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RESEARCH ARTICLE

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# Vibration parameters assessment to develop a continuous lateral canopy shaker for mechanical harvesting of traditional olive trees

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## Abstract

The fruit harvesting is a key factor involving both product quality and profitability. Particularly, mechanical harvesting of traditional oil olive orchards is hint by tree training system for manual harvesting, tree size and several and slanted trunks which makes difficult trunk shaker work. Therefore, canopy shaker technology could be a feasible alternative to develop an integral harvester able to work on irregular canopies. The aim of this research was to determine vibration parameters applied to the olive tree for efficient mechanical harvesting by canopy shaker measuring fruit removal efficiency and debris. In this work, a continuous lateral canopy shaker harvester has been developed and tested on large olive trees in order to analyse the operating harvester parameters and tree properties to improve mutual adaptation. Vibration amplitude and frequency, rod density and ground speed were assessed. Vibration amplitude and frequency beside ground speed were decisive factors on fruit removal efficiency. Increasing rod density has not influenced on removal efficiency although it increased significantly debris. Promising results has been reached with 77.3% of removal efficiency, applying a 28 s shaking duration, 0.17 m amplitude vibration and 12 rod drum. This result was obtained reporting 0.26 s of accumulative shaking time over 200 m/s$^2$ resultant acceleration. The canopy shaker mechanism enabled more than 65% of detached fruits to fall vertically, facilitating catch fruit. In order to improve removal efficiency it is advisable to adapt trees, set high amplitude in the shaker mechanism, and enhance the contact time between rods and tree.

**Additional key words**: *Olea europaea* L.; fruit detachment; integral harvester; frequency; amplitude; removal efficiency.

**Authors' contributions:** Conceived and designed the experiments: RRSG, FJJ, FJCR and GLBR. Performed the experiments: RRSG, FJJ, FJCR and GLBR. Analyzed the data: RRSG, FJJ and FJCR. Contributed analysis tools: SCG and JAGR. Wrote the paper: RRSG, FJJ, FJCR and SCG. Obtaining funding, administrative and technical coordination of the research project: JAGR and GLBR.

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## Introduction

New orchard designs are replacing traditional plantations in a number of crops that are typically rainfed, such as almond [*Prunus dulcis* (Mill.) DA Webb], pistachio (*Pistacia vera* L.) and olive (*Olea europaea* L.), in order to reduce associated production costs. Traditional plantations are characterized by having trees that are old, large, widely-spaced (Ramos & Santos, 2010) and usually with low production levels (Pergola *et al*., 2013). The main advantage that modern plantations offer is that they allow for the mechanization of certain operations, particularly fruit harvesting. Nevertheless, traditional plantations are widespread globally and play an important social and environmental role, which makes it difficult or unfeasible to substantially change these plantations or even eliminate them entirely. Particularly notable in this respect is olive cultivation in the Mediterranean basin, where 97% of world production is concentrated. More specifically, in Spain, which is home to more than 50% of world olive oil production (AICA, 2014), there are 2,420,000 ha of olive crop, and traditional plantations

represent 74% of this total (ESYRCE, 2013). The economic viability of these plantations depends not only on their current profitability, but also on other factors (Gómez-Limón & Riesgo, 2010). Among the design factors, of particular note are the existing range of structures and types of plantations, depending on the available irrigation, planting density, number of trunks per tree, slope of the terrain, and so on (Wiesman, 2009). Other factors, such as a poorly managed production process, low rates of intergenerational transfer, the dispersal of the plantations, the emergence of more profitable, modern plantations and the impact of agricultural policies (Beltrán-Esteve, 2013) all have a significant impact on traditional plantations. As a result, production costs in traditional plantations (AEMO, 2012) are very high (2.02-2.3 €/kg oil) compared to the cost in modern plantations (1.32-1.73 €/kg oil).

To make traditional plantations more profitable, production costs need to be reduced. In traditional olive plantations, the main production cost is harvesting, which can represent more than 40% of the total (Barranco *et al*., 2010). Olive harvesting can be carried out with a number of different, compatible technical methods (Famiani *et al*., 2014). Traditional olive harvesting is done by hand, combined with the use of hand-held harvesting systems (Sola-Guirado *et al*., 2014) or with mass harvesting systems, typically trunk shakers or rarely canopy shakers (Ferguson, 2006). All these harvesting technologies have limitations in that they do not work continuously and require high working times per tree.

