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# UNIVERSITÀ DEGLI STUDI DI TORINO

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**Ergonomic analysis of the effects of a telehandler's active suspended cab on Whole Body Vibration level and operator comfort**

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1 RUNNING HEAD: Active suspension system in telehandlers: an ergonomic analysis of WBV and  
2 comfort

3 **Ergonomic analysis of the effects of a telehandler's active suspended**  
4 **cab on Whole Body Vibration level and operator comfort**

5

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32 **ABSTRACT**

33 INTRODUCTION: Exposure to whole body vibration (WBV) is one of the most important risks for  
34 musculoskeletal disorders (MSDs). The objective of the study was to investigate whether an active  
35 cab suspension system fitted on a telehandler was effective in reducing WBV and in improving  
36 comfort.

37 METHOD: Sixteen male healthy professional operators drove a telehandler on a 100m ISO 5008  
38 smooth track at two different speeds (5 and 12 kph) with activated and deactivated cab suspension  
39 system. Adopting an ergonomic approach, different aspects of the human-machine interaction were  
40 analyzed: 1) vibration transmissibility, 2) subjective ratings of general comfort and local body  
41 discomfort, and 3) anthropometric characteristics of the users.

42 RESULTS: A series of ANCOVAs showed that the suspension system was effective in reducing  
43 WBV at both speeds but did not affect the perception of comfort by the operators. Moreover,  
44 individuals with higher Body Mass Index (BMI) experienced more comfort. Some neck/shoulder  
45 and lumbar complaints and perceived hard jolts seemed to remain even when the system was  
46 activated. No correlations were found between objective and subjective measures.

47 PRACTICAL APPLICATIONS: Results suggest that the operators, given their wide range of  
48 physical variability, may need more adjustable or customizable WBV reduction systems.

49

50 *Keywords: Active suspension; Anthropometric variability; Comfort; Telehandler; Whole-body*  
51 *vibration transmissibility*

52

53 **1. INTRODUCTION**

54 *1.1 Background and motivation*

55 Exposure to whole body vibration (WBV) has been identified as one of the most important risks for  
56 musculoskeletal disorders (MSDs) (Lyons, 2002; Osborne et al., 2012), having severe effects on

57 low-back pain, neck-shoulder disorders, early degeneration of the spine and herniated discs  
58 (Bovenzi & Zadini, 1992; Griffin, 1990; Kittusamy & Buchholz, 2004). MSDs are a main issue of  
59 concern in agricultural industry: in the United States, a 2008 report showed that about 20 percent of  
60 farm workers suffer from musculoskeletal injuries (Kandel, 2008). In Europe, 2,070,000 out of over  
61 40 millions occupational diseases among agricultural operators are MSDs (EU OSHA, 2010).  
62 Agricultural and earth-moving machinery operators are particularly at risk because they are usually  
63 exposed to vehicle vibrations for a long time (Mayton et al., 2008): indeed they typically spend  
64 many hours on the machine (Lin, 2011) and they have to accomplish many operations on different  
65 types of uneven terrain (Wikström, 1993), with the vehicle moving at various forward speeds (Lines  
66 et al., 1995; Scarlett et al., 2007).

67 The awareness of the risks related to WBV exposure led to the development of standards and  
68 requirements to maintain healthy working conditions. The development of WBV standards started  
69 in 1966 in Europe, resulting in the publication of ISO 2631 (Paschold & Sergeev, 2009). This  
70 standard is included into the European Commission Directive 2002/44/EC as a framework to  
71 measure, with the appropriate frequency weightings, the daily WBV exposure. The Directive  
72 imposes, on the European Union countries, duties on employers to protect employees who may be  
73 exposed to WBV vibration at work, and other persons who might be affected by the vibrations,  
74 whether they are at work or not. A partially different situation exists in the United States, where the  
75 WBV exposure limits are based upon the ISO 2631 standard but are voluntary (Paschold & Sergeev,  
76 2009).

