



## RESEARCH ARTICLE

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# Olive fruit detachment force against pulling and torsional stress

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## Abstract

Olive harvesting often requires high hand labour, considering that workers, with long poles or hand held devices, aid trunk shaker due to low harvesting efficiency. Currently, fruit detachment force (FDF) and fruit fresh weight were used to predict harvesting efficiency, although during harvesting process, fruit is subjected to bending and twisting movement besides pulling forces simulated by FDF measurements. For these reasons, the aim of the present study was to determine FDF evolution under different stalk twisting angles. In order to provide more information about mechanical behaviour of olive stalk, a trial was carried out during ripening process on four olive (*Olea europaea* L.) cultivars: Frantoio, Arbequina, Leccino and Maurino. FDF under traction force was measured after applying different stalk twisting angles (0°, 90°, 180°, 270°, 360°, 540°, 720°). FDF was considered to be 0 when fruit was detached from the bearing branch during the twisting process. Fruit weight, firmness, ripeness index and oil content were also measured to determine the optimal period for olive harvesting and olive ripening stage at each sampling date. FDF was significantly reduced, usually over 180°, when stalk was rotated before applying the pull force to measure FDF, keeping differences along fruit ripening process. Moreover, stalk twisting was an important variable for olive detachment, considering that fruits detached without pulling forces varied between 10.7 and 58.8% of the total fruits according with the different sampling dates. For these reasons, present and future harvesting systems, should take advantage of stalk susceptibility against torsion or bending strain to increase harvesting efficiency.

**Additional keywords:** fruit retention force; olive harvesting; stalk twisting; stalk spinning; fruit rotation; trunk shaker; fruit physics.

**Abbreviations used:** DOY (day of year according to National Snow and Data Center -NSIDC-, from 1 to 365 or 366 in a leap year); FDF (fruit detachment force, this value represents the pulling force at which fruit was detached from bearing branches); FW (fruit fresh weight).

**Authors' contributions:** FJCR analyzed the data and wrote the manuscript. All authors conceived and carried out the experiments, read and approved the final manuscript.

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## Introduction

The European Union (EU) is the top world olive oil and table olives producer, being the main producer areas located in the Mediterranean basin. Spain, Italy and Greece hold more than 95% of the total EU olive oil production during 2015/16 harvesting season (IOOC, 2015). In those countries, olive growing has an outstanding economic and social importance (MAPAMA, 2016), playing an important role as economic activity in a large number of rural areas. Currently, the decrease of competitiveness in olive sector threatens the survival of olive farms and mills (Pomarici & Vecchio, 2013), that needs to improve farm efficiency through modernisation, shared machinery

management or outsourcing labours (Vilar-Hernández *et al.*, 2011). In the last decades, olive orchards management evolved towards more intense planting densities and use of high level of mechanization (Novello *et al.*, 2014); however, there is still margin for improvement in the farming techniques (Carmona-Torres *et al.*, 2014).

Manual fruit harvesting is unavoidable for many fresh fruit and vegetables, but it suffer low working capacity and uncertain labour availability, although orchard layout, dwarf trees and picking aids can improve manual harvesting performance (Sanders, 2005). Furthermore, manual fruit harvesting may contribute to the development of ailments in the worker musculoskeletal system (Mlotek *et al.*, 2015) as well as

hand held shaker combs and branch shakers (Çakmak *et al.*, 2011). Nevertheless, in a large number of olive orchards, harvesting is currently performed using different mechanical devices such as trunk shakers, hand held devices or integral harvesters. In large olive growing areas there are high labour requirements during harvesting operation, mainly for traditional olive orchards in which effective field capacity for harvesting operation are often poor (Famiani *et al.*, 2014; Castillo-Ruiz *et al.*, 2015a). Current olive harvesting systems achieve harvest efficiency ranging from 90%, achieved by trunk shakers in favourable conditions, to 80%, achieved by lateral canopy shakers, while manual harvesting can reach 98% of total harvest efficiency (Sola-Guirado *et al.*, 2014). However, trunk shaker performance depends on several external conditions such as fruit ripeness (Blanco-Roldán *et al.*, 2009), tree structure (Castro-García *et al.*, 2008) or machine features (Castro-García *et al.*, 2015). Furthermore, it would be desirable that commercial mass harvesting systems for olives will achieve harvesting efficiencies above 90% (D'Agostino *et al.*, 2008), without using manual or hand held systems to remove left fruit. In fact, the breakeven point for olive harvesting efficiency is considered 85% (Farinelli *et al.*, 2012a) due to limitations of commercial harvesters in standard harvesting conditions. Nonetheless, straddle canopy shakers usually achieve harvesting efficiency values over 95% (Farinelli & Tombesi, 2015), although these systems have different harvesting efficiency depending on the cultivar (Vivaldi *et al.*, 2015), canopy volume and training system (Tombesi & Farinelli, 2014).

Although harvesting at early ripening stages is becoming a current technique to enhance phenol content in fruit for premium olive oil, at early harvesting season, it is more difficult to achieve high harvesting efficiency (Blanco-Roldán *et al.*, 2009). Therefore, a better understanding of the detachment process is essential to improve mechanical harvest efficiency. Up to date, fruit detachment force (FDF) is used as the main index to describe the resistance of fruit to detachment from the tree, but it measures only traction force. It was divided by fruit fresh weight (FDF/FW) to obtain a more representative index able to predict the harvesting efficiency of trunk shaker (Farinelli *et al.*, 2012b). Furthermore, FDF/FW decreases when fruit ripeness moves forward or when abscission chemicals are applied (Sessiz & Özcan, 2006). However, up to date it is unclear how FDF, acceleration or tree architecture are involved in fruit detaching process (Tombesi *et al.*, 2017).

Current harvesting systems cause a limited stalk twisting. In trees subject to forced vibrations produced by trunk shakers, fruit experienced stalk twisting angles

under 70 °, with peak angles around 150 ° (Castillo-Ruiz *et al.*, 2016). Moreover during cherry harvesting using limb shaker, twisting has limited influence on the number of motion patterns in comparison with tilting or beam column motion patterns (Zhou *et al.*, 2016). Furthermore, some test and simulations performed in oranges harvested by a canopy shaker determine that only 18% of FDF was applied to fruit stalk suggesting that fruit undergoes twisting and bending processes during mechanical harvesting (Savary *et al.*, 2011).

