclusive and further investigations are needed to improve vibrational comfort in telehandler users. However, the present study suggests that the operators, given their wide range of physical variability, may need more adjustable or customizable WBV reduction systems: this may be particularly relevant for those users who have characteristics near to the extreme end of the variability (e.g. aged people, women or migrant workers), whose presence is increasing among the workforce population of the developed countries (De Haan and Rogaly, 2002; De Schutter, 2013; Ilmarinen, 2006).

References

Basri, B., Griffin, M.J., 2013. Predicting discomfort from whole-body vertical vibration when sitting with an inclined backrest. Appl. Ergon. 44 (3), 423–434. http://dx.doi.org/10.1016/j.apergo.2012.10.006.

Bertani, M., 2014. Motion-Control-Lösungen für Telehandler. ATZoffhighway 7 (1), 64–69.

Blood, R.P., Ploger, J.D., Johnson, P.W., 2010. Whole body vibration exposures in forklift operators: comparison of a mechanical and air suspension seat. Ergonomics 53 (11), 1385–1394. http://dx.doi.org/10.1080/00140139.2010.519053.

Blüthner, R., Seidel, H., Hinza, B., 2008. Laboratory study as basis of the development for a seat testing procedure in horizontal directions. Int. J. Ind. Ergon. 38 (5–6), 447–456. http://dx.doi.org/10.1016/j.ergon.2007.08.008.

Bovenzi, M., Zadini, A., 1992. Self-reported low back symptoms in urban bus drivers exposed to whole-body vibration. Spine 17 (9), 1048–1059.

Bovenzi, M., Rui, F., Negro, C., D'Agostin, F., Angotzi, G., Bianchi, S., Stacchini, N., 2006. An epidemiological study of low back pain in professional drivers. J. Sound. Vib. 298 (3), 514–539. http://dx.doi.org/10.1016/j.jsv.2006.06.001.

Cann, A.P., Salmoni, A.W., Eger, T.R., 2004. Predictors of whole body vibration exposure experienced by highway transport truck drivers. Ergonomics 47 (13), 1432–1453. http://dx.doi.org/10.1080/00140130410001712618.

Cavallo, E., Deboli, R., Paletto, G., Preti, C., 2005. Ripetibilità dei dati di vibrazioni sui sedili di trattrici agricole tramite pista artificiale. In: Cesini, G., Iannotti, A., Mattei, E., Di Bella, A., Peretti, A. (Eds.), Atti 32° Convegno Nazionale AIA Associazione Italiana di Acustica – Ancona, 15-17 Giugno 2005, pp. 303–306. ISBN 88-88942-09-2.

Cavallo, E., Ferrari, E., Bollani, L., Coccia, M., 2014a. Attitudes and behavior of adopters of technological innovations in agricultural tractors: a case study in Italian agricultural system. Agr. Syst. 130, 44–54. http://dx.doi.org/10.1016/j.agsy.2014.05.012.

Cavallo, E., Ferrari, E., Bollani, L., Coccia, M., 2014b. Strategic management implications for the adoption of technological innovations in agricultural tractor: the role of scale factors and environmental attitude. Technol. Anal. Strateg. 26 (7), 765–779. http://dx.doi.org/10.1080/09537325.2014.890706.

Cavallo, E., Ferrari, E., Coccia, M., 2015. Likely technological trajectories in agricultural tractors by analysing innovative attitudes of farmers. Int. J. Technol. Policy Manag. 15 (2), 158–177. http://dx.doi.org/10.1504/IJTPM.2015.069203.

Corlett, E.N., Bishop, R.P., 1976. A technique for assessing postural discomfort. Ergonomics 19 (2), 175–182. http://dx.doi.org/10.1080/00140137608931530.

Costa, N., Arezes, P.M., 2009. The influence of operator driving characteristics in whole-body vibration exposure from electrical fork-lift trucks. Int. J. Ind. Ergon. 39 (1), 34–38. http://dx.doi.org/10.1016/j.ergon.2008.06.004.

