Vibration produced by hand-held olive electrical harvesters

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Abstract

The paper reports the results of some laboratory and field tests aimed at assessing the acceleration levels transmitted to the hand-arm system by electric portable harvesters for olive. Four harvesting heads, different for shape and kinematic system, and five bars, different for diameter, length and material (aluminium and carbon fibre), were used in assembling eleven harvesters. The vibrations were measured in two points, next to the handgrips. The laboratory tests allowed the evaluation of the acceleration levels in standard controlled conditions, while the field tests allowed the assessing of the effects of the tree canopy with respect to the no load running. The laboratory tests showed that in reducing the vibration level plays a major role the kinematic system of the harvesting head and then the bar material. The classical flap-type harvester produced accelerations of around 20 m/s^2, while by using a harvesting head with two parts in opposite movement, the accelerations were lowered to about 6 m/s^2. The use of carbon fibres for the bars, besides the reduction in weight, produced also a reduction in acceleration (from 21 to 16 m/s^2). The field tests proved that the tree canopy had a negative effect on the vibrations transmitted to the hand-arm system, especially when the aluminium bar of small diameter was used.

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Introduction

Italy is among the major producers of olive oil in the Mediterranean basin, alongside Spain, Greece and Turkey (FAO, 2010). The main figures of the Italian olive growing are: 1,190,000 ha of cultivated surface, mainly concentrated in the Centre-South of the peninsula, 3,400,000 t of olives and 513,000 t of oil (ISTAT, 2010). The Italian oil is on average about a fifth of the oil yearly produced all over the world (IOC, 2011). Moreover, Italy is both a big importer and exporter of olive oil: in 2010 they were imported 610,000 t, to the value of 1.20 billion of Euros, and exported 380,000 t, to the value of 1.17 billion of Euros (ISMEA, 2012).

Even so, due to some aspects related to production costs and market force dynamics, the Italian olive oil sector is going through a ticklish moment. Income maintenance and quality preservation require, among other things, a reduction of production costs. Drupe harvesting is the most expensive phase of the olive production, mainly when full mechanisation is not possible due to several factors as farm fragmentation (in Sicily, 70 percent of farms are smaller than 2 ha), tree structure, irregular tree layout, and sloping lands. In these cases the use of hand-held vibrating tools, approximately capable of triplicate the productivity of the workers with respect to the manual harvesting, is taken into great consideration (Famiani *et al*., 2008).

Unfortunately, the increase in the mechanisation level has introduced additional sources of risk for operators. In fact, since their appearance in the market, these tools have been characterised by lack of comfort due to the quite high levels of noise and vibration, as well as to the fatigue caused by the weight (Iannicelli and Ragni, 1994; Blandini *et al*., 1997; Caruso *et al*., 2005; Deboli *et al*., 2008; Pascuzzi *et al*., 2008). These aspects are often underestimated by users, mainly interested in the gain of productivity.

Vibration is probably the most important risk connected with the use of these portable harvesters and can be reduced after proper design or optimal selection of the operating parameters (Monarca *et al*., 2007; Pascuzzi *et al*., 2008; Mallick, 2010). Workers, when operate with hand-held power tools, in most of the cases do not perceive acceleration levels as being too high, so increasing the exposure risk (Vergara *et al*., 2008). Vibration on the hand-harm system can lead to chronic disorders known as Raynaud syndrome, or vibration white finger, or dead finger, a disease which shows itself after a latency period and which demands attention from all the medical personnel (Chetter *et al*., 1998). Disorders are reversible if vibration exposure is reduced or eliminated (Ramos *et al*., 1996; Griffin, 2008).

The biodynamic response of the hand-arm system is affected by several factors, among which acceleration level, vibration direction, frequency, posture, grip force, operating tool, mechanical impedance and handle features can be cited (Buström, 1997; Monarca *et al*., 2003; Dong *et al*., 2004; Aldien *et al*., 2006; Besa *et al*., 2007; Deboli *et al*., 2008; Dewangan and Tewari, 2008; Concettoni and Griffin, 2009). Moreover, some of these factors are correlated with the effectiveness of anti-vibrating gloves, which can be used to reduce vibration exposure for operators (Dong *et al*., 2005), so reducing at the same time the work stress (Tewari and Dewangan, 2009).