77 In order to comply with rules and standards and to promote operators' health, safety and comfort,  
78 many technological and design innovations have been introduced on vehicles by manufacturers  
79 during last decades (for a review, see Donati, 2002 and Tiemessen et al., 2007). Innovations range  
80 from suspended seats (Hostens et al., 2004) to correct ergonomic layout of vehicle interior (Pope et  
81 al., 1998) and to cab suspension systems (Velmurugan et al., 2012). Concerning cab suspension,  
82 different solutions have been developed, from passive systems to more recent semi-active and

83 active ones (Fischer & Isermann, 2004): active systems in particular represent an important  
84 innovation, not only for WBV control but also for the improvement of ride quality, handling and  
85 performance under different operating conditions (Ikenaga et al., 2000; Wong, 2001).

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

94 Studies evaluating the effectiveness of suspension systems typically adopt an objective/mechanical  
95 approach, focusing in particular on acceleration and frequency analysis to determine workers'  
96 exposure limit and action values stated by rules and standards (De Temmerman et al., 2005;  
97 Hansson, 1995). Nonetheless, current sales trends show that the operator's comfort is becoming  
98 more and more important in determining the market value of agricultural machines (Vink, 2005).

99 Previously, customers wished that their basic needs would be fulfilled at an affordable cost, while,  
100 in recent years, customers' decision to purchase a machine has become increasingly influenced by  
101 comfort (Cavallo et al., 2014a; Krause & Bronkhorst, 2003). Furthermore, comfort is one of the  
102 technological trajectories adopted by off-road vehicle manufacturers to develop their products  
103 (Cavallo et al., 2014b; Cavallo et al., 2015).

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

109 The role played by some anthropometric characteristics, such as stature, body mass and Body Mass  
110 Index (BMI), of the users of different vehicles in affecting WBV exposure and MSDs development  
111 has been investigated in previous studies but contrasting results are reported (Blood et al., 2010;  
112 Costa & Azeres, 2009; Mani et al., 2011; Milosavljevic et al., 2011, 2012; Sadeghi et al., 2012).  
113 Among these characteristics, the BMI is used by the World Health Organization to classify  
114 underweight, overweight and obesity in adults (WHO, 2000). Thus, it is a relevant index to be  
115 considered, because of the increasing rate of overweight and obesity conditions in the developed  
116 countries (WHO, 2000, 2004). Moreover, as an index calculated as the body mass in kilograms  
117 divided by the square of the stature in meters ( $\text{kg/m}^2$ ), it is a combination of measurements. It is  
118 therefore essential for the interpretation of measurements, since, as reported by WHO (1995), body  
119 mass alone has no meaning unless it is related to an individual's stature. However, the relation  
120 between BMI and exposure to vibration is controversial: some studies pointed out that MSDs  
121 related to WBV exposure increase when the BMI raises (Bovenzi et al., 2006). On the opposite,  
122 results from other studies showed that vibrational discomfort decreases (Leino et al., 2006) and  
123 energy absorption increases (Wang et al., 2006) when the BMI raises.  
124 Little is known, however, about the influence of this anthropometric characteristic on the perception  
125 of comfort in field machinery operators, whose population is undergoing the same trend of  
126 increasing overweight and obesity conditions as the general population (WHO, 2004).

## 127 1.2 Aims of the study

128 The objective of the present study was to investigate whether an active cab suspension system fitted  
129 on a telehandler was effective in reducing WBV and in improving comfort for the operators. The  
130 study adopted an ergonomic approach “*concerned with the understanding of the interactions among*  
131 *humans and other elements of a system [...]*”, which considers users' involvement essential “*in*  
132 *order to optimize human well-being and overall system performance*” (International Ergonomics  
133 Association, 2015; see also Karwowski, 2006). The importance of this approach is highlighted also

134 by the European Directive 42/2006 (European Commission, 2006), which states that “*Under the*  
135 *intended conditions of use, the discomfort, fatigue and physical and psychological stress faced by*  
136 *the operator must be reduced to the minimum possible, taking into account ergonomic principles*  
137 *such as: allowing for the variability of the operator's physical dimensions, strength and stamina;*  
138 *providing enough space for movements of the parts of the operator's body; avoiding a machine-*  
139 *determined work rate; avoiding monitoring that requires lengthy concentration; adapting the*  
140 *man/machinery interface to the foreseeable characteristics of the operators.*” (Annex 1, p.21).