Cranes & Access, 2012. The economic indicator. In: Crane & Access, vol. 14(5). The Vertikal Press Ltd, Brackley, pp. 35–49. Available on-line at. http://www.vertikal.net/fileadmin/journals/ca/2012/ca_2012_5_p34-49.pdf (accessed 04.02.15.).

Deboli, R., Calvo, A., Preti, C., 2012. Comparison between ISO 5008 and field whole body vibration. J. Agr. Eng. 43 (2), 49–54. http://dx.doi.org/10.4081/jae.2012.e8.

De Haan, A., Rogaly, B., 2002. Introduction: migrant workers and their role in rural change. J. Dev. Stud. 38 (5), 1–14. http://dx.doi.org/10.1080/00220380412331322481.

De Looze, M.P., Kuijt-Evers, L.F., Van Dieën, J.A.A.P., 2003. Sitting comfort and discomfort and the relationships with objective measures. Ergonomics 46 (10), 985–997. http://dx.doi.org/10.1080/0014013031000121977.

De Schutter, O., 2013. The agrarian transition and the 'feminization' of agriculture. In: Food Sovereignty: a Critical Dialogue – Conference Paper #37. Yale University, New Haven.

De Temmerman, J., Deprez, K., Hostens, I., Anthonis, J., Ramon, H., 2005. Conceptual cab suspension system for a self-propelled agricultural machine – part 2: operator comfort optimisation. Biosyst. Eng. 90 (3), 271–278. http://dx.doi.org/10.1016/j.biosystemseng.2004.08.007.

Demić, M., Lukić, J., Milić, Ž., 2002. Some aspects of the investigation of random vibration influence on ride comfort. J. Sound. Vib. 253 (1), 109–128.

Deprez, K., Moshou, D., Anthonis, J., De Baerdemaeker, J., Ramon, H., 2005. Improvement of vibrational comfort on agricultural vehicles by passive and semi-active cabin suspensions. Comput. Electron. Agric. 49 (3), 431–440. http://dx.doi.org/10.1016/j.compag.2005.08.009.

Donati, P., 2002. Survey of technical preventative measures to reduce whole-body vibration effects when designing mobile machinery. J. Sound. Vib. 253 (1), 169–183. http://dx.doi.org/10.1006/jsvi.2001.4254.

EN 13490, 2001. Mechanical Vibration – Industrial Trucks – Laboratory Evaluation and Specification of Operator Seat Vibration. European Committee for Standardization, Brussels, Belgium.

EU OSHA, 2010. European Risk Observatory Report. OSH in Figures: Work-related Musculoskeletal Disorders in the EU – Facts and Figures. European Agency for Safety and Health at Work, Luxembourg. Available at: https://osha.europa.eu/en/tools-and-publications/publications/reports/TERO09009ENC (accessed 03.10.15.).

European Commission, 2006. Directive 2006/42/EC of the European Parliament and of the Council of 17 May 2006 on Machinery, and Amending Directive 95/16/EC (Recast), Official Journal of the European Union, L 157, 9.6.2006. Available at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ: L:2006:157:0024:0086:EN:PDF (accessed 03.02.15.).

Fischer, D., Isermann, R., 2004. Mechatronic semi-active and active vehicle suspensions. Control Eng. Pract. 12 (11), 1353–1367. http://dx.doi.org/10.1016/j.conengprac.2003.08.003.

Govindu, N.K., Babski-Reeves, K., 2014. Effects of personal, psychosocial and occupational factors on low back pain severity in workers. Int. J. Ind. Ergon. 44 (2), 335–341. http://dx.doi.org/10.1016/j.ergon.2012.11.007.

Griffin, M.J., 1990. Handbook of Human Vibration. Academic Press, New York, NY.