To increase operator's comfort and to try to respect the threshold limit values imposed by the recent regulations (European Commission, 2002; Italian Regulation, 2005, 2008), many makers have marketed for some years, together with the usual pneumatic or mechanic models, portable harvesters powered by electric motors, characterised by greater lightness, greater handiness and which resulted very effective in reducing the noise level with respect to those powered by two-stroke engines (Biocca *et al*., 2008).

The development of these new tools has involved changes in shape and dynamics of the harvesting system, as well as in the material for their construction (introduction of carbon fibres to reduce the weight). These changes may affect the accelerations transmitted to the workers during their use, so different levels of vibration may be expected (Çakmak *et al*., 2011) and the agreement with the current regulations must be verified.

Based on the results of previous works (Cerrulo *et al*., 2010; Cerruto *et al.*, 2011), this research aims to evaluate the vibrations transmitted to the hand-arm system by different electric portable harvesters at varying bar features (material, length and diameter), dynamic of the harvesting head, and operating conditions (in laboratory, at no load, and in field, under ordinary working conditions).

Materials and methods

The portable harvesters

Experimental tests were carried out by using electric portable harvesters produced by a local manufacturer. Four harvesting heads were considered, different for number and arrangement of the teeth (the small bars that beat branches and olives during the harvest), as well as for direction of the oscillations (Figure 1). All the teeth are in carbon fibres and of the same size (diameter=5 mm, length=370 mm).

More in detail, the harvesting heads H1, H2 and H3 present an aluminium-made box and the same mechanism to activate the teeth. The teeth are connected to a 36-cm main arm that in H1 and H2 is disposed orthogonally to the motor shaft, while in H3 is disposed parallel, so the oscillating planes are orthogonal. The harvesting heads H1 and the H2 carry 8 teeth with different arrangement, while H3 12, arranged in the classical flap-type shape, widely used in pneumatic models. Users can assemble the three heads by modifying number and position of the teeth according to their needs.

The harvesting head H4 has a plastic-made box to which are connected two arms with opposed oscillations on a plane orthogonal to the motor shaft. Each arm carries 4 teeth.

The harvesting heads H1, H2 and H3 are merchandised with bars different for material (aluminium and carbon fibres), diameter (35 and 40 mm), and length (2010 and 2210 mm), but with the same thickness (2 mm), while H4 is marketed only with an aluminium telescopic bar, 1 mm thick, diameters of 28 and 35 mm, and lengths of 2060 (minimum) and 2850 mm (maximum).

The main features of harvesting heads and bars are reported in Table 1.

The electric motor (maximum power of 900 W and rotating speed of around 6000 rpm, fixed by an electronic card), of the same type for all the harvesters tested, is feed by means of an external 12 V DC battery; the electric cable is placed inside the bar, from which it emerges near the handgrip equipped with the activation switch. The motor shaft is connected to a box that, with a gear ratio of 10:58, gets the arms with the teeth moving with oscillating frequency of 18 Hz.

Vibration measurement

The laboratory and field tests were conducted in different stages: firstly the laboratory tests and then the field ones.

The three harvesting heads H1, H2 and H3 were tested with the three bars B1, B2 and B3, according to a full factorial experimental design, while H4 was tested with the telescopic bar B4/B5 only. By comparing the bars B2 and B3, it was possible to evaluate the effect of the material (aluminium and carbon fibres) on the vibrations, while by comparing the bars B1 and B3, the effects of diameter (35 and 40 mm) and length (2010 and 2210 mm) were evaluated. Finally, the study of the harvester H4 allowed the assessment of a completely different dynamic system.

