Evaluation of the vibrations transmitted to the hand-arm system in the use of portable harvesters for olives

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Abstract: The use of portable harvesters in olives harvesting is presently widely diffused in Sicily, south Italy, both to reduce the costs of production and to assure the olive oil quality. Nevertheless, it's well known that the use of such tools may involve risk of exposure to vibration transmitted to the hand-arm system which is a potential cause of muscular/skeletal pains, and specific pathologies such as Hand-Arm Vibration Syndrome (HAVS), Vibration-Induced White Finger (VWF) and Carpal Tunnel Syndrome (CTS). The aim of this study was to assess the level of exposure to vibration transmitted to the hand-arm system of the operators during the use of portable harvesters for olives. Two different commonly used types of tools were evaluated performing both laboratory and field tests. One was a hook type harvester provided with an internal combustion engine; the other an electric portable harvester consisting of a bar ending with a comb, equipped with an electric motor. The daily action value established by the European Directive 2002/44/EC was always considerably exceeded by the two harvesters for both hands both in the laboratory and in the field tests; however, the electric comb showed A(8) values about halved with respect to the hook type, equal to 20.79 and 18.69 m s^{-2} respectively for right and left hand in the field tests against 42.07 and 30.03 m s^{-2} obtained with the hook type harvester.

Keywords: acceleration, daily exposure, mechanization, *Oleaeuropaea* L., safety

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1 Introduction

Mechanical harvesting of olives is a very important aspect in olive growing both to reduce the costs of production and to assure oil quality (Testa et al., 2014). Manual harvest indeed does not allow to operate at the right time. Moreover it is time-consuming and requires intensive labour (Bodria et al., 2013). In olive oil production, where poor harvesting efficiency is probably one of the worst hidden costs, mechanized techniques have led to significant efficiency increase (Vieri and Sarri, 2010; Castillo-Ruiz et al., 2015). In such context, hand-held harvesting units detaching the drupe through vibration are frequently used. Famiani et al. (2014) studied different kinds of machine-aided systems to harvest fruit from very large olive trees and hand-held pneumatic combs among these, obtaining a good performance in terms of harvest yield.

The hook type and flat type portable harvesters are the most popular tools due to their adaptability to be used in olive tree orchards grown in sloped areas, where the trunk shaker can't be used. Trunk shakers in fact have become widespread in traditional olive tree orchards, considering that their efficiency depends on the olive fruit properties, tree structure and operating parameters of the machine (Blanco-Roldan et al., 2009). However, many orchards in Italy do not support the introduction of the trunk shaker generally coupled to a wheeled tractor, because of the sloped or irregular soils, irregular shaped trees, asymmetrical branches or for the inadequate distance between the plants (Leone et al., 2015). These are the main reasons for the spread of portable olives harvesters in all the Mediterranean countries. In Italy

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442,000 tons of virgin olive oil were produced in 2013, being the second world producer after Spain (FAO, 2015).

Hand-held olives harvesters detach the drupes through vibration and the workers could be consequently exposed to high levels of hand-arm vibrations that can lead to the HAVS, a vasospastic and neurodegenerative occupational disease whose major symptom is the Raynaud syndrome, or VWF causing pain within the affected extremities, discoloration (paleness), and sensations of cold and/or numbness (Pattnaik et al., 2012). Another specific pathology as the CTS may be correlated to the risk of exposure to vibration transmitted to the hand-arm system (Gerhardsson et al., 2005; Bovenzi et al., 2015). Costa et al. (2013) verified that only a small fraction (12%) of the workers exposed to HAVS perceived a whitening of the fingers during the workday but a much larger fraction (82%) reported feeling numbness at the hands when using portable harvesters for olives.

The vibration level transmitted to the hand-arm system by portable harvesters equipped with combustion engine in standard operative conditions was measured by Pascuzzi et al. (2009) who obtained values overcoming the daily eight hours exposure limit value of 5 m s^{-2}, established by the European Directive 2002/44/EC. The vibrations transmitted to the hand-arm system by hook type olive harvesters were also evaluated in Saraçoğlu et al. (2011) both in idling and in operating conditions, obtaining finger blanching in 10% of the exposed workers after less than 0.63 year of use; these authors suggest a new arrangment of work schedules to include vibration-free periods.