There is a need for technological change in the mechanical harvesting of traditional plantations as it is not possible to use an integral harvester without making major changes to the plantations. However, it should also be noted that in many production areas, integral harvesters cannot be used due to steeply sloping terrain or for reasons relating to fruit quality, the small size of the cultivation area or tradition (Vieri & Sarri, 2010). In this regard, canopy shaker technology could prove to be a feasible alternative for carrying out continuous fruit removal with simultaneous collection (Ravetti & Robb, 2010).

A number of canopy shaker systems have been developed which simulate the traditional method of beating canopies with sticks through the use of a range of mechanisms (Peterson, 1998). Nevertheless, the most widely-used systems are the over-row canopy harvesters, although they require trees with their trunks aligned in continuous hedgerow canopies. Less well developed are the lateral canopy shakers which can operate on one side of the tree and that can be used in the harvesting of citrus (Brown, 2005), jatropha (Hong *et al*., 2012), blackberries (Takeda & Peterson, 1999), or olives (Castro-Garcia *et al*., 2009). However, although these systems provide an interesting alternative for use in traditional plantations, the fact that they are not designed for nor adapted to the specific attributes of traditional plantations limits their application. Moreover, the majority of them do not allow collect the removal fruit. Previous results have shown the feasibility of removal and collected olive fruits simultaneously with a mechanism provided of an alternative and crossing movement between the rods beating (Sola-Guirado *et al*., 2014). However, it is necessary to adjust the main operating parameter of the mechanism (frequency, amplitude, speed ground, and rod density) (Sumner *et al*., 1975). A simultaneous adaptation of the machine and the crop is required for these systems in order to be effectively employed (Gil-Ribes *et al*., 2014).

The aim of this research was the study of the main vibration parameters applied to the olive tree for efficient mechanical harvesting by lateral continuous canopy shaker. For this, it has been developed an experimental harvester based on canopy shaker technology with a catch frame for use in traditional oil olive plantations. In addition, parameters such as the location of the removal fruits on the catch frame and the non-detached fruits on tree, the damage caused to the tree and the ground speed were considered in the analysis.

## Material and methods

The mechanical harvesting trials were carried out in a traditional olive plantation located in Cordoba (lat: 37° 43' 10.09" N, long: 4° 48' 29.98" W), southern Spain. Field tests were conducted in December 2013, under similar weather conditions and with similar fruit ripeness, in a traditional rainfed commercial olive orchard of the 'Hojiblanca' cultivar. Trees were over 100 years old, in good physiological health and with an orchard density of 80 tree/ha in a quincunx planting pattern with irregular canopy shape. Each tree had several trunks and was traditionally trained for manual harvesting. Trees showed a mean canopy volume of 81.41 ± 21.16 $m^3$/tree with a mean fruit production of 64.62 ± 27.25 kg/tree. The mean value of fresh fruit weight was 3.67 ± 0.76 g and detachment force was 3.95 ± 0.95 N. The tests were carried out with the machine making contact with the trees on their exterior branches.

A canopy shaker prototype with adjustable operating parameters was designed and developed (Fig. 1). The shaking system was based on a slider-crank mechanism with high amplitude of movement (from 0.12 to 0.17 m) capable of reaching excitation frequencies ranging between 0.5 y 6 Hz in its six beating drums (Fig. 2). The shaking system was made up of six iden-

tical cranks, offset 120º and moved by a main crankshaft powered by a hydraulic engine of 200 $cm^3$, 34 kW and 58 Nm. Each crank moved one drum on a slider via a connecting rod. Connecting rods were designed with a length of 1.72 m in order to get acceleration values in the drums following a sinusoidal movement. Each drum had up to 24 rods in a radial arrangement, which were responsible for transmitting the movement from the machine to the tree branches. Rods were designed with high values of stiffness and natural frequencies in order to make an effective impact on the tree canopy. In order to reach most of the fruit located on the canopy exterior, the rods were designed to be 1.4 m long. Each drum featured a free rotation movement which allowed continuous collection around the tree. Drums were spaced 0.4 m apart vertically and the lowest drum was set 1 m off the ground, which allowed a catch frame to be attached.