Hansson, P.A., 1995. Optimization of agricultural tractor cab suspension using the evolution method. Comput. Electron. Agric. 12, 35–49. http://dx.doi.org/10.1016/0168-1699(94)00036-P.

Hostens, I., Deprez, K., Ramon, H., 2004. An improved design of air suspension for seats of mobile agricultural machines. J. Sound. Vib. 276 (1), 141–156. http://dx.doi.org/10.1016/j.jsv.2003.07.018.

Howell, D.C., 2010. Statistical Methods for Psychology, seventh ed. Thomson Wadsworth, Belmont, CA.

Ikenaga, S., Lewis, F.L., Campos, J., Davis, L., 2000. Active suspension control of ground vehicle based on a full-vehicle model. In: American Control Conference, 2000. Proceedings of the 2000, vol. 6. American Automatic Control Council, Chicago, IL, pp. 4019–4024. http://dx.doi.org/10.1109/ACC.2000.876977.

Ilmarinen, J., 2006. Towards a Longer Working Life: Aging and the Quality of Worklife in the European Union. Finnish Institute of Occupational Health, Helsinki.

International Ergonomics Association, 2015, http://www.iea.cc/(accessed 30.10.15.).

ISO 5053, 1987. Powered Industrial Trucks – Terminology. International Organization for Standardization, Geneva, Switzerland.

ISO 10326-1, 1992. Mechanical Vibration – Laboratory Method for Evaluating Vehicle Seat Vibration – Part 1: Basic Requirements. International Organization for Standardization, Geneva, Switzerland.

ISO 2631-1, 1997. Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole-body Vibration – Part 1: General Requirements. International Organization for Standardization, Geneva, Switzerland.

ISO 7096, 2000. Earth-moving Machinery – Laboratory Evaluation of Operator Seat Vibration. International Organization for Standardization, Geneva, Switzerland.

ISO 5008, 2002. Agricultural Wheeled Tractors and Field Machinery – Measurement of Whole-body Vibration of the Operator. International Organization for Standardization, Geneva, Switzerland.

ISO 7250-2, 2010. Basic Human Body Measurements for Technological Design. Part 2: Statistical Summaries of Body Measurements from Individual ISO Populations. International Organization for Standardization, Geneva, Switzerland.

ISO 7250-1, 2012. Basic Human Body Measurements for Technological Design – Part 1: Body Measurement Definitions and Landmarks. International Organization for Standardization, Geneva, Switzerland.

ISO 12934, 2013. Tractors and Machinery for Agriculture and Forestry – Basic Types – Vocabulary. International Organization for Standardization, Geneva, Switzerland.

Kandel, W., 2008. Profile of Hired Farmworkers: a 2008 Update. Economic Research Report, 60. Economic Research Service, U.S. Department of Agriculture, Washington, D.C.

Karwowski, W., 2006. International Encyclopedia of Ergonomics and Human Factors, second ed. CRC Press, Boca Raton, FL.

Kittusamy, N.K., Buchholz, B., 2004. Whole-body vibration and postural stress among operators of construction equipment: a literature review. J. Saf. Res. 35 (3), 255–261. http://dx.doi.org/10.1016/j.jsr.2004.03.014.

Krause, F., Bronkhorst, R.E., 2003. Comfortable Earth-moving Machinery: Knowledge and Experiences from the Eurocabin Project. TNO Work and Employment, Hoofddorp.

Kroemer, K.H., 2005. "Extra-ordinary" ergonomics: how to accommodate small and big persons. In: The Disabled and Elderly, Expectant Mothers, and Children, vol. 4. CRC Press, Boca Raton, FL.

Kuijt-Evers, L.F.M., Krause, F., Vink, P., 2003. Aspects to improve cabin comfort of wheel loaders and excavators according to operators. Appl. Ergon. 34 (3), 265–271. http://dx.doi.org/10.1016/S0003-6870(03)00032-2.