Flat type olive harvesters equipped with electric motor have been diffused in Italy because of their light weight respect to the hook type, which are generally driven by a little two-stroke engine. The vibration characteristics of flat type olive harvesters where studied by Çakmak et al. (2011) at both idling and full load conditions. Also Calvo et al. (2014) analyzed the vibrational behavior of different electric beaters for olive harvesting and discussed the consequences of their use on the operators, underlining that workers often passively accept to have a tingling sensation in the fingers at the end of the olive harvesting daily work. They conclude that physical risks, as vibration of hand-arm system, are still little known in the Italian olive growing sector where operators are exposed to HAVS with a large amount of hand-held machines (*e.g.* brush cutters, pneumatic shears, hand guided cultivators) during all the year long.

Furthermore, one of the main issue is represented by the absence of a C type European standard to measure vibration data for hand-held olive harvesters; this is why manufacturers are not able to give reliable data and useful information to the final users. Deboli et al. (2014a) implemented a test methodology to fill this gap through a prototype device to simulate the vibration response of the olive tree branches in order to repeat the acceleration measures of hand-held olive harvesters. An innovative system aimed at estimating the exposure of the hand-arm system to vibration, according to the Standard ISO 5349-1(2004), based on Micro Electro-Mechanical Systems (MEMS) technology was developed by Aiello et al. (2012) who designed a compact wearable unit to be attached to the waist of the operator and a fixed station for data storage and analysis.

The objective of this study was to assess the level of exposure to hand-arm vibration of the operators during the use of two commonly used portable harvesters for olives: a hook tool equipped with a combustion engine and a teeth tool provided with an electric motor.

2 Materials and methods

2.1 Portable harvesters for olives used in the tests

Two widespread portable tools for olives harvesting were examined: Cifarelli SC800, named A, and PellencOlivion P230, named B (Figure 1) whose technical features are given in Table 1. Both of them have been in use for a period of one year in the same operative conditions before carrying out the tests. The first one is provided with an internal combustion engine; it consists of a bar ending with a hook which transmits the vibrations induced by the machine to the tree branch. The second one is an electric portable harvester, consisting of a bar ending with a comb with eight teeth in carbon fibers, representing the harvesting head; the drupes detachment is obtained by means of the direct impact of the teeth on the canopy.

A. Cifarelli SC800

B. Pellenc Olivion P230

Figure 1 Portable harvesters for olives used in the tests

Table 1 Harvesters technical features

	A	B
Engine	Cifarelli C5	Electric
Engine displacement, cm^3	52	-
Strokes, n	2	-
Cooling	air	-
Power, W	2400	380
Tank capacity, L	1.7	-
Lithium-ion battery, V	-	12
Mass, kg	14.9	2.5
Length of the bar, mm	2000	2300
Stroke of the bar, mm	60.2	-
Hook width, mm	40.5	-
Rake width, mm	-	380
Working frequency, rpm	2000	840

2.2 Vibration measurements

A basicentric coordinate system was used for the vibration measurements, according to ISO 5349-1 (2004) regulation: y_h axis parallel to the axis of the handle; x_h perpendicular to the axis of the handle oriented by the back towards the palm of the hand and, at last, the z_h axis perpendicular to the plan formed by the two previous axes as shown in Figure 2.

Accelerations were measured by using the portable vibrometer HD2070 (Delta OHM, Italy) (Figure 3), a four channel vibration analyzer applying the FFT (Fast Fourier Transform) and the 1/3 octave analysis according to ISO 5349-1 (2004) and ISO 5349-2 (2004) regulations. The frequency weighted root mean square accelerations were evaluated for each axis and the vibration total value a_{hv}, expressed in m s^{-2}, was obtained in equation (1):

$$a_{hv} = \sqrt{a_{hwx}^2 + a_{hwy}^2 + a_{hwz}^2} \quad (1)$$

where, a_{hwx}, a_{hwy} and a_{hwz} are the frequency-weighted acceleration values for the single axes. The equivalent vibration total value related to 8 work hours A (8) (for equation (2)) was also determined (European Directive 2002/44/EC):

$$A(8) = a_{hv}\sqrt{\frac{T}{T_0}} \quad (2)$$

where, T is the total daily duration of the exposure in seconds, that was assumed equal to 4 hours (14,400 s), and T_0 is the reference duration of 8 hours (28,800 s). The exposure time was assumed to be 4 hours, considering a 7 hours working day with 3 hours used to position the nets and to recover the fruits.