**Figure 1.** Prototype of lateral canopy shaker harvesting a traditional olive tree.

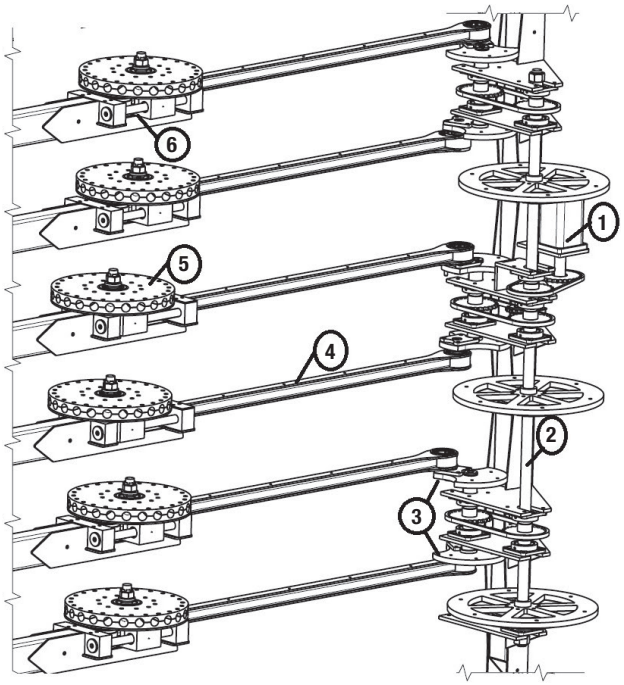


**Figure 2.** Schematic description of vibration system of canopy shaker prototype. 1. Hydraulic engine; 2. Main crankshaft; 3. Crankpins; 4. Connecting rod; 5. Drum to hold the rods; 6. Slider of each drum.

The widely-spaced trees allow the use of a lateral canopy harvester working around tree canopies. In this study four lineal wipes along tree sides were performed by the prototype in the harvesting process.

The canopy shaker prototype was adapted to the harvesting of traditional olive plantations by adjusting the key operational variables according to preliminary results (Gil-Ribes *et al*., 2014). Vibration parameters were studied by changing the amplitude (A) and frequency (F) of the drums. In addition, the interaction between the harvester and the tree was studied by changing the prototype's rod density (D) and ground speed (S). Two test values were established for each operating parameter: low (0) and high (1), as shown in Table 1. The reference configuration for the test was set with low values for all the operating parameters (A0F0D0S0). Subsequently, each operating parameter was tested individually by changing its value from low to high. Accordingly, five harvester configurations were tested, using nine trees per harvester configuration.

Harvester configurations were evaluated according to their fruit removal efficiency and debris production. Debris production was defined as the damage caused to the tree in terms of number of broken branches and shoots. Fruit removal efficiency was determined taking into account only the exterior canopy, at a depth of 1.5 m in the area where the rods made contact with tree branches. Therefore, the fruit from the canopy interior (canopy depth > 1.5 m) were not used to determine fruit removal efficiency, but rather were manually harvested and weighed after the mechanical harvesting process. Production debris was then collected and visually classified into three levels according to branch diameter, in order to determine a debris index (Eq. [1]) (Spann & Danyluk, 2010; Hong *et al*., 2012) according their severity. The fruit damage was not considered for this study because the detached fruit was bounded to oil production.

$$\text{Debris index} = n_1 + 2\,n_2 + 3\,n_3 \qquad [1]$$

where n is the quantity of debris according the diameter of damaged branches: $n_1$ (<2 mm), $n_2$, (between 2 and 25 mm), and $n_3$ (>25 mm).

The location of fruit detached by the canopy shaker prototype was determined by dividing the catch frame into four zones, as shown in Fig. 3. Zone 1 collected the detached fruit in the vertical projection of the drums. Zones 2 and 3 collected the fruit that fell in the direction of the forward movement, at the beginning and end of the shaking process, respectively. Zone 4 collected the fruits that fell or were projected towards the canopy interior. The ground under the trees was covered with nets in order to collect the detached fruit that were not picked up by the catch frame.

The forced vibration produced in each operating parameter configuration was measured using two triaxial piezoelectric accelerometers (PCB 356A02, Depew, NY, USA). During the tests, the acceleration sensors were randomly distributed in the outer fruit-bearing branches of the canopy. Each acceleration signal was recorded in a frequency range of 500 Hz, with a sampling frequency of 1.28 kHz. In addition, a zoom factor was used to reduce the frequency range. The conditioning, recording and analysis of the acceleration signals were performed with a PC-based dynamic signal analyzer (OROS 25 PC-Pack II, Meylan, France).

In order to analyse the canopy shaking process, the resultant acceleration value was determined as the vector sum of time signals at each sensor (Fig. 4). For each time signal of resultant acceleration, the following signal descriptors were calculated:

- Shaking time: time elapsed between the first and the last resultant acceleration value over 40 m/s$^2$.
- Accumulative shaking time: sum of the time intervals where the resultant acceleration values were above 40 and sum of the time intervals where the resultant acceleration values were above 200 m/s$^2$.
- Number of impacts with instant resultant acceleration was above 200 m/s$^2$.