Fruit detachment is affected by stalk geometrical properties and its behaviour during tree shaking (López-Jiménez, 1979). Motion of fruit-stem subsystem can be described with three translational and three rotational degrees of freedom, which corresponds to precession, nutation and spin of the fruit (Upadhyaya *et al.*, 1981). Concerning stalk structure, it can be divided into three different parts from bearing branch to fruit, these parts are peduncle, rachis and pedicel. These sections may be considered as different abscission areas for olive, and fruit abscission is affected by harvesting date and cultivar, while fruit fresh weight (FW) does not show a significant effect (Castillo-Llanque & Rapoport, 2009).

The aim of the present work was to determine FDF evolution under different stalk twisting angles along the ripening process in different Spanish and Italian cultivars. Cultivar influence on stalk susceptibility to torsion strain was also assessed in order to give data for present and future harvesting systems.

## Material and methods

### Developed method to apply torsional and pulling forces simultaneously

Traction force was measured using a hand held Push - Pull Dynamometer FD 101 (TR Turoni, Forlì, Italy) that had 0 to 1000 g range and 10 g resolution. The dynamometer hook was custom-modified in order to make possible fruit turning along the attaching rod to generate the same stalk twisting as fruit turning (Fig. 1). In addition, an angle scale was added to measure fruit turning that was applied manually. As a consequence of fruit turning, different stalk twisting angles were applied to fruit (0°, 90°, 180°, 270°, 360°, 540°, 720°) before applying a traction force to measure FDF. FDF was considered to be 0 when fruit was detached from the bearing branch during the stalk twisting process. If fruit suffered the same stalk twisting during harvesting process, fruit detachment would occur without additional forces.

This method was validated on an only year and location considering that it was apply to follow



**Figure 1.** Dynamometer with modified hook for make stalk twisting before fruit detachment force (FDF) measurement

the whole FDF evolution along maturation with several samples along ripening process. FDF changes along ripening process were well-known, then, this method compared the standard FDF measurement method with the new one that included torsion stresses. Therefore, it was not necessary to perform measurements in several locations during several years due to FDF was widely studied in the bibliography and it is possible to compare obtained results with other experiments.

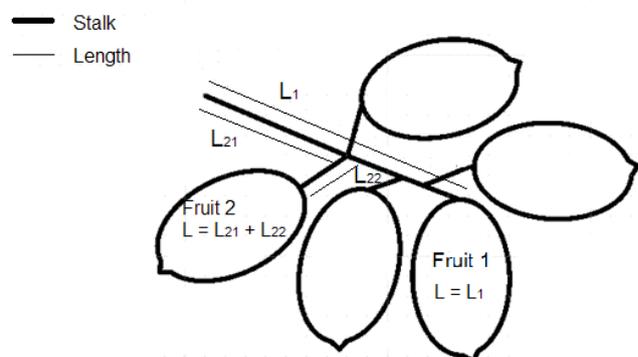
### Experiment design

Fruit sampling was carried out in 2015 in a young intensive olive orchard (10 years old) placed at Deruta, nearby Perugia, Central Italy (42°57'39.2"N, 12°25'02.5"E). In the orchard there were four different olive (*Olea europaea* L.) cultivars: Frantoio, Arbequina, Leccino and Maurino, planted in different rows, three per each cultivar. The orchard was divided in three blocks laid out perpendicular to the maximum slope and to the cultivar row. Each sampling included three trees, one per block and 30 fruits per tree to determine FDF. Sampling dates were established each week for Arbequina and Frantoio while Maurino and Leccino were sampled every two weeks. Furthermore, 0.3 kg per tree was sampled to measure other variables such as fruit FW, maturation, oil content and fruit firmness. Stalk length was measured in the first sampling, considering the whole length from the attachment point with fruit bearing branch to the attachment point with each fruit from the bearing branch (Fig. 2). This length added peduncle, rachis and pedicel (Castillo-Llanque & Rapoport, 2009).

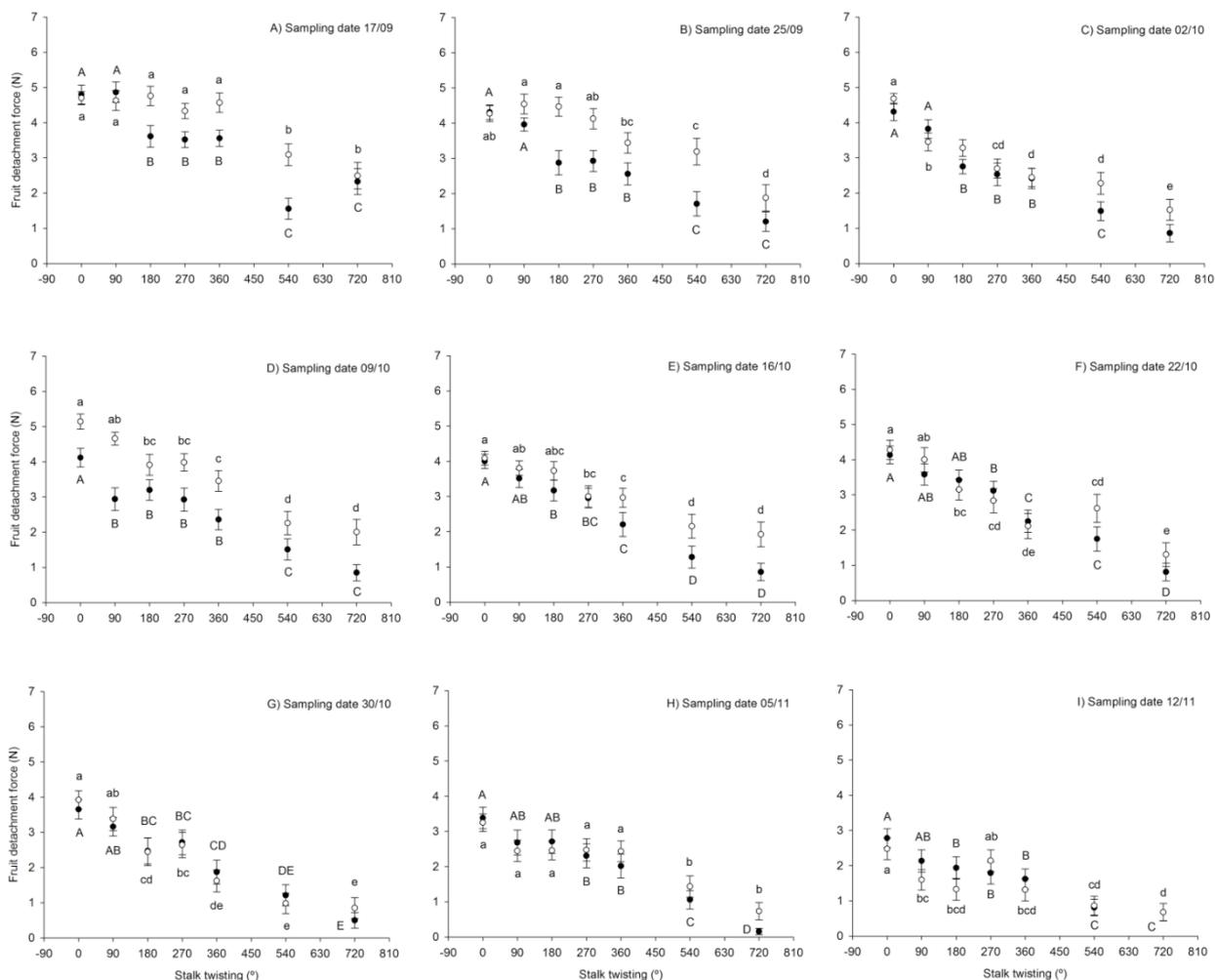
Two cultivars, Frantoio and Arbequina, were sampled every week from September 17 (260 DOY)