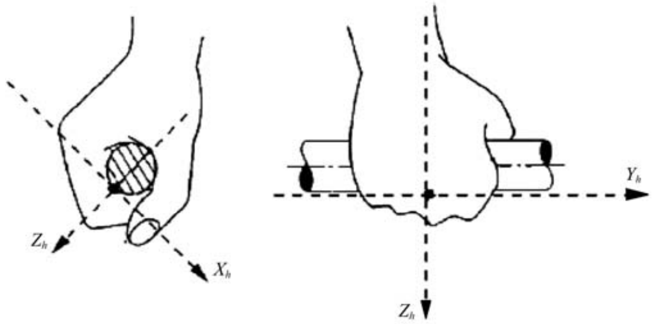


Figure 2 Basicentric coordinate system

Figure 3 HD2070 vibrometer used in the tests

The vibrometer is provided with a 10 mV $m^{-1}\cdot s^2$ triaxial accelerometer with an adapter in compliance with the standards (model HD2030 AC4 by Delta OHM, Italy) placed between the hand and the handle; the accelerometer was fixed in a central position between middle and ring finger (Figure 4).

Figure 4 Triaxial accelerometer and its adapter used in the tests

The measurement points were positioned at the grip level for both hands of the operator in standard working conditions for harvester A. For harvester B, they were placed near the hand grip and 1 m far from the start of the bar.

2.3 Experimental tests and statistical analysis

The tests involved real-time data acquisition and processing of vibrations transmitted to the hand-arm system during the use of the two tools by the same operator (1.80 m tall, 80 kg weight, right-handed operator).

Two test conditions were realized, recording acceleration data both for right and left hand not simultaneously: laboratory and field tests. The first one was realized at the maximum engine speed in idling conditions without that the hook or the comb were in contact with any type of object, with the rod positioned at an angle of 45° to the horizontal plane. The field tests were performed in an olive grove located inside the Department of Agricultural and Forest Science of the University of Palermo (38°06'N and 13°20'E, 48 m above sea level). Each test was performed in triplicate and the measurement time was 60 s.

A factorial experiment consisting of three factors was organized to evaluate eventual significant differences between the two harvesters in terms of the vibrations transmitted to the hand-arm system. The factors we considered were: “Hand”, “Axis”, “Harvester” and “Test”. The “Test” factor has the objective of evaluating the effect of external factors that can affect the transmitted vibrations and consists of two levels: laboratory and field tests; the “Hand” factor is featured by two levels (left and right) referred to the operator’s hand; the “Axis” factor considers the three levels X, Y and Z of the basicentric coordinate system. The “Harvester” factor is represented by the two harvesters. Overall, we considered a 3×2×2×3×2 factorial experiment consisting of 72 observations of the vibration level recorded in the different combinations of the factors. We wanted to assess whether there were significant differences in the mean vibrations values transmitted by the two harvesters to the hand-arm system for both hands on the three axes. The most appropriate analysis of variance model is a crossed analysis of variance (ANOVA).

3 Results and discussion

3.1 Frequency-weighted acceleration values for the three axes and vibration total values

Frequency-weighted acceleration values (mean ± standard deviation) measured for the two harvesters in X, Y and Z axes during lab and field tests are reported in Table 2 ($a_{hwx,y,z}$) together with vibration total values (a_{hv}) according to Equation (1). The prerequisites for ANOVA application (independence of errors, random distributions and equal variances applying the Bartlett test) were satisfied.

When tested in laboratory, harvester A showed higher coefficients of variation (CV) than harvester B on X, Y and Z axes on average in both hands (only for the right hand on Y axis harvester B showed a higher variability respect to harvester A). In the field tests, harvester A gave mean vibrations higher than harvester B in the X and Y axes for left hand and in Z axis in right hand. Regarding the vibration total values, harvester A showed greater mean accelerations compared to B but with a minor variability registered in the three replicates. Again, when tested in the field, X and Y axes on the left hand, and Y and Z axes on the right hand, showed the most evident differences in the mean accelerations between the two harvesters. The highest variability was obtained for harvester A, both in the field and in the laboratory tests, denoting a higher variability in the vibration levels recorded in the three tests.