The resultant acceleration value of 40 m/s$^2$ corresponds to the minimum value that the canopy shaker

**Table 1.** Modifications of operating parameters in harvesting process with a canopy shaker prototype. The reference harvester configuration was set with all operating parameters in low values (A0F0D0S0).

| Operating parameter | Nomenclature | Machine modification | Levels | Values | Harvester configuration |
|---|---|---|---|---|---|
| Amplitude (m) | A | Crank length | Low (0) | 0.12 | A1F0D0S0 |
| | | | High (1) | 0.17 | |
| Frequency (Hz) | F | Revolutions of main crankshaft | Low (0) | 4.0 | A0F1D0S0 |
| | | | High (1) | 5.0 | |
| Rod density (#) | D | Rods per drum | Low (0) | 12 | A0F0D1S0 |
| | | | High (1) | 24 | |
| Ground speed (km/h) | S | Tractor velocity | Low (0) | 0.5 | A0F0D0S1 |
| | | | High (1) | 1.0 | |

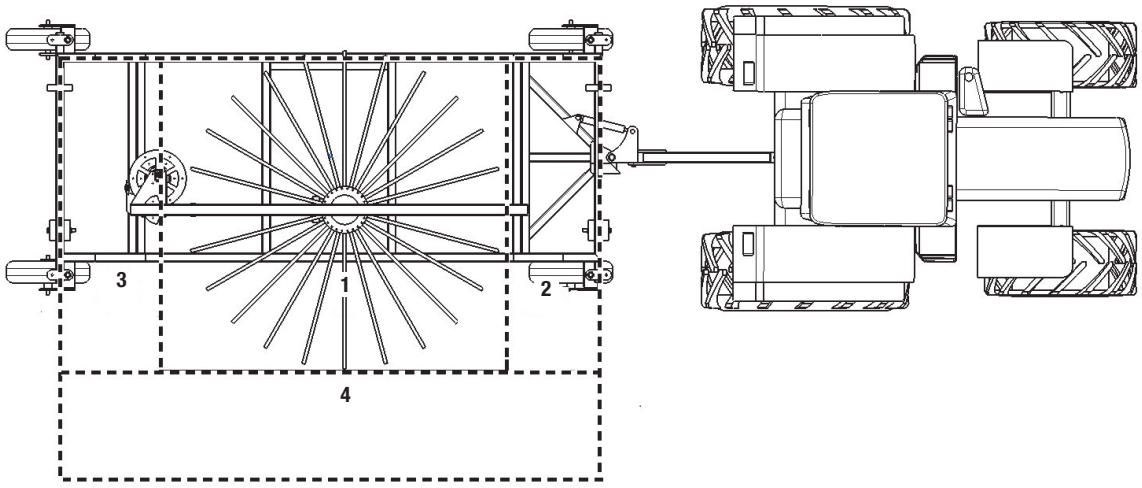


**Figure 3.** Zone distribution of the catch frame to collect detached fruits by canopy shaker prototype. Detached fruit collected: (1) in the vertical projection of the drums, (2-3) in the direction of the forward movement, (4) outside the catch frame when fruits were fallen or were projected towards the canopy interior.

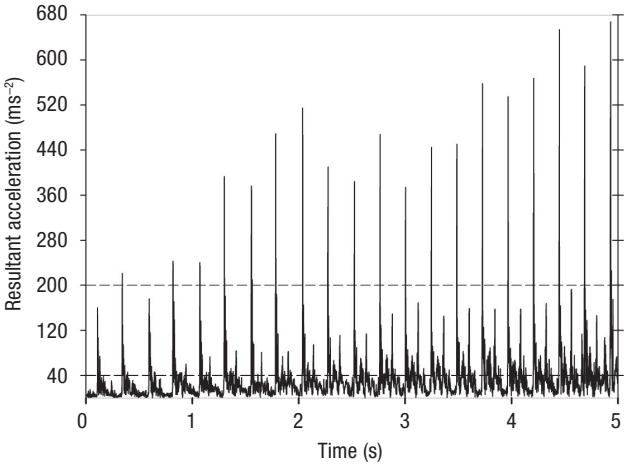


**Figure 4.** Example of resultant acceleration signal time performed by the canopy shaker prototype on olive tree branch.

produces in the reference configuration, whereas the resultant acceleration value of 200 m/s$^2$ represents the minimum value required to detach the olives according to Adrian & Fridley (1965) in the range of mean values determined in the tests for fruit detachment force and fruit mass of 1 N and 5 g, respectively.