to November 12 (316 DOY), while Leccino and Maurino were sampled only every two weeks in order to determine optimal sampling rate for olive fruit. Fruit FW was measured by weighting 100 fruits the same day that the samples were taken. These fruits were also evaluating to determine ripening index following the Jaen method (Eq. [1]) separating fruits into 8 classes according to the fruit external and internal pigmentation (Uceda & Hermoso, 1998). The same fruit sampling was also used for fruit firmness measurements with a hand held dynamometer FD 101 (TR Turoni, Forli, Italy) that had 0 to 1000 g range and 10 g resolution. To perform the measure, a steel cylindrical tip with 1 mm diameter was pulled to the fruit to prick it and keep the highest resistance. Furthermore, FDF/FW was calculated for each fruit sampling, as a different forecasting value for harvesting efficiency.

$$\text{Ripening index} = \frac{\sum(RS \cdot n)}{100} \quad [1]$$



**Figure 2.** Measuring process to determinate stalk length for fruit cluster. Stalk length (L) was measured individually for each fruit considering from the stalk-to-branch joint to the stalk-to-fruit joint.



**Figure 3.** Mean and standard error for fruit detachment force at different stalk twisting angles for different sampling dates. Different uppercase letters indicate significant differences ( $p < 0.05$ ) for Arbequina cultivar (●) while different lowercase letters indicate significant differences ( $p < 0.05$ ) for Frantoio cultivar (○). Both of them show differences in detachment force at different spinning angles according to Duncan's test. The DOY of each sampling date is reported in Table 1.

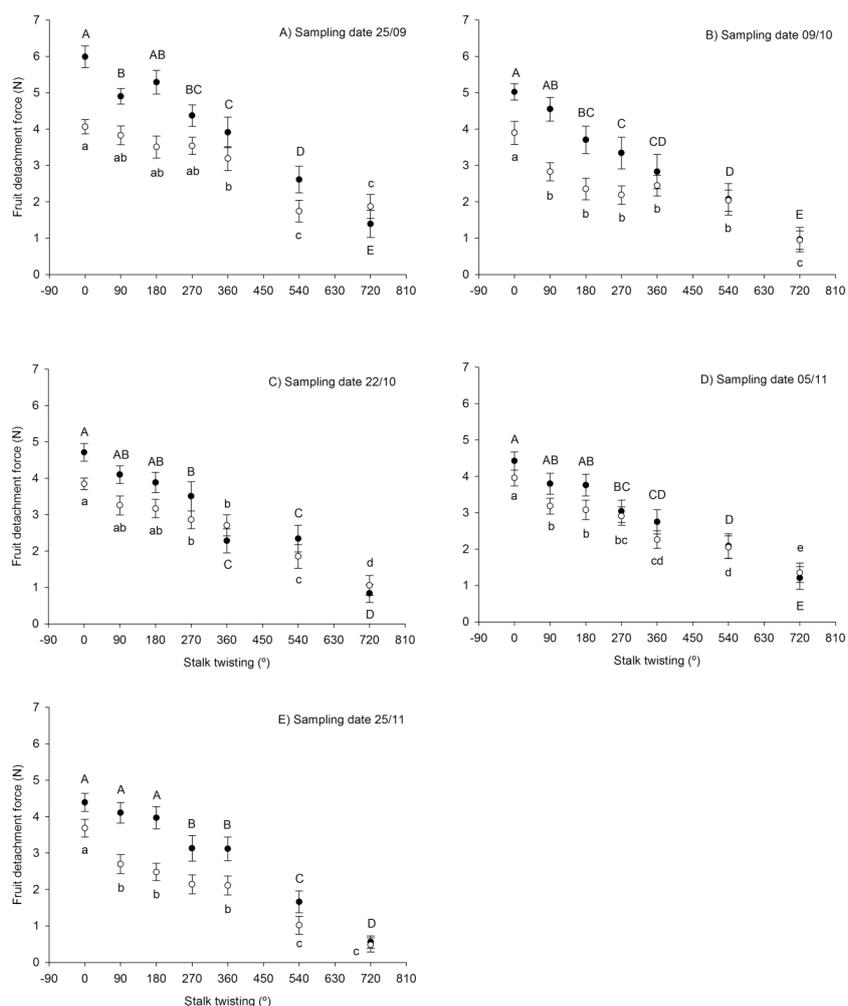
where RS was the ripening stage of the fruit from 0 to 7 and n was the number of fruits in each ripening stage.

Oil and water content was determined as well using near infrared spectrometry (NIRS) previously calibrated for the same olive cultivars. For this purpose, one sample of about 0.2 kg was taken for each tree being milled. The resultant olive paste was stirred and homogenized before measure, being located in the measuring dish of a Infrared analyzer (SpectraAnalyzer Zeotec BRAN+LUEBBE, Rendsburg, Germany). It measured the oil and water content, expressed on FW basis, using a previous calibration for the same cultivars. In addition, oil content related to dry matter

was also calculated to track the oil accumulation process (Farinelli *et al.*, 2002).