Table 2 Descriptive statistics for accelerations data measured in all the test conditions

$a_{hwx,y,z}$, m s^{-2}		Lab test				Field test			
		Harvester A		Harvester B		Harvester A		Harvester B#	
		Left hand	Right hand	Left hand	Right hand	Left hand	Right hand	Left hand	Right hand
a_{hwx}	Mean#	11.43#	19.63#	25.23#	24.20#	31.77#	25.47#	24.73#	29.23#
	CV#	0.45#	0.26#	0.07#	0.05#	0.17#	0.23#	0.12#	0.15#
a_{hwy}	Mean#	19.47#	57.50#	1.45#	1.77	25.73#	51.57#	3.18#	2.05#
	CV#	0.17#	0.16#	0.10#	0.25#	0.26#	0.10	0.20#	0.12#
a_{hwz}	Mean#	13.27#	9.72#	6.38#	2.56#	8.46#	15.07#	8.78#	3.10#
	CV#	0.21	0.13#	0.09#	0.08#	0.56#	0.07#	0.04#	0.04
a_{hv}	Mean#	26.30#	61.73#	26.03#	24.37#	42.47#	59.50#	26.43#	29.40#
	CV#	0.22#	0.13#	0.06#	0.05#	0.04#	0.12#	0.10#	0.15

The ANOVA results are reported in Table 3. We evaluated the existence of significant effects on the fixed factors Harvester, Hand, Axis and Test and their interactions. The results are highly significant both for fixed and conditioned effects. Hand and Harvester interactions with Test are not significant, meaning no significance of the mean vibration recorded on the two hands between field and laboratory condition. We can affirm that the two harvesters do not lead to different results if we consider the mean vibration measured for each of them in field and laboratory tests. The other interaction effects are significant.

Table 3 Crossed ANOVA results on the frequency-weighted acceleration values for all factors and their interactions

Source	Partial	df	MS	F	P>F
Model	15541.34	23	675.71	45.52	0.00
Hand	480.40	1	480.40	32.36	0.00
Test	166.71	1	166.71	11.23	0.00
Axis	3176.11	2	1588.06	106.98	0.00
Harvester	3058.14	1	3058.14	206.01	0.00
Harvester×Axis	5248.22	2	2624.11	176.77	0.00
Hand×Harvester	715.68	1	715.68	48.21	0.00
Hand×Test	25.63	1	25.63	1.73	0.20
Harvester×Test	38.57	1	38.57	2.60	0.11
Hand×Harvester×Test	44.09	1	44.09	2.97	0.09
Hand×Harvester×Axis×Test	2587.78	12	215.65	14.53	0.00
Residual	712.54	48	14.84		
Total	16253.881	71	228.92791		

Note: R^2=0.96; R_{Adj}^2=0.94; Root MSE = 3.85.

The predicted marginal mean vibrations for the different levels of the fixed factors Axis, Harvester and Hand are shown in Figure 5 both for field and laboratory tests. The three levels of Axis factor (X, Y and Z) are significantly different; field and lab tests show overlapping results except for X axis where vibrations measured during the lab tests are lower than those measured in the field as indeed emerged from the descriptive statistics (Table 2). The mean vibrations transmitted to the hand-arm system by the two harvesters are significantly different (B lower than A). Harvester B shows no differences between field and lab tests while harvester A gave a significantly lower vibration mean value in the lab tests. With reference to the Hand fixed effect, we obtained significant differences between field and lab tests for the left hand while no differences were obtained for the right hand.

Significant differences were found between the two harvesters on the right hand in Y and Z axes (Figure 6) with harvester A showing acceleration values higher than B. In particular, the two machines show a very different behavior in the Y axis for both hands. On the contrary, no differences were found on the X axis for both hands.

Figure 7 points out the presence of significant differences between the levels of the factors Axis-Hand-Test in the two harvesters. It shows the different level of vibrations of the harvesters in the Y axis for both hands in the two test conditions and the significantly higher accelerations transmitted by the harvester A respect to B.

The maximum vibration intensity was obtained on the right hand in the Y direction both in the lab (57.50 m s^{-2}) and in the field test (51.57 m s^{-2}) for harvester A, the hook type. This is explained by the design characteristics of the machine; in fact, the operator grasps the right handle so that the Y axis corresponds to the vibrating rod during harvest and furthermore it is not equipped with damper. Similar results were obtained in Saraçoğlu et al. (2011) where the same harvester was tried in field test (a_{hwy} = 61.01 m s^{-2}). They also obtained the Z axis being the less stressed with a_{hwz} equal to 14.27 m s^{-2} in the left hand and 12.09 m s^{-2} in the right one, very close to those measured in the present study. Also Pascuzzi et al. (2009) obtained acceleration values on the Z axis a third lower than X and Y on the right hand.