Kumar, A., Mahajan, P., Mohan, D., Varghese, M., 2001. IT – information technology and the human interface: tractor vibration severity and driver health: a study from rural India. J. Agr. Eng. Res. 80 (4), 313–328. http://dx.doi.org/10.1006/jaer.2001.0755.

Leino, S.P., Marjanen, Y., Launis, S., 2006. Human comfort and motion under simulated vibration exposure of mobile machinery. In: Eberhardsteiner, J., Mang, H.A., Waubke, H. (Eds.), Proceedings of 13th International Congress on Sound and Vibration, Vienna, Austria.

Lemerle, P., Boulanger, P., Poirot, R., 2002. A simplified method to design suspended cabs for counterbalance trucks. J. Sound. Vib. 253 (1), 283–293. http://dx.doi.org/10.1006/jsvi.2001.4260.

Lin, C., 2011. Ergonomic assessment of excavator seat. Int. J. Appl. Sc. Eng. 9 (2), 99–109.
Lines, J.A., Stiles, M., Whyte, R.T., 1995. Whole body vibration during tractor driving. J. Low. Freq. Noise Vib. 14 (2), 87–104.
Lyons, J., 2002. Factors contributing to low back pain among professional drivers: a review of current literature and possible ergonomic controls. Work 19 (1), 95–102.
Mani, R., Milosavljevic, S., Sullivan, S.J., 2011. The influence of body mass on whole-body vibration: a quad-bike field study. Ergon. Open J. 4, 1–9. http://dx.doi.org/10.2174/1875934301104010001.
Mansfield, N.J., Newell, G.S., Notini, L., 2009. Earth moving machine whole-body vibration and the contribution of sub-1 Hz components to ISO 2631-1 metrics. Ind. Health 47 (4), 402–410. http://dx.doi.org/10.2486/indhealth.47.402.
Masali, M., 2013. L'Italia si Misura, vol. 2. Aracne Editrice, Roma.
Mayton, A.G., Kittusamy, N.K., Ambrose, D.H., Jobes, C.C., Legault, M.L., 2008. Jarring/jolting exposure and musculoskeletal symptoms among farm equipment operators. Int. J. Ind. Ergon. 38 (9), 758–766. http://dx.doi.org/10.1016/j.ergon.2007.10.011.
Mehta, C.R., Tewari, V.K., 2000. Seating discomfort for tractor operators – a critical review. Int. J. Ind. Ergon. 25 (6), 661–674. http://dx.doi.org/10.1016/S0169-8141(99)00054-2.
Milosavljevic, S., Mcbride, D.I., Bagheri, N., Vasiljev, R.M., Mani, R., Carman, A.B., Rehn, B., 2011. Exposure to whole-body vibration and mechanical shock: a field study of quad bike use in agriculture. Ann. Occup. Hyg. 55 (3), 286–295. http://dx.doi.org/10.1093/annhyg/meq087.
Milosavljevic, S., Mani, R., Ribeiro, D.C., Vasiljev, R., Rehn, B., 2012. Exploring how anthropometric, vehicle and workplace factors influence whole-body vibration exposures during on-farm use of a quad bike. Int. J. Ind. Ergon. 42 (4), 392–396. http://dx.doi.org/10.1016/j.ergon.2012.04.004.
National Instruments, 2012. LabVIEW System Design Software. Available at: http://www.ni.com/labview/ (accessed 03.02.15.).
Osborne, A., Blake, C., Fullen, B.M., Meredith, D., Phelan, J., McNamara, J., Cunningham, C., 2012. Risk factors for musculoskeletal disorders among farm owners and farm workers: a systematic review. Am. J. Ind. Med. 55 (4), 376–389. http://dx.doi.org/10.1002/ajim.22001.
Paschold, H.W., Sergeev, A.V., 2009. Whole-body vibration knowledge survey of U.S. occupational safety and health professionals. J. Saf. Res. 40 (3), 171–176. http://dx.doi.org/10.1016/j.jsr.2009.02.008.