### Data analysis

Statistical analyses have been applied to the studied variables. FDF at different stalk twisting angles and stalk length were analyzed statistically by ANOVA and using the Duncan's-test to compare the means. FDF was analyzed for each cultivar separately at different twisting angles, while stalk length was compared between cultivars. Furthermore, polynomial regressions were performed depending on the day of year (DOY) for maturation Jaen index and fruit firmness.



**Figure 4.** Mean and standard error for fruit detachment force at different stalk twisting angles for different sampling dates. Different uppercase letters indicate significant differences ( $p < 0.05$ ) for Leccino cultivar (●) while different lowercase letters indicate significant differences ( $p < 0.05$ ) for Maurino cultivar (○). Both of them show differences in detachment force at different spinning angles according to Duncan’s test. The DOY of each sampling date is reported in Table 1

**Table 1.** Percentage of detached fruits only by applying twisting forces for different cultivars in all sampling dates.

Sampling date	DOY	Arbequina	Frantoio	Leccino	Maurino
17/09	260	14.3	10.7	-	-
25/09	268	26.5	16.0	21.4	21.1
02/10	274	27.2	19.4	-	-
09/10	282	33.0	18.0	36.4	31.0
16/10	289	35.3	21.8	-	-
22/10	295	32.0	33.7	30.0	27.2
30/10	303	45.2	45.6	-	-
05/11	309	47.6	39.1	28.9	24.5
12/11	316	53.1	58.8	-	-
25/11	329	-	-	27.6	37.1
Mean		34.9	29.2	28.9	28.2
SE		4	5.3	3.1	2.1

## Results

FDF was significantly reduced when stalk twisting was applied before pulling the fruit out. Differences were kept along fruit ripeness process, although stalk sensitivity to torsion strains varied, depending on the sampling date. Moreover, significant differences ( $p < 0.05$ ) were commonly found over  $180^\circ$  of stalk twisting, and when ripening process was advanced, fruit were often detached only by applying a stalk twisting over  $360^\circ$  (Figs. 3 and 4).

Generally, FDF reduction along with stalk twisting was lower at advanced stages of ripening, as a consequence, percentage of detached fruit without traction increased. Olive stalk susceptibility to stalk twisting, demonstrated that stalk torsion strain could play an important role for olive harvesting, when it caused an important percentage of fruit detachments by itself, particularly at the end of the ripening process (Table 1).

Stalk length could explain FDF behaviour at different stalk twisting angles. Stalk length showed significant differences ( $p < 0.05$ ) for the four tested cultivars. These cultivars could be grouped in two categories: short stalk cultivars, such as Arbequina and Leccino, and long stalk cultivars, such as Frantoio and Maurino, although no significant differences were found between Leccino and Maurino (Fig. 5).

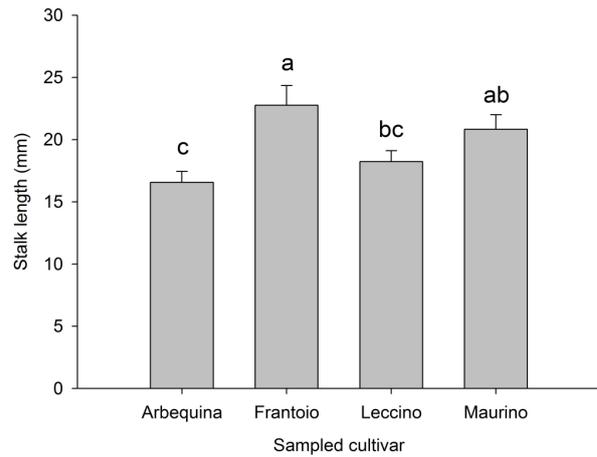
Fresh FW and oil accumulation reached a saturation level at the end of the ripening process, as particularly evident in Leccino and Maurino cultivars. This point indicated the optimal harvesting period in terms of incomes and harvesting ease. Trees were harvested in mid (Arbequina and Frantoio) and end November when optimal maturity, established on the base of oil content and FDF, was reached (Fig. 5).

Sampling process was carried out along the whole oil accumulation process, comprising an important part of the fruit growing season with maturation indexes from 0 to 6 within the Jaen maturation index (Fig. 6). Oil content on a dry weight basis was an indicator for optimal harvesting date regarding economic yield, while FW could be used as a predictor of fruit harvesting ease. Fig. 6 shows that all cultivars provided a significant quadratic trend for maturation Jaen index ( $R^2=0.84$ ;  $p < 0.01$ ) (Eq. [2]) for the sampled period, while fruit firmness provided significant quadratic trend ( $R^2=0.8$ ;  $p < 0.01$ ) (Eq. [3]).

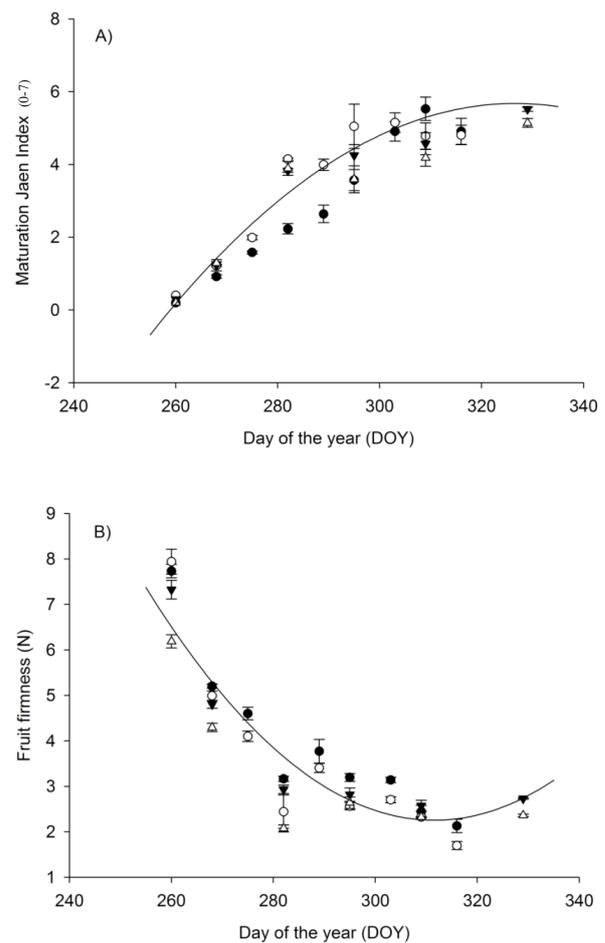
$$\text{Maturation Jaen index} = -0.00124 \cdot \text{DOY}^2 + 0.81 \cdot \text{DOY} - 126.6 \quad [2]$$

$$\text{Fruit firmness (N)} = 0.0016 \cdot \text{DOY}^2 - \text{DOY} + 157.6 \quad [3]$$