## Results

Modifying the operating parameters of the canopy shaker prototype generated different results for fruit removal efficiency and debris index. Fig. 5A shows fruit removal efficiency values for the five harvester configurations. The reference configuration (A0F0D0S0) obtained a mean fruit removal efficiency value of 55.2%. Increasing the values from low to high for both the amplitude and the frequency of the vibration, resulted in higher mean fruit removal efficiency values than with other configurations. However, there was no significant difference between these mean values (70.0 and 77.3%, respectively) ($p$ <0.05). Modifying rod density did not lead to any increase in fruit removal efficiency values relative to those values produced with the reference configuration. Increasing the ground speed led to a significantly lower mean fruit removal efficiency value (42.0%) ($p$ <0.05).

Fig. 5B shows the damage caused to the tree by different experimental configurations of the prototype, in terms of broken branches and shoots. Only the increase in rod density produced a mean debris index value that was significantly higher (10.1) than that for the reference configuration of the harvester (4.5) ($p$ <0.05). Although increased ground speed value led to a reduced mean debris index value (1.6), the differences compared to the reference configuration were not significant ($p$ <0.05). The average values of number of debris per tree in all the configurations were 0.51 ± 0.95($n_3$), 0.94 ± 0.96($n_2$) and 2.17 ± 1.9($n_1$).

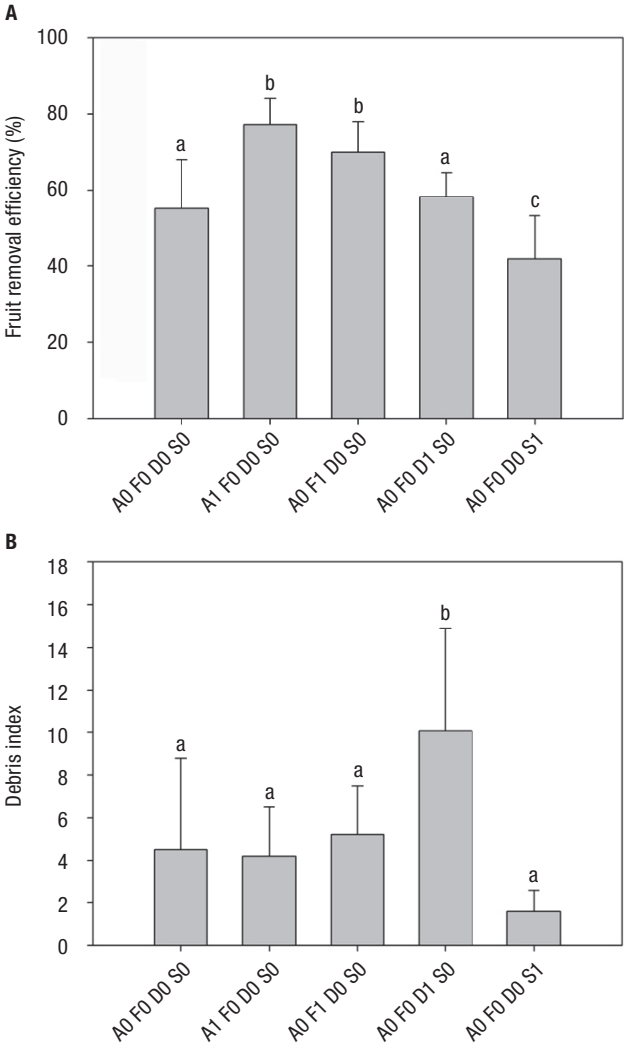


**Figure 5.** Evaluation of fruit removal efficiency (A) and debris production (B) on different harvester configurations with a canopy shaker prototype. The same letter above bars shows no significant differences (Duncan's test, $p$<0.05). A: amplitude, D: rod density, F: frequency, S: forward speed. 0 (value in low level) and 1 (value in high level) correspond with different levels of each variable.

None of the harvester configurations managed to detach the fruit from the interior of the canopy, at a depth greater than 1.5 m from the exterior canopy. The fruit from the canopy interior represented 13.2 ± 6.7% of total production, with no significant differences between the mean values of trees assigned to each configuration ($p$ <0.05).