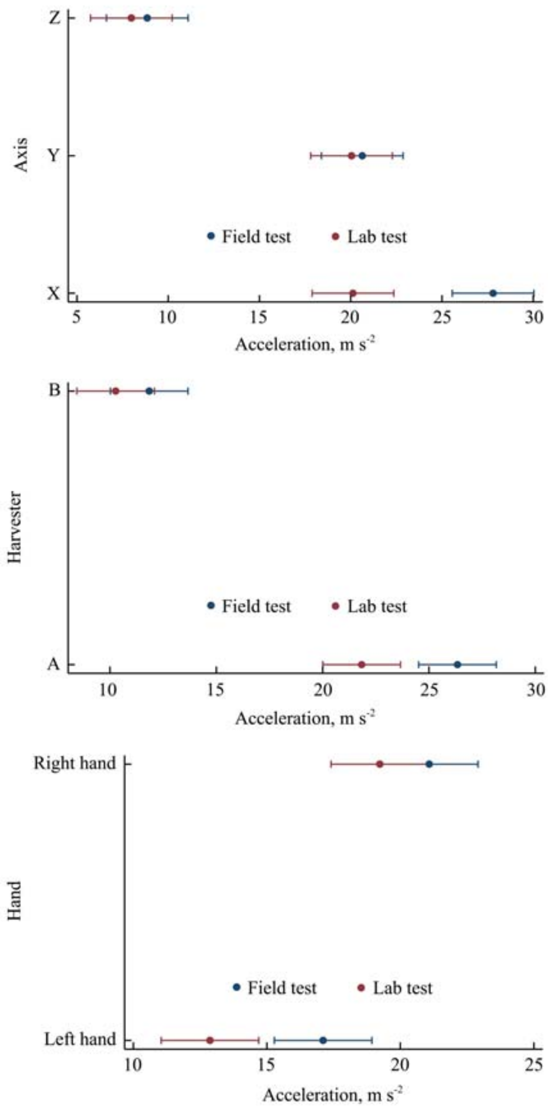


Figure 5 Axis, Harvester, Hand mean frequency-weighted acceleration values for the Test factor

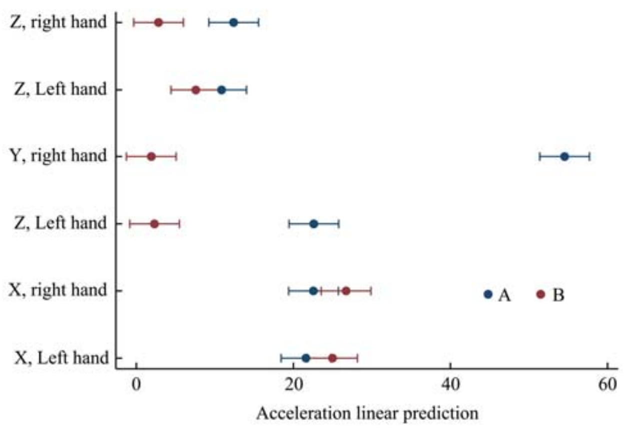


Figure 6 Mean frequency-weighted acceleration values for the different levels of Axis-Hand and Harvester factors

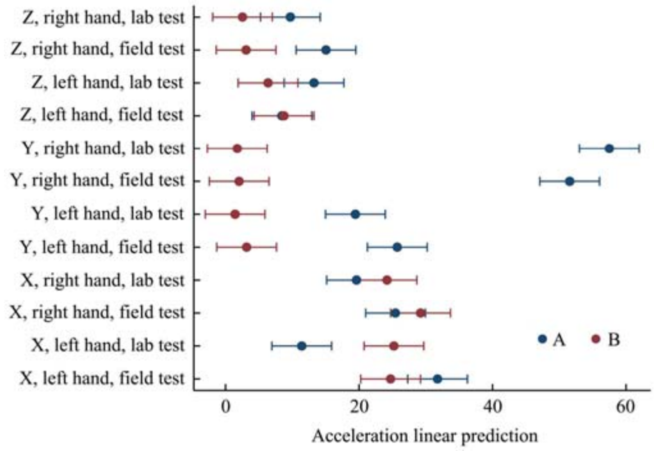


Figure 7 Mean marginal frequency-weighted acceleration values for the different levels of Axis- Hand-Test in the two harvesters

With reference to the second type of harvester, the comb model, considerations can be drawn according to Çakmak et al. (2011). They obtained that the most stressed direction was the X axis in the left hand, with a value of 31.04 m s^{-2}, comparable to the value of 24.73 m s^{-2} we measured in loading condition for the same type of tool.

We also performed a crossed ANOVA (Table 4) on the vibration total values shown in Table 2.