During laboratory tests, to smooth the influence of external factors, the harvesters were used by the same person. The tests were carried out by fixing the angle of the bar according to three directions, so to cover all the possible orientations assumed during the working activity: vertical, inclined at about 45° and horizontal. Furthermore, vibrations were measured, at different times, in two points (MP1 and MP2) for each bar, at the grip level for both hands of the operator (Figure 2). Their position was fixed by observing the operator in standard working condition.

Table 1. Main features of bars and harvesting heads.

	Bars			
	B1	B2	B3	B4/B5
Material	Al	CF	Al	Al
Diameter, mm	35	40	40	35/28
Thickness, mm	2	2	2	1
Length, mm	2010	2210	2210	2060/2850
Mass, kg	1.356	1.342	1.416	1.650
	Harvesting heads			
	H1	**H2**	**H3**	**H4**
Teeth	8	8	12	8
Mass, kg	1.545	1.545	1.365	1.250

Al, aluminium; CF, carbon fibres; B, bar; H, head.

Figure 1. Harvesting heads (from H1, top left, to H4, bottom right).

Overall, 66 measurement sessions [(3 harvesting heads × 3 bars + H4 harvesting head × 2 bars) × 3 inclinations × 2 measurement points] were carried out, each lasting at least 5 min.

The field tests were carried out in an olive-yard with irregular spacing and olive of variety *Nocellara Etnea*, pruned according to the vase method and having an average tree crown diameter of about 4 m. As a first study, only the H3 harvesting head, applied to the three bars B1, B2 and B3, was tested. Again, vibrations were measured in two points on the bar as during the laboratory tests. To allow the ordinary working conditions, the bar inclination should be continually changed and therefore it was not considered as a factor, so other 6 measurement sessions were carried out. The measurement time for the different configurations ranged from about 4 to 13 min, so to complete the harvesting of one tree during each run (Figure 3). This variability was due to the high differences among the tree yield. The harvesters were operated by the same person, but for practical reasons, different by that one which worked during the laboratory tests. This could affect the comparison between laboratory and field tests, but nevertheless allows carrying out a first evaluation of the canopy effects.

Accelerations were measured by using three mono axial accelerometers DJB, model A/123/S (DJB Instruments Ltd., Suffolk, UK), screwed on the faces of a small cube tied to the bars with a metallic clamp, so to be equivalent to a triaxial accelerometer. The reference axes were selected according to the basicentric coordinate system defined by the UNI EN ISO 5349-1:2004 regulation (ISO, 2004): x-axis perpendicular to the palm surface area, y-axis parallel to the longitudinal axis of the grip, and z-axis directed along the third metacarpus bone of the hand (Figure 4).

During the laboratory tests, the signals of the accelerometers were amplified by means of three amplifiers MESA, model C24 (SCS Controlli e Sistemi srl, Padova, Italy), and then recorded on digital tapes by means of a four channel digital audio tape recorder. Subsequently they were acquired in a PC by means of a dB4 four-channel acquisition unit and the recording module of the dBFA Suite software (01dB-Metravib, Lyon, France). Instead, during the field tests, the signals were directly recorded on the hard disk of a notebook by means of the dB4 unit and the recording module of the dBFA Suite software (01dB-Metravib).

Subsequently all the recorded signals were analysed by using the post-processing module of the dBFA Suite software (01dB-Metravib), that allows for several post-processing analyses, among which narrow band analysis (FFT), 1/3 octave analysis, and frequency weighting for the hand-arm system.

Data analysis

According to the UNI EN ISO 5349-1:2004 regulation (ISO, 2004), signal analysis was performed in the range 5.6-1400 Hz (third of octave bands from 6.3 to 1250 Hz) by applying the FFT and the 1/3 octave analysis. Being the maximum frequency of interest 1400 Hz, a signal length of about 10 s is enough for the digital analysis. So, to have some replications useful for the statistical analysis and to evaluate the variability in time, sub-samples of 1 min were extracted from each acceleration signal recorded during the measurement sessions. The number of sub-samples was equal to 4 for the laboratory tests and ranged from 4 up to 13 for the field tests due the different length of the acquisition time. The frequency weighted root mean square (RMS) accelerations were computed for each axis (a_{hwz}, a_{hwy}, and a_{hwz}) and then the global weighted acceleration a_{hw} was calculated as:

$$a_{hw} = \sqrt{a_{hwx}^2 + a_{hwy}^2 + a_{hwz}^2} \quad \text{(Eq. 1)}$$

Finally, the daily vibration exposure value, $A(8)$, standardized to an

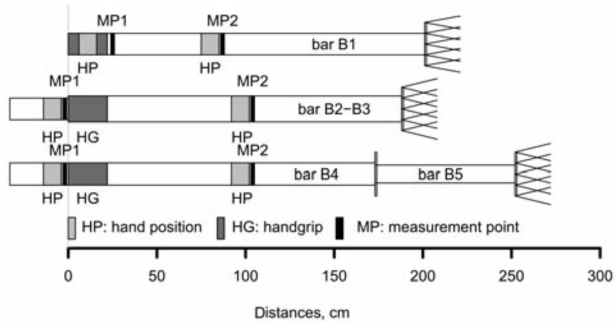

Figure 2. Schematic view of harvesters and measurement points (MP1 and MP2).

Figure 3. Olive harvesting with the portable harvesters.

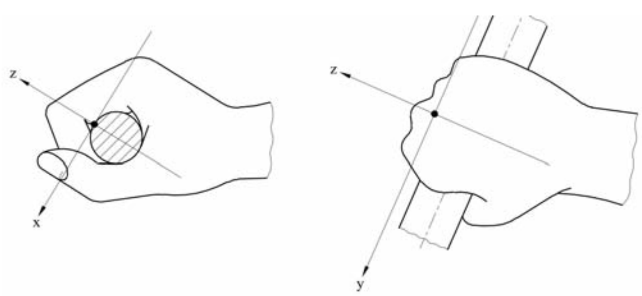

Figure 4. Reference axes for vibration measurement.

8-h reference period, was obtained:

$$A(8) = \sqrt{\frac{T}{T_0}} a_{hw} \qquad \text{(Eq. 2)}$$

being T_0=8 h and T the daily exposure time (h).

The $A(8)$ values were compared with the daily exposure action value of 2.5 m/s^2 and the daily exposure limit value of 5.0 m/s^2 established by the European Directive 2002/44/EC (European Commission, 2002).

RMS values were statistically analysed to detect significant differences related to bar type, harvesting head and working conditions (laboratory *vs* field tests). All computations and graphical representations were performed by means of the open source software *R* (R Development Core Team, 2009).

Results and discussion

Laboratory tests

The analyses were carried out on the weighted global acceleration values. Given the experimental design, as a first approach the interaction bar × harvesting head was treated as a single factor, to compare the harvesting head H4 *vs* the other ones and to evaluate the effects of bar angle and measurement point on the vibrations. The results are summarised in Figure 5.

It allows for the following observations:
- the harvesting head H4 produces vibrations much lower than the other ones;
- the differences between the two bars B4 and B5 when used with the harvesting head H4 seem to be not statistically significant;
- the differences among the three bar angles seem to be not statistically significant;
- the mean value of the global acceleration in the measurement point MP2 is greater than that measured in MP1.

Being the distribution of the global acceleration values not normal and not being possible to normalise it after the usual data transformations (P-level<0.001), the statistical comparisons were performed by applying the more robust Kruskal-Wallis non-parametric test rather than the analysis of variance. The results of the comparisons are reported in Table 2 and they confirm the observations derived from Figure 5.

The vibration level produced by the harvesting head H4 is much lower than that produced by the other ones (P-level<0.001): the opposite oscillations of the two arms allow for a partial compensation of the vibrations transmitted to the hand-harm system, whatever bar length and angle. This means that the vibration level is mainly affected by the kinematic system rather than the power source type (electric, mechanic or pneumatic). The acceleration measured in MP2 is greater than that measured in MP1 (P-level<0.001) probably because the measurement point MP2 is closer to the harvesting head, the source of the vibrations. The bar angle does not affect the vibration level (P-level=0.172) transmitted to the hand-harm system, so guidelines to the users are unnecessary from this point of view. Finally, the differences in vibration level when using the harvesting head H4 with the telescopic bar at minimum (B4) or maximum (B5) length are not statistically significant.