All studied cultivars showed high susceptibility of FDF and FDF/FW ratio to stalk twisting, while some



**Figure 5.** Mean and standard error for stalk length measured from attached branch to fruit for considered cultivars. Different letters show significant differences ( $p < 0.05$ ) between cultivars according to Duncan's test.



**Figure 6.** Maturation Jaen index (A) and fruit firmness (B) along the sampling process for different olive cultivars. In both cases,  $R^2$  values provided high significance ( $p < 0.01$ ).  $\circ$  Frantoio,  $\bullet$  Arbequina,  $\blacktriangledown$  Leccino,  $\square$  Maurino.

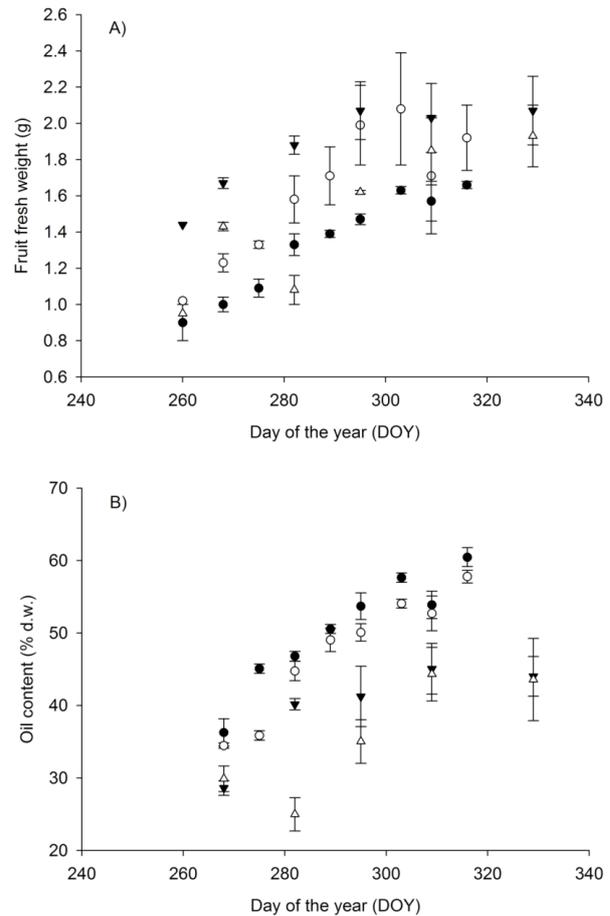
cultivars such as Arbequina, Leccino and Maurino varied FDF at a lesser extent along ripening process than along stalk twisting. Fruit detachment became easier along ripening process because of FDF reduction, although this reduction was usually greater only by applying a stalk twisting angle over 360°. However, all cultivars did not show the same pattern: Arbequina, Leccino and Maurino decreased more regularly along ripening, while Frantoio was more irregular. Furthermore, FDF was consistently reduced at wider stalk twisting angles in all cultivars suggesting a possible facilitation of harvesting process mainly for early harvesting. FW played also a role along the maturation process, softening FDF changes in frequently sampled cultivars as Arbequina and Frantoio, while in less frequently sampled cultivars, FDF/FW ratio provided higher differences between different stalk twisting angles than along ripeness process (Figs. 3, 4 and 8).

## Discussion

FDF decreased when it was measured after applying stalk twisting angles. FDF reduction was greater when stalk twisting was higher, which could play an important role in fruit detachment process. Although in other crops twisting movement pattern has limited importance (Zhou *et al.*, 2016), in olive inertial and bending forces can be key factors in fruit detachment process (Tsatsarelis, 1987). Therefore, current and future harvesters could take advantage of torsion strain at stalk level, due to the effect on FDF decrease. This could be particularly important for increasing harvesting efficiency in early harvesting, when trunk shaker causes a lower percentage of detached fruit than in late harvesting (Blanco-Roldán *et al.*, 2009).

Stalk twisting had different effect on FDF depending on cultivar: Leccino usually had higher FDF for all twisting angles than Maurino, while Arbequina and Frantoio had a more erratic behaviour. In early harvesting, Frantoio was roughly more difficult to detach as long as Arbequina was more difficult to detach during the final part of the ripening process. Those differences can be related to stalk length, physiological aspects or water stress. Furthermore, FDF depends strongly on stalk diameter (Lavee *et al.*, 1982) varying between different olive cultivars (Farinelli *et al.*, 2012b). Stalk length may affect harvesting performance due to vibration transmission from fruit bearing branches to stalk-to-attachment point or to stalk-to-fruit attachment point.