Table 4 Crossed ANOVA results on the vibration total values

Source	Partial	df	MS	F	P>F
Model	5134.92	7	733.56	32.50	0.00
Hand	1084.07	1	1084.07	48.03	0.00
Test	140.65	1	140.65	6.23	0.02
Harvester	2631.32	1	2631.32	116.58	0.00
Test×Harvester	27.09	1	27.09	1.20	0.29
Hand×Harvester	981.76	1	981.76	43.50	0.00
Test×Hand×Harvester	270.02	2	135.01	5.98	0.01
Residual	361.13	16	22.57		
Total	5496.05	23	238.96		

Note: R^2=0.93; R_{Adj}^2=0.91; Root MSE = 4.75.

The fixed effects Hand, Test and Harvester are significant, indicating statistically significant differences between the conditioned means on varying the factors levels. The interaction effects between Hand and Harvester and between Hand, Harvester and Test are significant. The effect between Test and Harvester is not significant showing no difference in the total vibration for the two harvesters in the field and lab tests. Figure 8 shows these results.

The vibration total value hides the effect of the single axle acceleration but allows to consider the overall effect of the use of such equipment on the operators and also leads to evaluate the acceptability of their use considering the limit established by the European Directive 2002/44/EC for the daily action value. In particular, in our study the vibration total value allows to compare the two types of harvesters examined. It should be emphasized their different behavior especially in the field tests, where significant differences were found between the two types in both hands. Moreover, the a_{hv} values obtained for harvester A are overlapping to those reported in Saraçoğlu et al. (2011); concerning harvester B tested in the field, the vibration total values for the right hand (29.40 m s^{-2}) was similar to that obtained by Çakmak et al. (2011) (22.50 m s^{-2}) and the same is for the left hand. Deboli et al. (2014b) obtained vibration total values in the range 11.6-17.2 m s^{-2} for a rotary comb type harvester.

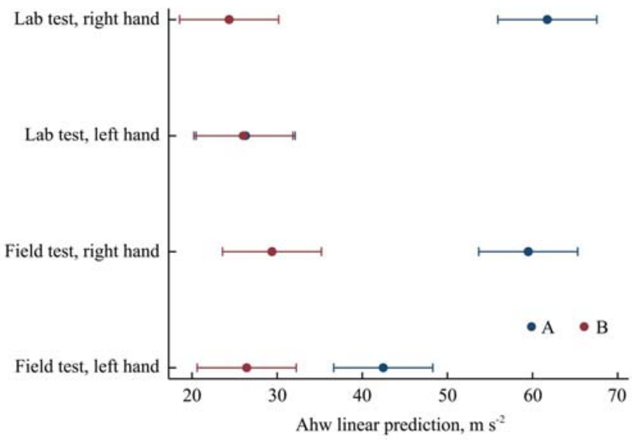


Figure 8 Vibration total values for the different levels of Test-Hand and Harvester factors

The daily action value established by European Directive 2002/44/EC (5.0 m s^{-2}) was considerably exceeded by the two harvesters for both hands (Table 5). The highest equivalent vibration total value related to 8 work hours A (8) was obtained in the right hand by harvester A (43.65 m s^{-2}) during lab tests, being about 2.5 fold higher than B (17.23 m s^{-2}); in the left hand the A (8) values obtained by the two machines were similar. Harvester A showed an A (8) right hand value about 2.3 times higher than left hand; harvester B gave very similar A (8) values in both hands. Similar considerations can be taken with reference to the field tests, wherethe highest A (8) value was obtained again by harvester A (42.07 m s^{-2}) in the right hand.

Table 5 Equivalent vibration total values related to 8 work hours [A(8) (m s^{-2})] for both harvesters and both hands during laboratory and field tests

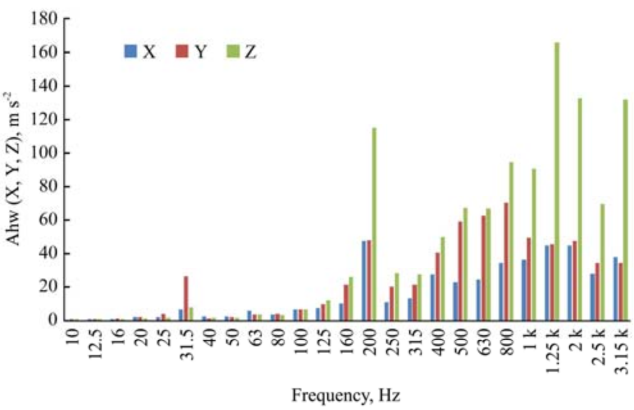
	Lab tests		Field tests	
	Right hand	Left hand	Right hand	Left hand
A	43.65 ± 5.62	18.60 ± 4.10	42.07 ± 4.96	30.03 ± 1.18
B	17.23 ± 0.89	18.41 ± 1.19	20.79 ± 3.18	18.69 ± 1.88

Note: data are reported as means ± standard deviations of three replicates.