141 Thus, the study was addressed to assess not only the objective effects of the suspension system on  
142 vibration transmissibility but also the benefits perceived by the users, considered in their  
143 anthropometric variability.

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

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

## 154 **2. MATERIALS AND METHODS**

### 155 *2.1 Participants*

156 Sixteen male healthy professional telehandler drivers took part in the study. Individuals with a  
157 minimum of 5 years of driving experience on telehandlers (driving-experience cut-off as in Kumar  
158 et al., 2001) were chosen to participate in the study. The mean age and experience operating

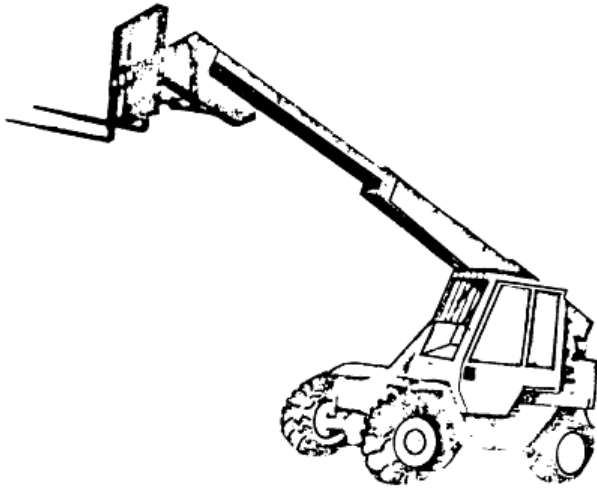


159 telehandlers were 39.4 years (SD=12.2; range 18-60) and 20.0 years (SD=14.49; range 10-50),  
160 respectively. The participants completed a brief questionnaire about their work experience and  
161 musculoskeletal disorders history. All the participants did not report any musculoskeletal disorders  
162 and were suitable for the investigation trials. All the participants signed an informed consent to  
163 participate in the study.

## 164 *2.2 The telehandler*

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

171 The telehandler used in the study was a Merlo make, P55.9CS model. It is a 2 axles, 4 wheel drive  
172 vehicle equipped with 103 kW Diesel engine and hydrostatic transmission. The maximum forward  
173 speed is 40 kph (25 mph). The vehicle is representative of the typical telehandler architecture  
174 adopted by most of the manufacturers: the cab, with the driving station, is on the left and the engine  
175 on the right of the vehicle median plane. The telescopic boom, in 3 sections for a maximum length  
176 of 9 m, is on the median plane of vehicle. The maximum loading mass of the telescopic boom is  
177 5500 kg. The telehandler was equipped with hydro-pneumatic active cab suspension system  
178 designed to reduce vibration magnitude along the vertical direction, from the buttock to the head (z-  
179 axis) of the driver. The cab is joined to the chassis of the vehicle by front and rear mechanical  
180 articulated connections. They make possible the cab to displace 120 mm vertically under the force  
181 of the active dumper, placed between the chassis and the floor of the cab. The system is covered by  
182 Merlo patent.



183

184 Figure 1. Example of telehandler (from ISO 5053:1987).

### 185 *2.3 Whole-Body Vibration*

186 Vibration level was measured using three ICP accelerometers mounted respectively on the driver's  
187 seat, on the floor of the cabin close to the base of the seat, and on the chassis of the telehandler. The  
188 accelerometer on the seat was a set pad. The vibration levels were measured along the three  
189 orthogonal directions (x, y and z) according to the coordinate system for a seated person (ISO 2631-  
190 1:1997). However, since the vertical vibrations are usually dominant in vehicles (Basri & Griffin,  
191 2013), they significantly contribute to vibration magnitude exposure of the driver (Cann, Salmoni &  
192 Eger, 2004), and the active suspended cab system has been designed to operate along this direction,  
193 only the vertical direction (z axis) was considered for the purposes of the present paper.