All the measured values are reported in Figure 6, which visually confirms the results previously discussed and, in addition, shows that, in most cases, the variability among the 1-min sub-samples is rather moderate (only H3 presents great variability in MP2 when used with the bar B1), meaning an almost constant level of exposure of the operator.

Subsequently, to study more in detail the effects of bar type and harvesting head, the nine combinations (bar B1, B2, B3 × head H1, H2, H3) were analysed separately as a full factorial experimental design. The results of the non-parametric tests are reported in Figure 7.

They show that the carbon fibre bar (B2) produces, on average, accelerations lower than the aluminium one (B3) with the same diameter and length. Moreover, the comparison carbon fibre *vs* aluminium is statistically significant (P-level<0.001): 16.3 *vs* 21.1 m/s^2 (median values). Carbon fibre, therefore, besides the reduction in weight, has also a positive effect in reducing the vibrations transmitted to the

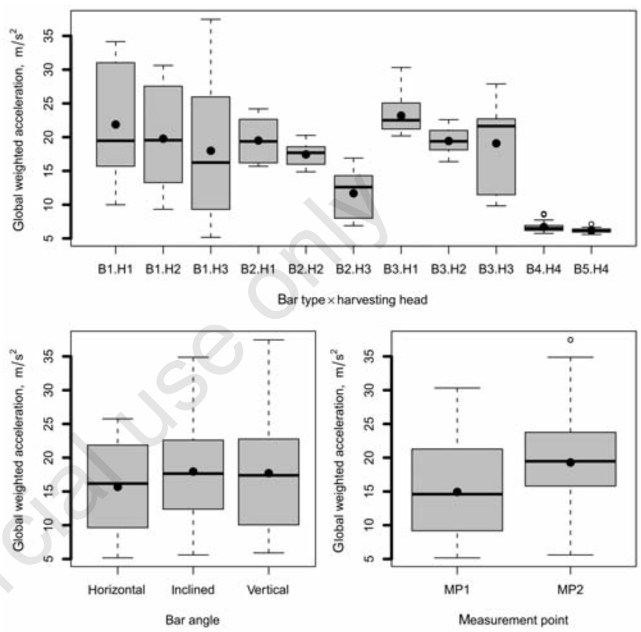

Figure 5. Box plot of global weighted acceleration at varying harvesting head, bar type, bar angle and measurement point; points represent mean values.

Table 2. Comparisons among the global weighted accelerations of the main factors.

	Mean, m/s^2	Median, m/s^2
Harvesting heads		
H1 + H2 + H3	18.9[a]	18.9[a]
H4	16.4[b]	16.3[b]
Measurement points		
MP1	14.9[b]	14.6[b]
MP2	19.3[a]	19.5[a]
Bar angles		
Horizontal	15.7 ns	16.2 ns
Inclined	17.9 ns	17.7 ns
Vertical	17.7 ns	17.4 ns
Bars B4 and B5		
B4-H4	6.7 ns	6.5 ns
B5-H4	6.2 ns	6.1 ns

Group separation by Kruskal-Wallis test for P-level=0.05. H, head; MP, measurement point; B, bar; ns, not significant; [a,b]values having a common letter are not significantly different at P-level=5%.

hand-harm system. The differences between the two aluminium bars (B1 *vs* B3) are instead not statistically significant.

The differences among the three harvesting heads are significant too: H1 produces the highest vibrations, H3 the lowest ones. The different disposition of the teeth with respect the motor shaft and the different oscillation plane can therefore affect the vibrations transmitted to the hand-harm system.

Finally, bar angles and measurement points confirm the results of the whole analysis: no statistically significant differences among the bar angles and higher vibration for the hand which holds the bar (MP2) with respect that near the handgrip (MP1).