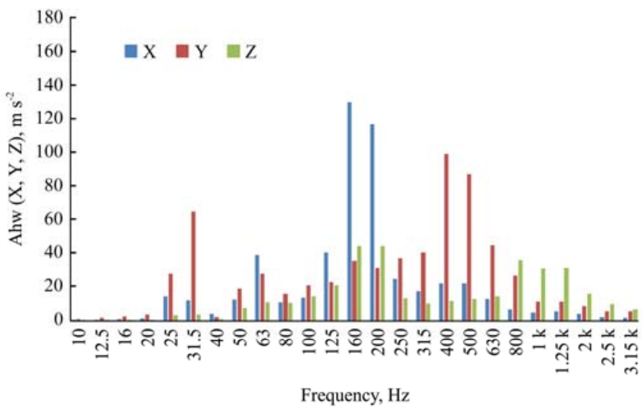
The results are very alarming both for the two types if compared to the daily action values of 5.0 m s^{-2}. In the best of the conditions reported (harvester B, right hand, lab test), the legal limit is exceeded three times as verified by other authors (Calvo et al., 2014; Manetto and Cerruto, 2013; Pascuzzi et al., 2009). The problem directly connected to these results is the occurrence of serious occupational diseases as HAVS, VWF and CTS considering that the operators exposed to high vibrational levels have misperception of the effects of the risk they are exposed to (Costa et al., 2013).

3.2 Frequency analyses for 1/3 octave bandwidth of the vibrations measured

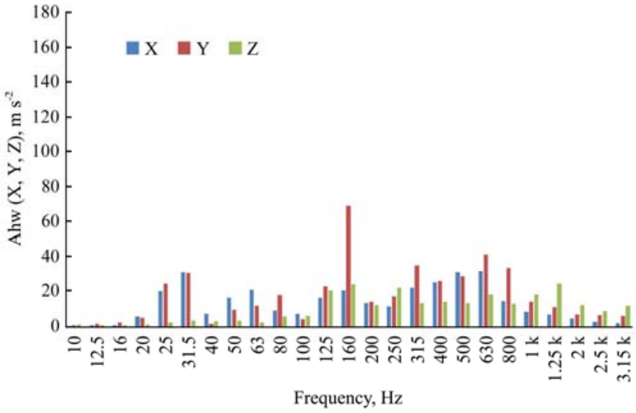
The frequency analyses for 1/3 octave bandwidth of the vibrations measured are reported in Figures 9 and 10 for both harvesters as bar diagrams.