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

### 197 *2.4 Subjective ratings*

198 Subjective measures were collected by means of a questionnaire, developed considering the  
199 instrument by Bovenzi et al. (2006) and the scales typically used in the subjective measurements of  
200 comfort (for a review, de Looze et al., 2003; Mehta & Tewari, 2000). The questionnaire submitted

201 to the participants was composed of 3 items, to assess their perception of comfort, the possible body  
 202 discomfort, and the jolts perceived while driving. First, the participants were asked to rate the  
 203 comfort perceived regarding vibrations during each trial on a 11-point rating scale, ranging from 0  
 204 (no comfort at all) to 10 (extreme comfort). Then, they were asked to identify body areas  
 205 experiencing little/moderate/hard/very hard discomfort during the trial on a body map (Corlett &  
 206 Bishop, 1976). Finally, the participants were asked to indicate how often (never, sometimes, often),  
 207 they perceived, while driving the telehandler, so hard jolts to lose contact with the seat.

208 *2.5 Anthropometric parameters*

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

212 The anthropometric characteristics of the participants in the study are reported in Table 1. The  
 213 sample was a good representation of the anthropometric variability of the Italian population (ISO  
 214 7250-2, 2010; Masali, 2013), with participants from both the 5-10<sup>th</sup> and the 90-95<sup>th</sup> percentiles  
 215 (some participants were even above the 99<sup>th</sup> percentile with regard to body mass).

216 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 <sup>2</sup> )	28.9	5.8	22-42

217

218 *2.6 Testing procedure*

219 Objective measurements were carried out while the telehandler was driven over a 100 m ISO  
 220 smooth track (ISO 5008:2002). Previous studies confirmed that the use of ISO-5008 track provides

221 a reasonable basis for comparison of the WBV to which the operator of a field wheeled-vehicle is  
222 exposed, due to the high repeatability of vibration data (Cavallo et al., 2005; Deboli et al., 2012;  
223 Scarlett et al., 2005; Zehsaz et al., 2011).

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

- 225 1. Trial 1 (Low, OFF): speed of 5 kph, deactivated suspension
- 226 2. Trial 2 (Low, ON): speed of 5 kph, activated suspension
- 227 3. Trial 3 (High, OFF): speed of 12 kph, deactivated suspension
- 228 4. Trial 4 (High, ON): speed of 12 kph, activated suspension

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

### 235 *2.7 Data processing*

236 Vibration data were processed to obtain root-mean-square (rms) accelerations in  $\text{m/s}^2$  and the  
237 frequency spectra in one-third octave band ranging from 0.5 to 80 Hz. This range is indeed  
238 interesting from a hygienist's point of view as reported in the ISO standard 2631-1 (1997). The  
239 signals were therefore weighted using the weighting curve  $W_k$  for the z axis as described in the  
240 same standard. These aspects are developed in detail in a dedicated paper while the present paper  
241 focuses on vibration transmissibility (ISO 10326-1:1992).

242 Vibration transmissibility was evaluated by computing the floor/chassis and the seat/chassis  
243 indexes. The indexes were calculated following the method used for the SEAT (Seat Effective  
244 Amplitude Transmissibility) factor, as stated by the EN 13490 (2001) and ISO 7096 (2000)  
245 standards. The floor/chassis index accounted for the effects of the cab suspension system, whereas

246 the seat/chassis index accounted for the joint effects of seat and cab suspension systems. The  
247 indexes were calculated by a 2 steps process. The first step was the calculation of the floor/chassis  
248 and seat/chassis rms ratios for each participant, at each of the third octave frequency bands taken  
249 into consideration, and in any of the 4 testing conditions. Then, in the second step, the ratios in the  
250 frequency range 2-8 Hz were summed up for any of the participants in each of the testing  
251 conditions. In the 2-8 Hz range the human vibration sensitivity is the highest (Griffin, 1990).