The first order interaction among harvesting heads, bars and measurement points are reported in Table 3.

They show that the bar B2 (carbon fibre) presents, on average, the lowest acceleration, whatever harvesting head. Moreover, the bars with greater diameter (B2 and B3, 40 mm) produce higher vibrations in measurement point MP1, while that with smaller diameter (B1, 35 mm) in MP2. This could be related to the different stiffness of the two types of bar, which affects the acceleration transmission towards the measurement points. Finally, the harvesting head H3 presents the highest difference between the two measurement points: 9.9 m/s^2 in MP1 and 21.9 m/s^2 in MP2 (median values).

Field tests

Acceleration data were analysed separately to compare laboratory *vs* field tests for harvesting head H3 when used with the bars B1, B2 and B3. Being the bar angle not statistically significant, laboratory tests with different bar angles were treated as further replicates.

Comparing weighted global acceleration values for each bar type, measurement point, and test condition, the box plots reported in Figure 8 were obtained.

The differences among the three bars and between the two measurement points confirm the whole laboratory test results: the carbon fibre bar (B2) produces on average the lowest level of vibration [12.0 m/s^2 *vs* 25.2 (B1) and 21.6 (B3), median values] and the vibration level in MP2 is higher than that in MP1 (21.8 *vs* 12.0 m/s^2, median values). Moreover, the bar B2 presents a more constant acceleration level: in fact, global RMS values ranges from 6.9 up to 20.4 m/s^2 (CV=27%), against the 5.2-37.4 m/s^2 of B1 (CV=45%) and 9.8-32.6 m/s^2 of B3 (CV=29%). Finally, the difference between the

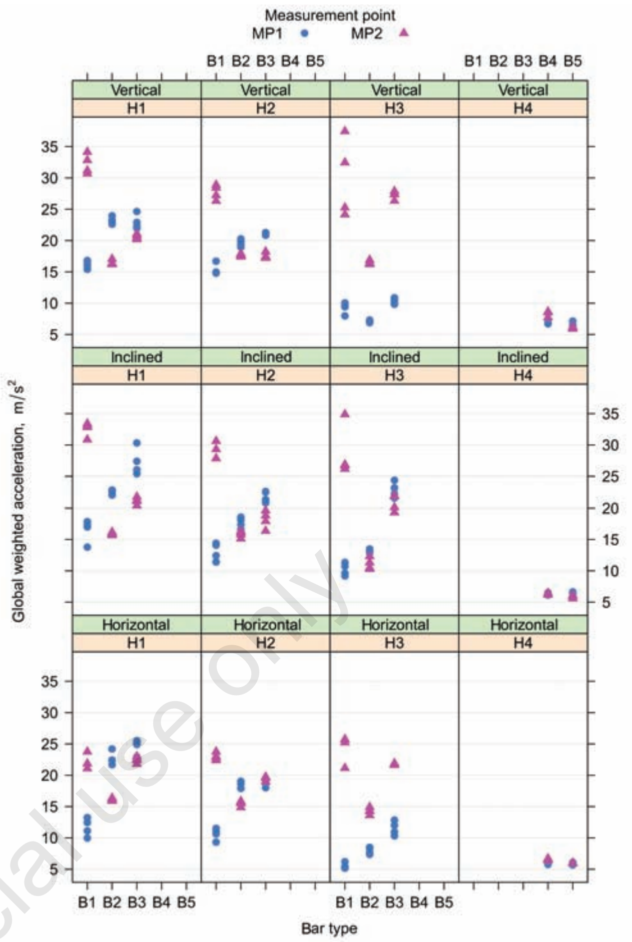

Figure 6. Global weighted acceleration values at varying harvesting head, bar type, bar angle and measurement point.