Pope, M.H., Wilder, D.G., Magnusson, M., 1998. Possible mechanisms of low back pain due to whole-body vibration. J. Sound. Vib. 215 (4), 687–697. http://dx.doi.org/10.1006/jsvi.1998.1698.
Sadeghi, N., Habibi, E., Sajjadi, S., 2012. The relationships between musculoskeletal disorders and anthropometric indices in public vehicle drivers. Int. J. Collab. Res. Intern. Med. Public Health 4 (6), 1173–1184.
Scarlett, A.J., Price, J.S., Semple, D.A., Stayner, R.M., 2005. Whole-body Vibration on Agricultural Vehicles: Evaluation of Emission and Estimated Exposure Levels. HSE Research Report No. 321. Health and Safety Executive, Sudbury, Suffolk, UK.
Scarlett, A.J., Price, J.S., Stayner, R.M., 2007. Whole-body vibration: evaluation of emission and exposure levels arising from agricultural tractors. J. Terramech. 44 (1), 65–73. http://dx.doi.org/10.1016/j.jterra.2006.01.006.
Strambi, F., Bartalini, M., Boy, S., Gauthy, R., Landozzi, R., Novelli, D., Stanzani, C., 2012. End users "Feedback" to improve ergonomic design of machinery. Work 41 (Suppl. 1), 1212–1220. http://dx.doi.org/10.3233/WOR-2012-0305-1212.
Tiemessen, I.J., Hulshof, C.T., Frings-Dresen, M.H., 2007. An overview of strategies to reduce whole-body vibration exposure on drivers: a systematic review. Int. J. Ind. Ergon. 37 (3), 245–256. http://dx.doi.org/10.1016/j.ergon.2006.10.021.
Velmurugan, P., Kumaraswamidhas, L.A., Sankaranarayanasamy, K., 2012. Optimisation of whole body vibration analysis for suspended cabin tractor semitrailer. Int. J. Veh. Noise Vib. 8 (2), 152–165. http://dx.doi.org/10.1504/IJVNV.2012.046466.
Vink, P., 2005. Comfort and Design. Principles and Good Practice. CRC Press, Boca Raton, FL.
Wang, W., Rakheja, S., Boileau, P.É., 2006. The role of seat geometry and posture on the mechanical energy absorption characteristics of seated occupants under vertical vibration. Int. J. Ind. Ergon. 36 (2), 171–184. http://dx.doi.org/10.1016/j.ergon.2005.09.006.
WHO, 1995. Physical Status: the Use of and Interpretation of Anthropometry. Report of a WHO Expert Committee. WHO Press, Geneva, Switzerland.
WHO, 2000. Obesity: Preventing and Managing the Global Epidemic. WHO Technical Report Series No. 894. WHO Press, Geneva, Switzerland.
WHO, 2004. Global Health Risks. Mortality and Burden of Disease Attributable to Selected Major Risks. WHO Press, Geneva, Switzerland.
Wikström, B.O., 1993. Effects from twisted postures and whole-body vibration during driving. Int. J. Ind. Ergon. 12 (1), 61–75. http://dx.doi.org/10.1016/0169-8141(93)90038-F.
Wong, J.Y., 2001. Theory of Ground Vehicles, third ed. John Wiley & Sons, New York, NY.
Yoshimura, T., Nakai, K., Tamaoki, G., 2005. Multi-body dynamics modelling of seated human body under exposure to whole-body vibration. Ind. Health 43 (3), 441–447. http://dx.doi.org/10.2486/indhealth.43.441.
Zehsaz, M., Sadeghi, M.H., Ettefagh, M.M., Shams, F., 2011. Tractor cabin's passive suspension parameters optimization via experimental and numerical methods. J. Terramech. 48 (6), 439–450. http://dx.doi.org/10.1016/j.jterra.2011.09.005.