The mean value of the quantity of fruit detached by the canopy shaker which did not fall into the catch frame was very small and not included in the study (<1%). The various harvester configurations tested did

not result in significant differences in terms of the mean values for the distribution of the fruits caught by the different catch frame zones ($p$ <0.05). The shaking system enabled 65.5±6.8% of the detached fruits to fall vertically into the area covered by the rods (zone 1). The transmission of the vibration in the tree canopy together with the interaction of the fruits with the branches and the trajectory of the fruits in the direction of the impact from the machine resulted in 10.3±3.7% of the fruit falling in the front part of the catch frame (zone 2) and 4.9±2.4% of the fruit falling in the back part of the catch frame (zone 3). The zone between the vibration system and the tree trunk (zone 4) caught 19.3±10.5% of the fruit.

Table 2 shows the values for forced vibration on the tree canopy produced by the tested harvester configurations. The reference configuration generated a mean canopy vibration time (between the first and last recorded peak acceleration value of 40 m/s$^2$) of 32.67 s. Only by increasing the ground speed value was the mean vibration time reduced to 16.14 s. The different harvester configurations showed no significant differences from the reference configuration in terms of mean values for accumulative shaking time and numbers of performed beats ($p$ <0.05). Increases in either frequency or rod density led to a significant increase in the mean value for accumulative shaking time over 40 m/s$^2$, while increase of ground speed led to a reduction of the mean value for accumulative shaking time over 40 m/s$^2$ ($p$ <0.05). Similarly, increased frequency or rod density produced an increase in the mean value for accumulative shaking time over 200 m/s$^2$ and number of performed beats, although the differences were not significant ($p$ <0.05). Significant linear correlations were found between fruit removal efficiency and some shaking signal descriptors such as shaking time and accumulative shaking time over 40 m/s$^2$ with a Pearson coefficient of 0.342 and 0.321, respectively.

## Discussion

Fruit detachment is influenced by the point of application of the vibration to the tree. Harvesting systems such as trunk shakers operate in high frequency ranges with low displacements, and with vibration applied to the trunks (Torregrosa *et al*., 2010), whereas canopy shakers operate with lower frequency and produce greater displacement, with the vibration applied directly to the fruit-bearing branches (Sola-Guirado *et al*., 2014). In this regard, direct application of the vibration to the branches is more effective than vibration applied to the trunk, given the difficulty in transmitting the shaking energy to fruit located at some distance from the excitation source (Zhou *et al*., 2013). Furthermore, the response of the tree in terms of fruit detachment depends on fruit location and distance from the point of vibration (Zhou *et al*., 2014).

Trees in rainfed olive groves have low-density canopies (Villalobos *et al*., 2000) where the vibration is transmitted through a limited number of rod-branch contact points. Results show that the vibration transmitted from the machine to the tree was effective for fruit removal despite using lower rod density. Nevertheless, rod-branch interaction is a complex phenomenon because it depends on several factors such as geometry, quantity, location and resistance of branches (Rosa *et al*., 2008), where fruit undergo a process of twisting and bending and are subject to tensile and shear stress. Energy transmission efficiency and its distribution pattern are strongly influenced by branch size, age and chain morphology (Du *et al*., 2012). Increasing rod density does not mean that fruit detachment is produced by direct rod-fruit contact (Castro-Garcia *et al*., 2009) and that consequently more fruit is removed. This could be due to the fact that fruit removal may be caused by the resultant stress from the motion of the fruit in different directions and the nature of the change in direc-

**Table 2.** Evaluation of shaking signal on branches with the experimental canopy shaker device on different configurations. A: Amplitude, D: Rod density, F: Frequency, S: Ground speed; 0 (value in low level) and 1 (value in high level) correspond with different levels of each variable. A0F0D0S0 is the reference configuration of the canopy shaker harvester. Same letter in the same column shows no significant difference between configuration with a high value of operating parameter (A1 F0 D0 S0, A0 F1 D0 S0, A0 F0 D1 S0, A0 F0 D0 S1) and the reference configuration (Duncan's test, $p$<0.05).