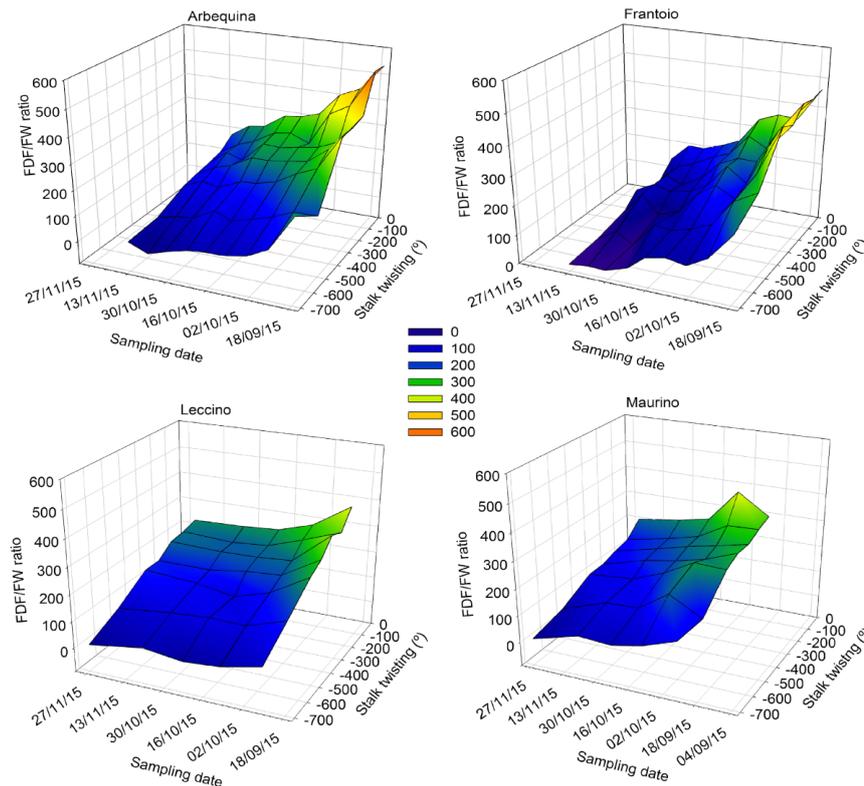
Provided data support the hypothesis that bending forces collaborate along with traction and inertial forces in fruit detachment process, as reported fruit species: in oranges, FDF decreases when the pulling direction forms



**Figure 7.** Mean and standard error for fruit fresh weight (A) and oil content on dry basis (B) for all cultivars in every sampling date. ○ Frantoio, ● Arbequina, ▼ Leccino, □ Maurino.

a greater angle with the pistil-calyx axe (Torregrosa *et al.*, 2014). Furthermore, in manual apple picking bend and pull forces are combined to reduce detachment energy as compared to the application of sole pulling force (Li *et al.*, 2016). Several fruit twisting can also facilitate fruit picking (Chiu *et al.*, 2013), mainly for table olives, which are highly susceptible to bruising.

Harvesting efficiency depends on several factors such as shaking frequency (Leone *et al.*, 2015; Tombesi *et al.*, 2017), abscission agent application (Sessiz & Özcan, 2006), tree features (Farinelli *et al.*, 2012a), time, and harvesting date (Castro-Garcia *et al.*, 2015). Different shaking technologies and vibration patterns could be applied to olive harvesting with similar final results (Sola-Guirado *et al.*, 2014). Different harvesting systems have variable harvesting efficiency within the canopy with possible effect on the oil quality considering that fruit with the highest oil yield and oil quality are located in the outermost part of the canopy (Castillo-Ruiz *et al.*, 2015b). Finally, future machines should match bending, torsion and traction forces with



**Figure 8.** Fruit detachment force to fruit fresh weight (FDF/FW) ratio evolution along ripening process for different stalk twisting angles and different cultivars.

inertial ones to accomplish a quick and effective fruit detachment that reduces required hand labour, which is currently used to assist trunk shaker harvesting with long poles or hand held devices.

Fresh FW increased along the maturation process due to tissue growth and oil accumulation (Farinelli *et al.*, 2002). FW played an important role during olive harvesting process, FDF/FW affects harvesting efficiency (Farinelli *et al.*, 2012b) mainly due to stalk bending forces, inertial phenomena and fatigue (Tsatsarelis, 1987). During early harvesting, high FDF reduces harvesting efficiency, thus, it is necessary to increase shaking time to achieve high removal efficiency (Blanco-Roldán *et al.*, 2009). But prolonged tree shaking can cause bark damages in particular when the tree is still vegetative (Gurusinghe & Shackel, 1995).

All tested cultivars provided an FDF value under 3 N when the stalk twisting was over 180° except Leccino, which reached the same values when stalk twisting was over 360°. Therefore, FDF measurement combining pulling and twisting forces could also be a useful index to predict both, harvesting efficiency and maximum oil content on a dry mass basis, determining the optimal harvesting time (Portarena *et al.*, 2015).

Results showed a quadratic trend for maturation Jaen index and fruit firmness along the ripening process.

However previous research, based on non-destructive methods, reports that olive skin colour followed a quadratic trend for Arbequina and Picual cultivars while firmness follows a linear trend (García & Yousfi, 2005). Other non-destructive methods to measure olive ripeness could be based on near infrared spectroscopy (Gracia & León, 2011) considering that fruit firmness is an important variable which influence fruit damages during mechanical harvesting (Tombesi *et al.*, 2011). Furthermore, for straddle harvesters based on canopy shaking, harvesting efficiency could be predicted using firmness, colorimetric and pigmentation indexes (Camposeo *et al.*, 2013).

Currently, for olive and other fruit crops, fruit ripening influence on harvesting process is measured by FDF (Zipori *et al.*, 2014) and FDF/FW ratio (Polat *et al.*, 2011) applying only traction forces to the fruit stalk. Each harvesting machine can cause a different stalk twisting angle depending on the machine-tree interactions (Tombesi *et al.*, 2017). Once mean twisting angle is known, it would be possible to get more reliable estimation of expected harvesting efficiency on the base of FDF and FDF/FW ratio at the expected stalk twisting interval. This methodology could be useful to predict a mechanical harvest efficiency over 85% particularly for early harvesting, considering that it takes place when FDF/FW ratio goes under 2.3 (Farinelli *et al.*, 2012b).

Further research is required to explain how other forces such as bending or inertial forces influence fruit detachment in olives and other crops as well as how climatic conditions affect FDF and FDF/FW evolution.

In summary, olive stalk resistance against pulling force was reduced when stalk twisting was applied in some olive cultivars. Since earliest sampling dates, all cultivars showed FDF under 3 N at stalk twisting angles over 180°, except for Leccino, that required wider angles (up to 360°). At the same time, FDF and FDF/FW ratio were reduced along the ripening process, although FDF/FW ratio provided less variability data and also took into account inertial forces during harvesting process. Combined pulling and twisting forces provide a better estimation of the real fruit susceptibility to detachment, closer to real harvesting. Jaen ripeness index, fruit firmness and oil content on a dry matter basis should be used along with FDF at different twisting angles, as predictors for optimal harvesting period in order to achieve the highest profitability for olive growers. Finally, present and future harvesting systems should take advantage of stalk susceptibility against torsion or bending strain to achieve higher harvesting efficiency.