## 252 *2.8 Statistical analyses*

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

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

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

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

272 **3. RESULTS**

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

278

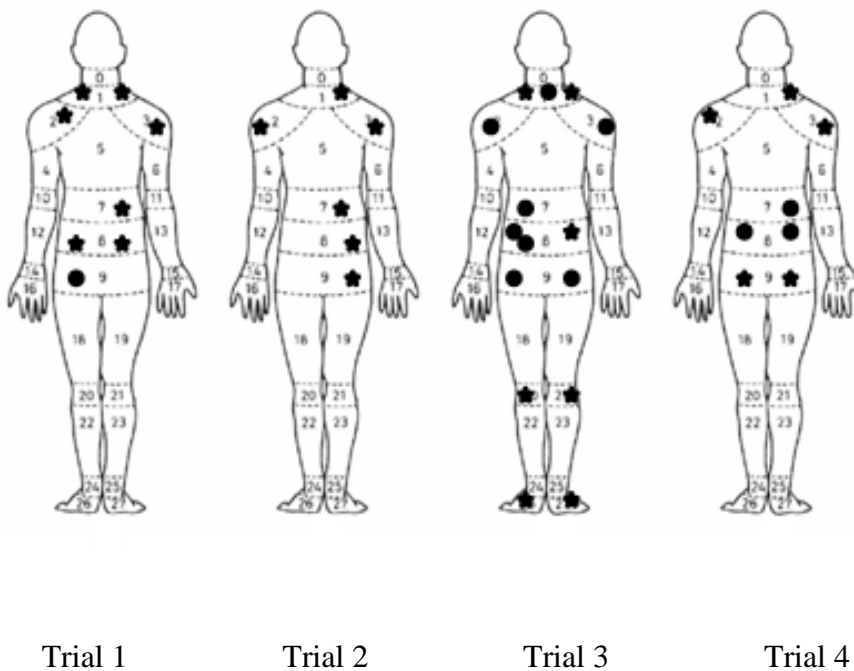
279 Table 2. Descriptive statistics of the seat/chassis and floor/chassis vibration indexes and comfort  
 280 ratings in the four trials.

Parameter	Cab suspension system	N	Speed					
			Low(5kph)			High(12kph)		
			Mean	SD	Range	Mean	SD	Range
Seat/chassis index (m/s <sup>2</sup> )	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 <sup>2</sup> )	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

281

282 Considering then the data coming from the body map, 5 participants reported body discomfort after  
 283 the trials with deactivated system (Trials 1 and 3) and 4 after the trials with activated system (Trials  
 284 2 and 4). Discomfort was reported mainly arising along the lumbar and neck/shoulders regions (see  
 285 Figure 2) and it was particularly reported for Trial 3. This was the condition with high forward  
 286 speed and deactivated suspension. A qualitative analysis of Figure 2 shows that, at low speed, there  
 287 was a slight difference in reported discomfort with activated and deactivated system (Trials 1 and

288 2), whereas some more consistent differences can be observed at high speed (Trials 3 and 4). In  
 289 particular at high-speed with activated system (Trial 4) there was not any discomfort reported for  
 290 knees and ankles. Similarly, in the same trial, discomfort at neck/shoulders and lumbar area  
 291 decreases.  
 292 Overall, when the cab suspension system was activated, there was a slightly reduced number of  
 293 participants complaining about body discomfort (from 5 to 4 participants) and a reduced intensity of  
 294 reported discomfort (from moderate to little), with some exceptions in the lumbar area (two  
 295 participants still reported little or moderate discomfort with activated system).  
 296