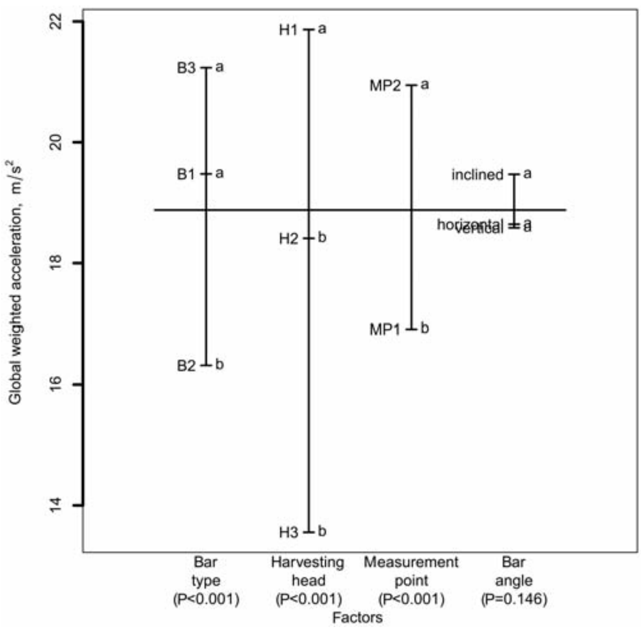

Figure 7. Plot design (median values) of the main factors related to bars B1, B2 and B3 and harvesting heads H1, H2 and H3 (group separation by Kruskal-Wallis test for P-level=0.05).

Table 3. First order interactions (median values, m/s^2).

	Harvesting heads		
Bars	**H1**	**H2**	**H3**
B1	19.5^{ab}	19.5^{a}	16.2^{ab}
B2	19.4^{b}	17.7^{b}	12.6^{b}
B3	22.5^{a}	19.4^{b}	21.6^{a}
	Bars		
Measurement points	**B1**	**B2**	**B3**
MP1	11.5^{b}	18.6^{a}	21.3^{a}
MP2	27.1^{a}	16.0^{b}	20.9^{a}
	Harvesting heads		
Measurement points	**H1**	**H2**	**H3**
MP1	22.5^{a}	18.3^{a}	9.9^{b}
MP2	21.1^{a}	18.5^{a}	21.9^{a}

Group separation by Kruskal-Wallis test for P-level=0.05. Comparisons among bars for each harvesting head and between measurement points for each bar and harvesting head. H, head; B, bar; MP, measurement point; ^{a,b,ab}values having a common letter are not significantly different at P-level=5%.

two aluminium bars B1 and B3 is not statistically significant.

Comparing laboratory and field tests, the global weighted acceleration values increase from 13.6 up to 18.4 m/s^2 (median values). This means that the tree canopy has on average a negative effect on the vibrations transmitted to the hand-arm system, mainly due to the bar B1. In fact, analysing the first order interactions (Figure 9), it emerges that only the bar B1 (aluminium, 35 mm diameter) shows a significant difference between laboratory and field test. On the other hand, the bar B3 (aluminium, 40 mm diameter), produces in field and in laboratory comparable acceleration values, but higher than those produced by the bar B2 (carbon fibre, 40 mm diameter). This leads to the conclusion that the bar material plays the most important role in reducing the acceleration values, whereas the bar diameter mainly affects the comparison between no load and harvesting running. When comparing the measurement points, it emerges that, in MP2, the acceleration values are similar in both test conditions, whereas in MP1 they are significantly lower during laboratory tests. Probably the tree canopy, differently from the no load running, interferes with the flap oscillations, causing a greater transmission of the vibrations to the other bar extremity (MP1). Finally, looking at the interaction measurement point × bar type, it emerges that the vibration level in MP2 is always greater than that measured in MP1 for each bar.

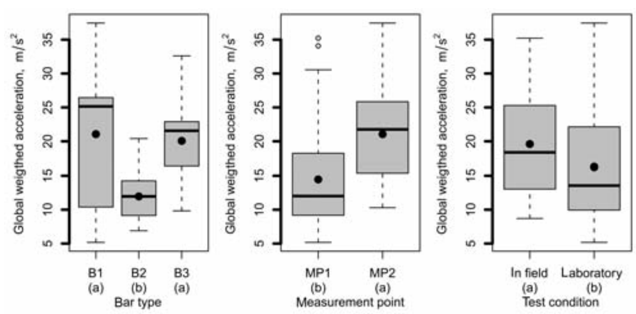

Figure 8. Global weighted accelerations values for each main factor; points represent mean values (group separation by Kruskal-Wallis test at P-level=0.05).