## References

- Blanco-Roldán GL, Gil-Ribes JA, Kouraba K, Castro-García S, 2009. Effects of trunk shaker duration and repetitions on removal efficacy for the harvesting of oil olives. *Appl Eng Agric* 25: 329-334. <https://doi.org/10.13031/2013.26883>
- Çakmak B, Saraçoğlu T, Alayunt FN, Özarlan C, 2011. Vibration and noise characteristics of flap type olive har-vesters. *Appl Ergon* 42: 397-402. <https://doi.org/10.1016/j.apergo.2010.08.015>
- Camposeo S, Vivaldi GA, Gattullo CE, 2013. Ripening indices and harvesting times of different olive cultivars for continuous harvest. *Sci Hortic (Amsterdam)* 151: 1-10. <https://doi.org/10.1016/j.scienta.2012.12.019>
- Carmona-Torres C, Parra-López C, Hinojosa-Rodríguez A, Sayadi S, 2014. Farm-level multifunctionality associated with farming techniques in olive growing: An integrated modeling approach. *Agric Syst* 127: 97-114. <https://doi.org/10.1016/j.agry.2014.02.001>
- Castillo-Llanque F, Rapoport HF, 2009. Identifying the location of olive fruit abscission, *Sci Hortic (Amsterdam)* 120: 292-295. <https://doi.org/10.1016/j.scienta.2008.11.006>
- Castillo-Ruiz FJ, Jimenez-Jimenez F, Blanco-Roldan GL, Sola-Guirado RR, Agüera-Vega J, Castro-Garcia S, 2015a. Analysis of fruit and oil quantity and quality distribution in high-density olive trees in order to improve the mechanical harvesting process. *Span J Agric Res* 13: 1-8. <https://doi.org/10.5424/sjar/2015132-6513>
- Castillo-Ruiz FJ, Pérez-Ruiz M, Blanco-Roldán GL, Gil-Ribes JA, Agüera J, 2015b. Development of a telemetry and yield-mapping system of olive harvester. *Sensors* 15: 4001-4018. <https://doi.org/10.3390/s150204001>
- Castillo-Ruiz FJ, Tombesi S, Farinelli D, 2016. Tracking olive fruit movement and twisting using video analysis during harvesting process. *Proc. VIII Int Olive Symp, Split (Croatia), Oct 10-14*. pp: 134-141.
- Castro-García S, Blanco-Roldán GL, Gil-Ribes JA, Agüera-Vega J, 2008. Dynamic analysis of olive trees in intensive orchards under forced vibration. *Trees* 22: 795-802. <https://doi.org/10.1007/s00468-008-0240-9>
- Castro-Garcia S, Castillo-Ruiz FJ, Jimenez-Jimenez F, Gil-Ribes JA, Blanco-Roldan GL, 2015. Suitability of spanish "manzanilla" table olive orchards for trunk shaker harvesting. *Biosyst Eng* 129: 388-395. <https://doi.org/10.1016/j.biosystemseng.2014.11.012>
- Chiu YC, Yang PY, Chen S, 2013. Development of the end-effector of a picking robot for greenhouse-grown tomatoes. *Appl Eng Agric* 29: 1001-1009.
- D'Agostino A, Giametta F, Giametta G, Mauro S, Zimbalatti G, 2008. Preliminary tests to assess the dynamics of the vibrations transmitted on olive trees by mechanized harvest by shakers. *Acta Hortic* 791: 285-295. <https://doi.org/10.17660/ActaHortic.2008.791.41>
- Famiani F, Farinelli D, Rollo S, Camposeo S, Di Vaio C, Inglese P, 2014. Evaluation of different mechanical fruit harvesting systems and oil quality in very large size olive trees. *Span J Agric Res* 12 (4): 960-972. <https://doi.org/10.5424/sjar/2014124-5794>
- Farinelli D, Tombesi S, 2015. Performance and oil quality of "Arbequina" and four Italian olive cultivars under super high density hedgerow planting system cultivated in central Italy. *Sci Hortic (Amsterdam)* 192: 97-107. <https://doi.org/10.1016/j.scienta.2015.04.035>
- Farinelli D, Boco M, Tombesi A, 2002. Intensity and growth period of the fruit components of olive varieties. *Acta Hortic* 586: 607-610. <https://doi.org/10.17660/ActaHortic.2002.586.128>
- Farinelli D, Ruffolo M, Boco M, Tombesi A, 2012a. Yield efficiency and mechanical harvesting with trunk shaker of some international olive cultivars. *Proc. VI international symposium on olive growing, Evora (Portugal), Sept 9-13*. pp: 379-384. <https://doi.org/10.17660/ActaHortic.2012.949.55>
- Farinelli D, Tombesi S, Famiani F, Tombesi A, 2012b. The fruit detachment force/fruit weight ratio can be used to predict the harvesting yield and the efficiency of trunk shakers on mechanically harvested olives. *Proc. I Int Symp on Mechanical Harvesting and Handling Systems of Fruits and Nuts, Lake Alfred (USA), Apr 2-4*. pp: 61-64. <https://doi.org/10.17660/ActaHortic.2012.965.5>
- Garcia JM, Yousfi K, 2005. Non-destructive and objective methods for the evaluation of the maturation level of olive fruit. *Eur Food Res Technol* 221: 538-541. <https://doi.org/10.1007/s00217-005-1180-x>
- Gracia A, León L, 2011. Non-destructive assessment of olive fruit ripening by portable near infrared spectroscopy. *Gra-*