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

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

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





311 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													-

312 Note. \*  $p < .05$ ; \*\*  $p < .01$ .



314 At low forward speed, the ANCOVA showed a significant main effect of the Trial on the  
315 seat/chassis index ( $F_{(1,14)}=7.95$ ;  $p=.014$ ;  $\eta^2=.362$ ), with a lower transmissibility with activated  
316 system ( $EMM=4.57$ ,  $ESD=0.21$ ), as compared to deactivated system ( $EMM=5.32$ ,  $ESD=0.26$ ). The  
317 BMI reported a main effect on the comfort rating ( $F_{(1,14)}=7.48$ ;  $p=.016$ ;  $\eta^2=.348$ ), with an increased  
318 perception of comfort at higher levels of BMI, with both deactivated and activated suspension  
319 system ( $\beta=.185$ ,  $t(14)=2.48$ ,  $p=.027$  and  $\beta=.214$ ,  $t(14)=2.83$ ,  $p=.013$ , respectively).  
320 No significant interaction effects between Trial and the BMI on any of the objective indexes  
321 (seat/chassis:  $F_{(1,14)}=4.05$ ;  $p=.064$ ; floor/chassis:  $F_{(1,14)}=3.28$ ;  $p=.091$ ) and comfort ratings  
322 ( $F_{(1,14)}=0.64$ ;  $p=.436$ ) were found.

323 At high forward speed, the ANCOVA showed a significant main effect of the Trial on the  
324 seat/chassis index ( $F_{(1,14)}=4.85$ ;  $p=.045$ ;  $\eta^2=.257$ ) and on the floor/chassis index ( $F_{(1,14)}=93.23$ ;  
325  $p=.000$ ;  $\eta^2=.869$ ). The transmissibility for the seat/chassis index was lower with activated system  
326 ( $EMM=3.85$ ,  $ESD=0.21$ ) than with deactivated system ( $EMM=5.56$ ,  $ESD=0.19$ ). Similarly, the  
327 transmissibility for the floor/chassis index ( $EMM=4.05$ ,  $ESD=0.03$ ) was lower compared to  
328 deactivated system ( $EMM=7.29$ ,  $ESD=0.08$ ). The BMI showed a main effect on the comfort rating  
329 ( $F_{(1,14)}=6.09$ ;  $p=.027$ ;  $\eta^2=.303$ ), with an increased perception of comfort at higher levels of the  
330 covariate, when the suspension system was activated ( $\beta=.250$ ,  $t(14)=3.88$ ,  $p=.002$ ).

331 No significant interaction effects between Trial and the BMI on any of the objective indexes  
332 (seat/chassis:  $F_{(1,14)}=0.14$ ;  $p=.717$ ; floor/chassis:  $F_{(1,14)}=0.29$ ;  $p=.600$ ) and comfort ratings  
333 ( $F_{(1,14)}=2.04$ ;  $p=.175$ ) were found.

#### 334 **4. DISCUSSION**

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

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

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

363 Although there was a small number of observations about perceived jolts, the analysis of jolting  
364 indicated that, at high speed, the activation of the suspension system did not wholly eliminate

365 perceived jolting. This issue should be further investigated in larger samples, since jarring and  
366 jolting exposure is an important risk for musculoskeletal symptoms among farm workers (Mayton  
367 et al., 2008).

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

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

384 Beyond its strengths, some limitations of the present study should be taken into account. The  
385 participants in the study were limited to 16 individuals, due to practical difficulties in gathering  
386 people from field machinery population in an experimental setting. Indeed, they are spread across  
387 the country and have different paces of work. In future research it would be useful to increase the  
388 sample size to obtain more generalizable results. Given the results of this study, it would be useful  
389 also to stratify the sample for underweight, overweight and obesity conditions, to better explore the  
390 role played by human body in affecting technical measurements and subjective ratings. Finally, data

391 were collected on one telehandler only. When the investigation was carried out, to the knowledge of  
392 the authors, Merlo was the only manufacturer having such active cab suspension system available  
393 on its vehicles. Nevertheless, different models, with different characteristics, such as mass, mass  
394 distribution, wheelbase, maximum dimension of the telescopic boom are available. Such different  
395 vehicles may be considered in a future investigation.

## 396 **5. CONCLUSION**

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

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

412 The results of the study are not conclusive and further investigations are needed to improve  
413 vibrational comfort in telehandler users. However, the present study suggests that the operators,  
414 given their wide range of physical variability, may need more adjustable or customizable WBV  
415 reduction systems: this may be particularly relevant for those users who have characteristics near to  
416 the extreme end of the variability (e.g. aged people, women or migrant workers), whose presence is

417 increasing among the workforce population of the developed countries (de Haan & Rogaly, 2002;  
418 De Schutter, 2013; Ilmarinen, 2006).

419

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