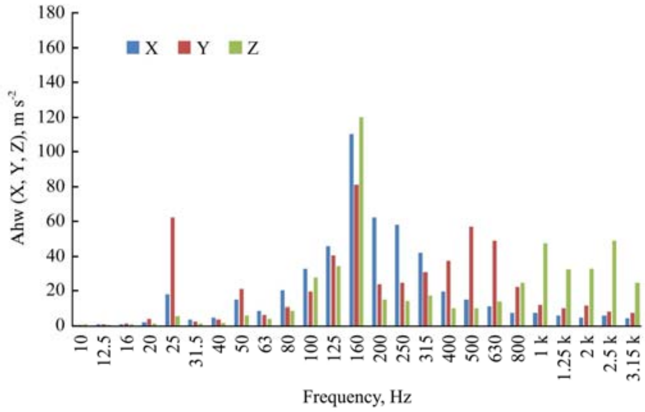
a. Llab test, left hand



b. Lab test, right hand

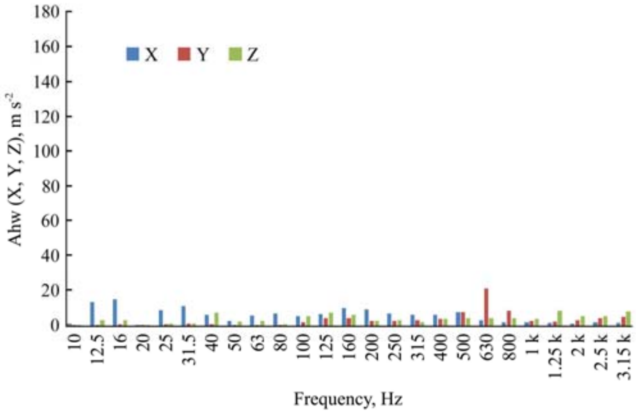


c. Field test, left hand

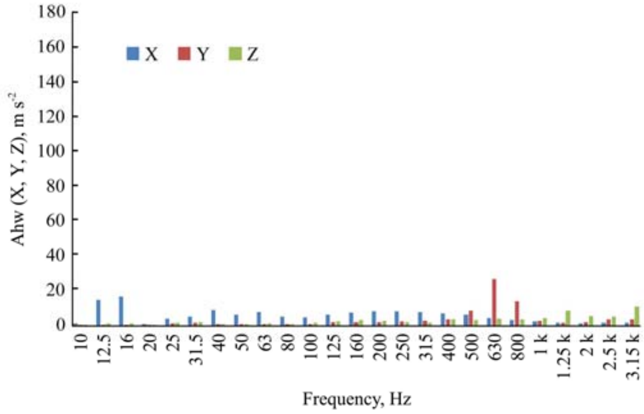


d. Field test, right hand

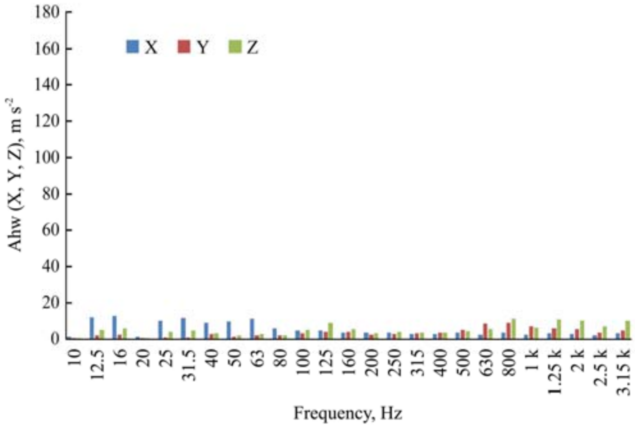
Figure 9 Frequency spectrum of vibrations for harvester A for X, Y and Z axes



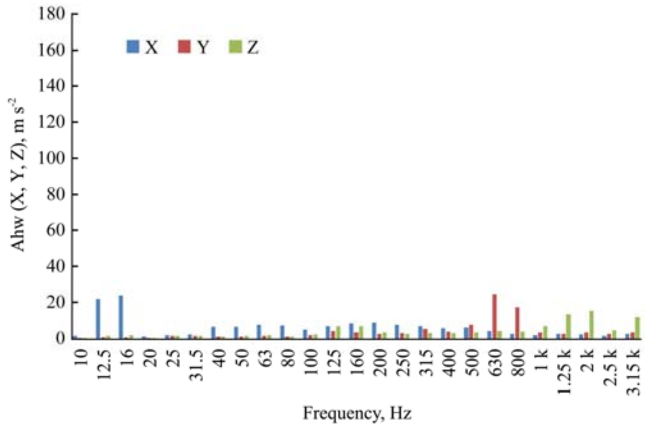
a. Llab test, left hand



b. Lab test, right hand



c. Field test, left hand



d. Field test, right hand

Figure 10 Frequency spectrum of vibrations for harvester B for for X, Y and Z axes

The two harvesters' behavior is very dissimilar; remarkable results were obtained for harvester A with a very intense vibrating system in the frequency range 100-1250 Hz for the right hand. For harvester B the highest acceleration values were measured in the frequency range 600-800 Hz.

4 Conclusions

The vibration level transmitted to the hand-arm system by portable harvesters in olive growing is a considerable problem for the operators' health in the agricultural sector as it can be related to the onset of the HAVS.

The experimental tests presented in this study confirm what other authors obtained investigating the exposure of the hand-arm system to vibration in olives harvesting with portable harvesters.

The findings of this study can be summarized as follows:

- for the hook type harvester, the maximum vibration intensity was obtained on the right hand in the Y direction;
- for the comb harvester, the most stressed direction was the X axis;
- the two harvesters show a different behavior in the Y axis for both hands, with the hook type values always significantly higher than the comb type ones;
- the Z axis is the less stressed direction for both harvesters and test conditions;
- vibration total values for the hook type are significantly higher than the comb type ones in the field tests;
- the daily action value established by European Directive 2002/44/EC was considerably exceeded by the two harvesters for both hands and test conditions.

Some good practices can be suggested to reduce the risk of acquiring occupational diseases associated the HAVS, such as using antivibrating gloves, reducing the time of exposure through the operators' rotation during the working day, acquiring knowledge through appropriate training courses.

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