- sas y Aceites 62: 268-274. <https://doi.org/10.3989/gya.08-9610>
- Gurusinghe SH, Shackel KA, 1995. The relation of cambial zone mechanical strength to growth and irrigation of almond [*Prunus dulcis* (Mill.) Webb.] trees. *J Am Soc Hortic Sci* 120: 170-176.
- IOOC, 2015. World olive oil figures. <http://www.internationaloliveoil.org/estaticos/view/131-world-olive-oil-figures> [10/03/2016].
- Lavee S, Avidan B, Ben-Tal Y, 1982. Effect of fruit size and yield on the fruit-removal-force within and between olive cultivars. *Sci Hortic (Amsterdam)* 17: 27-32. [https://doi.org/10.1016/0304-4238\(82\)90058-9](https://doi.org/10.1016/0304-4238(82)90058-9)
- Leone A, Romaniello R, Tamborrino A, Catalano P, Peri G, 2015. Identification of vibration frequency, acceleration, and duration for efficient olive harvesting using a trunk shaker. *T ASABE* 58: 19-26.
- Li J, Karkee M, Zhang Q, Xiao K, Feng T, 2016. Characterizing apple picking patterns for robotic harvesting. *Comput Electron Agric* 127: 633-640. <https://doi.org/10.1016/j.compag.2016.07.024>
- López-Giménez FJ, 1979. Estudio dinámico de los modelos Fruto-pedúnculo del olivo. Doctoral thesis. Univ. of Córdoba, Córdoba Spain.
- MAPAMA, 2016. Olive oil and table olives. [http://www.mapa.gob.es/es/agricultura/temas/producciones\\_agricolas/aceite-oliva-y-aceituna-mesa/aceite.aspx](http://www.mapa.gob.es/es/agricultura/temas/producciones_agricolas/aceite-oliva-y-aceituna-mesa/aceite.aspx) [10/03/2016].
- Młotek M, Kuta Ł, Stopa R, Komarnicki P, 2015. The effect of manual harvesting of fruit on the health of workers and the quality of the obtained produce. *Procedia Manuf* 3: 17-12-1719. <https://doi.org/10.1016/j.promfg.2015.07.494>
- Novello R, Bueno LA, Andrieu J, Miranda O, 2014. Comparative study of mechanical harvesting costs for different planting models in San Juan, Argentina. *Acta Hortic* 1057: 453-456. <https://doi.org/10.17660/Acta-Hortic.2014.1057.57>
- Polat R, Acar I, Bilim HIC, Saglam R, Erol AKB, 2011. Determination of spring rigidity and fruit detachment force with respect to harvesting technique in pistachio nut trees. *Afr J Agric Res* 6: 532-537.
- Pomarici E, Vecchio R, 2013. The Italian olive oil industry in the global competitive scenario. *Agric Econ* 59: 361-372.
- Portarena S, Farinelli D, Lauteri M, Famiani F, Esti M, Brugnoli E, 2015. Stable isotope and fatty acid compositions of monovarietal olive oils: Implications of ripening stage and climate effects as determinants in traceability studies. *Food Control* 57: 129-135. <https://doi.org/10.1016/j.foodcont.2015.03.052>
- Sanders KF, 2005. Orange harvesting systems review. *Biosyst Eng* 90: 115-125. <https://doi.org/10.1016/j.biosystemseng.2004.10.006>
- Savary SKJU, Ehsani R, Salyani M, Hebel MA, Bora GC, 2011. Study of force distribution in the citrus tree canopy during harvest using a continuous canopy shaker. *Comput Electron Agric* 76: 51-58. <https://doi.org/10.1016/j.compag.2011.01.005>
- Sessiz A, Özcan MT, 2006. Olive removal with pneumatic branch shaker and abscission chemical. *J Food Eng* 76: 148-153. <https://doi.org/10.1016/j.jfoodeng.2005.05.002>
- Sola-Guirado RR, Castro-García S, Blanco-Roldán GL, Jiménez-Jiménez F, Castillo-Ruiz FJ, Gil-Ribes JA, 2014. Traditional olive tree response to oil olive harvesting technologies. *Biosyst Eng* 118: 186-193. <https://doi.org/10.1016/j.biosystemseng.2013.12.007>
- Tombesi S, Farinelli D, 2014. Evaluation of canopy elasticity, light penetration and reciprocal shading for optimal canopy management in high density hedgerow olive orchards. *Acta Hortic* 1057: 315-320. <https://doi.org/10.17660/ActaHortic.2014.1057.36>
- Tombesi S, Tombesi A, Molfese M, Cipolletti M, Visco T, 2011. Evaluation of four cultivars regarding their suitability in high-intensity olive orchards. *Proc. XXVIII International Horticultural Congress - IHC2010, Lisbon (Portugal), Aug 22-27*. pp: 321-326. <https://doi.org/10.17660/ActaHortic.2011.924.40>
- Tombesi S, Poni S, Palliotti A, Farinelli D, 2017. Mechanical vibration transmission and harvesting effectiveness is affected by the presence of branch suckers in olive trees. *Biosyst Eng* 158: 1-9. <https://doi.org/10.1016/j.biosystemseng.2017.03.010>
- Torregrosa A, Albert F, Aleixos N, Ortiz C, Blasco J, 2014. Analysis of the detachment of citrus fruits by vibration using artificial vision. *Biosyst Eng* 119: 1-2. <https://doi.org/10.1016/j.biosystemseng.2013.12.010>
- Tsatsarelis CA, 1987. Vibratory olive harvesting: The response of the fruit-stem system to fruit removing actions. *J Agric Eng Res* 38: 77-90. [https://doi.org/10.1016/0021-8634\(87\)90120-X](https://doi.org/10.1016/0021-8634(87)90120-X)
- Uceda M, Hermoso M, 1998. La calidad del aceite de oliva. In: *El cultivo del olivo*; Barranco D, Fernandez-Escobar R, Rallo L (eds.). pp: 547-572. Junta de Andalucía-Mundi-Prensa, Madrid.
- Upadhyaya SK, Cooke JR, Rand RH, 1981. Limb impact harvesting, Part I: Finite element analysis. *T ASAE* 24: 856-863. <https://doi.org/10.13031/2013.34352>
- Vilar Hernández J, Velasco Gámez MDM, Puentes Poyatos R, Martínez Rodríguez AM, 2011. El olivar tradicional: alternativas estratégicas de competitividad. *Grasas y Aceites* 62: 221-229. <https://doi.org/10.3989/gya.091610>
- Vivaldi G, Strippoli G, Pascuzzi S, Stellacci AM, Camposeo S, 2015. Olive genotypes cultivated in an adult high-density orchard respond differently to canopy restraining by mechanical and manual pruning. *Sci Hortic (Amsterdam)* 192: 391-399. <https://doi.org/10.1016/j.scienta.2015.06.004>
- Zhou J, He L, Karkee M, Zhang Q, 2016. Analysis of shaking-induced cherry fruit motion and damage. *Biosyst Eng* 144: 105-114. <https://doi.org/10.1016/j.biosystemseng.2016.02.007>
- Zipori I, Dag A, Tugendhaft Y, Birger R, 2014. Mechanical harvesting of table olives: Harvest efficiency and fruit quality. *HortScience* 49: 55-58.