| Harvester configuration | Shaking time (s) | Accumulative shaking time (s) according to resultant acceleration (Acc) | | Number of impacts with Acc ≥ 200 m/s$^2$ |
|---|---|---|---|---|
| | | Acc ≥ 40 m/s$^2$ | Acc ≥ 200 m/s$^2$ | |
| A0 F0 D0 S0 | 32.67 ± 7.02 a | 4.60 ± 2.44 ab | 0.21 ± 0.26 a | 32.29 ± 28.94 a |
| A1 F0 D0 S0 | 28.22 ± 6.52 a | 4.71 ± 2.31 ab | 0.26 ± 0.17 a | 35.67 ± 13.65 a |
| A0 F1 D0 S0 | 36.63 ± 8.99 a | 7.33 ± 3.05 b | 0.41 ± 0.49 a | 43.00 ± 20.03 a |
| A0 F0 D1 S0 | 28.41 ± 6.64 a | 6.02 ± 3.11 b | 0.37± 0.29 a | 42.44 ± 17.10 a |
| A0 F0 D0 S1 | 16.14 ± 1.24 b | 1.77 ± 1.43 a | 0.05 ± 0.03 a | 20.33 ± 15.50 a |

tion at the bonding point of the fruit with the stem or the stem with the branch (Savary *et al*., 2011). Furthermore, the probability of direct contact between the rods and the fruit during the shaking and free-fall process could be the cause of the increase in damage to the detached fruit (Castro-Garcia *et al*., 2009), which has a particularly negative effect in terms of table olives quality (Jimenez-Jimenez *et al*., 2013). In any case, increased rod density led to greater debris production, and this increased further when the distance between rods was smaller but with the same displacement amplitude. Also, the average percentage of number of debris in all configuration with 60%, 26% and 14% for $n_1$, $n_2$, and $n_3$, respectively, show a similar pattern that other canopy shaker devices (Spann & Danyluk, 2010). The process of canopy shaking in traditional olive plantations has been greatly influenced by the operating parameters of the canopy shaker prototype, but essentially, it is the frequency and the amplitude of the vibration system that have been the key parameters for increasing fruit removal efficiency values. Ground speed was also a determining parameter in fruit removal efficiency. This factor greatly influences the time required to detach the fruit, which is particularly high in the case of olive oil plantations, principally at the start of the harvest period. In olive harvesting using trunk shakers, a harvesting time of 11.4 seconds is required to achieve fruit removal efficiency values of over 90% (Blanco-Roldán *et al*., 2009). Nevertheless, the time may vary depending on the date of the harvest, the variety or the species (Kouraba *et al*., 2004). Furthermore, the time may vary within the same crop if the point of application of the vibrations is changed, or if changes are made to the frequency of the vibration (Du *et al*., 2012), and can be much higher in other crops such as citrus. Other crops with more rigid trees, such as pistachios (Polat *et al*., 2007) or almonds, might require a much shorter vibration time.

Nevertheless, the fact that the required high fruit removal percentages are influenced by high collection times could be a limiting factor for the ground speed when using a continuous harvester (Agüera *et al*., 2013). This is a determining factor in high-density orchards where a better yield corresponds to an increase in harvest completion time (Bernardi *et al*., 2008). One-pass continuous harvesting represents an economically competitive alternative to multi-pass harvesting systems (He *et al*., 2013). In this regard, the reduction of ground speed has a negative effect on the work capacity of the prototype (ha/h) and may make mechanical harvesting less economically attractive (Shamshiri *et al*., 2013).

During the forced vibration, the tree responds differently depending on the properties of the vibration. Normally, fruit detachment occurs when the fruit detachment force caused by the vibration is greater than the retaining force of the fruit to its stem. However, a number of different authors show that factors other than the acceleration of the fruit play major roles in fruit detachment. In fact, canopy shakers show a particular vibration pattern, which cannot solely be defined by mean acceleration values due to the importance of the peak acceleration values produced in the canopy shaking process (Sola-Guirado *et al*., 2014). During the shaking process, the impact forces are particularly important for fruit removal efficiency when the fruit is ripe. Nevertheless, the number of rod impacts with acceleration values over 200 m/s$^2$ did not show any major differences in the fruit removal efficiency values for the different prototype configurations. Although the differences were not significant due to the high dispersion of the results, it is worth noting that there was an increase in the number of impacts when the rod density was increased, the frequency was increased or the ground speed was reduced. This result suggests that fruit removal efficiency and debris production are not increased by one-off or instantaneous resultant acceleration values in the branches during olive harvesting. This could, however, be different in the harvesting of other crops and may merit further study, primarily in those crops where impact or selective harvesting is possible, such as apple and apricot.