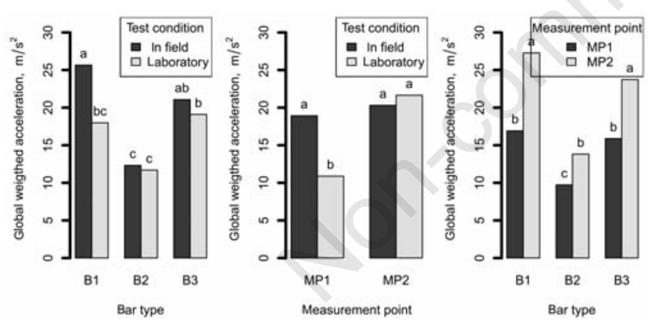

Figure 9. Global weighted accelerations for the first order interactions (median values, group separation by Kruskal-Wallis test at P-level=0.05).

Table 4. Global weighted acceleration values and signal length during the field tests.

Bar	MP1, m/s^2	Length, s	MP2, m/s^2	Length, s
B1	26.78	729	26.89	241
B2	10.56	418	13.74	602
B3	17.38	602	24.66	790

B, bar; MP, measurement point.

The global weighted acceleration values obtained by analysing the whole signal during the field tests are reported in Table 4.

They are little greater (from 0.7 up to 4.8%) than those obtained by averaging the 1 min sub-samples. In all cases, they are much higher than the daily limit value (2.5 m/s^2) and the daily action value (5.0 m/s^2) established by the European Directive 2002/44/EC (European Commission, 2002). Considering the acceleration levels in the MP2 measurement point (the most exposed), the daily exposure times should range from 0.1 to 0.3 h when A(8)=2.5 m/s^2 and from 0.3 to 1.1 h when A(8)=5.0 m/s^2. These times are clearly incompatible with the length of a standard work-day in agriculture (7 h), so the use of anti-vibrating gloves, despite their limited effectiveness, and the reduction of exposure times through rotating shifts of the operators during the working day, should be recommended.

Conclusions

The research activity has pointed out that global acceleration levels transmitted to the hand-arm system by the tested portable harvesters are quite high (about 20 m/s^2), much higher than the limit or action values established by the European Directive 2002/44/EC (European Commission, 2002).

The vibration level is mainly affected by the kinematic system rather than the power source type: by adopting a harvesting head with two arms in opposite oscillations, it can be significantly lowered to about 6 m/s^2. A significantly reduction in vibration levels can be also obtained by adopting carbon fibre bars rather than aluminium ones: keeping constant the bar diameter (40 mm), the average acceleration, in laboratory conditions, decreases from 21 to 16 m/s^2. However this result should be investigated more in depth as the carbon fibre can change its mechanic specifications due to its production process. In like manner, aluminium bars may change their mechanical features at varying alloy and thickness. Therefore other bars of other manufacturers should be tested. When comparing laboratory (no load) and field tests (harvest under ordinary working conditions), acceleration levels increase, due to both canopy effect and force exerted by the operator. The greater differences between laboratory and field tests arise when aluminium bars of small diameter are used. This implies that laboratory tests are needed to characterise materials and machines in standard and controlled conditions. In all cases, operators should take responsibility for occupational health and safety, take safety precautions to reduce continuous vibration exposures over long periods, and arrange the work organisation so to include vibration-free periods. In fact, beside the use of anti-vibratory gloves, the best protection against vibrations lies in adopting working practices aimed at prevention. This aspect, unlike for industrial environments, is often underestimated among farmers, due to the variability of the working conditions. Being the use of portable harvesters for drupe harvesting limited in time along the year, the harvest capacity is the main characteristic that influences the purchase, while health and safety aspects are often neglected.

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