The highest values of accumulative shaking time with resultant acceleration greater than 40 and 200 m/s$^2$ were obtained by increasing frequency values. However, no significant differences were found between the average values of the signal descriptors studied for each prototype configuration. This could be due to the high variability of the results or to the fact that the variation of the vibration frequency of the canopy shakers is lower, especially when compared to other harvesting systems such as trunk (Whitney *et al*., 1986) or branch shakers (Du *et al*., 2012). The results suggest that fruit removal efficiency could be increased with a greater number of impacts, by increasing the frequency or by reducing the ground speed of the machine.

Ground speed proved a strongly influence the length of time that the branches are vibrating. According to Kouraba *et al*. (2004) the vibration duration is a key parameter for achieving high harvesting efficiency. Furthermore, there is an exponential reduction in the quality of the non-harvested fruits in the tree as the duration of the vibration on the tree increases (Mateev & Kostadinov, 2004). The high linear correlation between fruit removal efficiency and certain shaking signal descriptors, such as vibration time and accumulative shaking time over 40 m/s$^2$, suggests that there are factors other than the resultant acceleration that

might explain the variability of the results. Nevertheless, the other shaking signal descriptors cannot explain its influence on the shaking process, due to the high dispersion of the results. This dispersion might be caused by the variability of other parameters relating to plantation characteristics, such as the structure of the tree branches (Zhou *et al*., 2014) or the irregularities of the canopy (Mariscal *et al*., 2000), as well as the limited contact given that the mechanism cannot operate in close proximity to the tree (Ferguson *et al*., 2012). This difficulty could be overcome by including a system that would allow the vibrating mechanism to operate in closer proximity to the tree and thus ensure the permanent contact of the rods with the fruit-bearing branches during movement of the vibration system. Furthermore, the shape of the tree must be trained to allow mechanical harvesting by canopy shaking systems in order to achieve high fruit removal efficiency levels (Savary *et al*., 2010).

Other parameters involved in mechanical harvesting were not taken into consideration in this study. Fruit removal efficiency is affected by modifications to tree structure (Savary *et al*., 2011), the location of the fruit in the canopy (Ferguson *et al*., 2010), the characteristics of the fruit itself (Farinelli *et al*., 2012) or even the physical properties of the wood of the tree resulting from its growth or management (El-Awady *et al*., 2008). The highest results of removal efficiency with the configuration studied have been relatively low comparing with available commercial canopy shakers (Whitney, 1999), so it is necessary to adjust every parameter to create a good configuration to achieve better results. The design of new harvesting machines to increase fruit removal efficiency also requires suitable tree structure in order for these machines to operate to their full potential (Visco *et al*., 2008). A model of traditional olive tree limbs would be very interesting to optimize the amplitude, frequency and also rod density of the removal system to achieve better results of efficiency and damage index (Gupta *et al.,* 2015).

The amount of fruit remaining in the canopy interior is due to the fact that the rods were unable to transmit the vibration farther than the depth of their penetration into the canopy. Similar studies on canopy shakers report the high damping values of the fruit-bearing branches that limit the fruit removal efficiency (Savary *et al*., 2010). Adapting the trees is the key to mechanical harvesting using canopy shaking systems, principally in the interior and lower areas of the canopy, which are less accessible to the rods (Ravetti & Robb, 2010).

A major factor for the development of a canopy shaker system is the ability to simultaneously collect the detached fruit in a catch frame. An integrated harvester allows an increase in the quantity and quality of the final product and can also reduce operational costs (Ferguson, 2006). Results show that integrated harvesting was made possible in traditional olive plantations by incorporating a catch frame to the canopy shaker prototype. The harvesting of fruit with this machine in movement was enabled by the limited horizontal component of the trajectory of the falling fruit, which could be explained by the fact that the alternating and off-set movement of the drums produces shear stress along the fruit-bearing branches causing the fruit to fall vertically. Furthermore, the height of the fall of the fruit was limited as the trees were trained for manual harvesting. The high volume of fruit harvested when the rods initially make contact with the tree canopy might be due to the reduced retention forces of some fruit, which are detached in the first moments (Smith & Ramsay, 1983). On the other hand, the projection of the fruit due to contact with the rods and branches and rebounding during the fall were of limited importance, occurring on the outermost part of the catch frame.

In conclusion, the development of canopy shaker technology to mechanical harvesting of traditional olive tree requires the adjustment of the main machinery parameters to the tree characteristics seeking for a compatible solution. Continuous contact between the machine and the tree has proved a decisive factor in the functioning of the machine. Furthermore, adjustments to the canopy shaking parameters, principally the frequency and the amplitude, together with ground speed values to ensure an adequate vibration time, have enabled an increase in fruit removal efficiency without any increase in the damage to the trees.

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