Mechanical behaviour of plum fruits as affected by preharvest methyl jasmonate applications

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Abstract: In this study, the effects of preharvest methyl jasmonate (MeJA) applications on the mechanical behaviour of plum fruits (cv. 'President') were investigated. The mechanical behaviour of plum fruits to compression affected by different harvesting time were determined in terms of rupture force, specific deformation, rupture energy, toughness and rupture power at constant compression speed of 62.4 mm min^{-1}. Quasi-static compression loading of plum fruits were conducted at three compression axes (X- Y- and Z- axis) under application of different doses of MeJA before the harvest. MeJA doses were as 0 mg L^{-1}, 1,120 mg L^{-1}, and 2,240 mg L^{-1} harvested on the different days viz. 28 August, 4 September and 11 September. The force required to initiate plum rupture on each axis decreased as MeJA doses increased from 1,120 mg L^{-1} MeJA to 2,240 mg L^{-1} MeJA. The rupture energy and rupture power values observed for plum fruits compressed along the Y- axis were higher than the values obtained when testing plum fruits in the X- and Z-axis orientations. The results indicated that the rupture force and rupture energy along all three axes are highly dependent on MeJA applications. These finding could therefore be useful in predicting the mechanical behaviour of plum fruits.

Keywords: plum, methyl jasmonate, rupture force, rupture energy, rupture power

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1 Introduction

Plums belong to the Rosaceae family and include the European species (*Prunus domestica* L.), which is consumed fresh or dried, and the Japanese species (*Prunus salicina* Lindell) mainly freshly consumed (Manganaris et al., 2008). Plums are considered climacteric, although some plum cultivars do not show the typical increase in ethylene production and respiration until late ripening (Manganaris et al., 2008). Japanese plum species are mainly used for fresh purposes while European species are popular for post-harvest processing (Rieger, 2006).

Turkey ranks the 6th in the world in terms of plum production with 268,696 tons of production (FAO, 2011). Plant growth regulators, either natural or synthetic compounds affect one or more physiological events in a plant. Growth regulatory substances have been evaluated among factors causing changes in physical, mechanical, chemical and bioactive compounds in fruits (Shin et al., 2008). The use of growth regulatory substances in modern farming to improve fruit quality has become widespread. Methyl jasmonate (MeJA) is used as plant growth regulator in many fruits (Rohwer and Erwin, 2008). MeJA is important cellular regulators involved in diverse developmental processes, such as seed germination, root growth, fertility, fruit ripening, and synthesis of ethylene, accumulation of anthocyanin and promotion of senescence (Fan et al., 1997; Rohwer and Erwin, 2008).

During harvest and postharvest operations, the fruits go through several static and dynamic pressures such as high speed impacts which cause bruises, crushes and

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cracks that increase the susceptibility to deterioration during storage (Bargale-Praveen et al., 1995). The design of machines and devices used in the harvest and postharvest production processing, the strength behaviour under quasi-static compression loading of agricultural materials should be required. The harvested agricultural products have been damaged by the mechanical harvesting methods with exert load and breaking stress (Kuna-Broniowska et al., 2012). To textural analysis and understanding of quality of produced plums, force-deformation characteristics are known. Compression orientation and speed affect the amount of force applied to post-harvest applications for plum fruits. The technological characteristics of different biomaterials are closely associated with the development microstructure as a result of deformations in cells and intercellular spaces (Sosa et al., 2012).

Several researchers have investigated the mechanical behaviour under compression loading of some fruits such as mango (*Mangifera indica* L.) (Jha et al., 2005), orange (*Citrus cinensis* L.) (Topuz et al., 2005), cactus pear (*Opuntia ficus india* L.) (Kabas et al., 2006), 'Hayward' kiwifruit (*Actinidia chinensis*) (Razavi and Parvar, 2007), pear cultivars (*Pyrus communis* L.) (Ozturk et al., 2009) and persimmon (*Diospyros kaki* Thunb.) (Altuntas et al., 2011).

The compression orientation influences the force applied (Dursun, 1997). Oloso and Clarke (1993) evaluated the effect of direction of loading on rupture force, rupture energy and rupture deformation under compression tests. Gurhan et al. (2001) evaluated the mechanical behaviour of three apricot cultivars under compression loading at three axes and different deformation speeds. Guner et al. (2003) evaluated the mechanical behaviour of hazelnut cultivars under compression loading and two deformation rates to determine the rupture force, specific deformation and rupture energy required to initiate nut and kernel rupture. Altuntas et al. (2012) evaluated the physical and mechanical properties of Fuji apple as affected by methyl jasmonate treatments. As the MeJA doses increased from 1,120 to 4,480 mg L^{-1}, the skin firmness of apple linearly increased. The skin and flesh firmnesses were lower in control than those of MeJA treatments.

No detailed study concerning the mechanical behaviour such as rupture force, specific deformation and rupture energy, toughness and rupture power of plum fruit under quasi-static compression loading has been reported yet. Technical information and data in the scientific literature with regards to the effects of preharvest MeJA applications on the strength behaviour of plum fruit are insufficient. Thus, the objective of this study was to examine the effects of pre-harvest MeJA applications on variations in rupture force, specific deformation and rupture energy, toughness and rupture power of plum fruit skin (cv. 'President').

2 Materials and methods

Plant material in the research was obtained in 2012 from the farmer orchard of Tokat (39°51' N and 40°55' E), situated in the Middle Black Sea Region in Turkey. The 'President' plum variety (*Prunus domestica*) grafted on myrobalan rootstocks were planted on the land in 2006, 4 m apart in row and 4 m between rows order (4×4). The trees used in the experiment were trained according to the modified-leader system. The trees selected for the experiment had uniform fruit load. MeJA (Sigma-Aldrich, Milwaukee, Wis.) was applied at doses of 1,120 (MeJA-1) and 2,240 (MeJA-2) mg L^{-1} two weeks before optimal harvest time (21 August 2012). Optimal harvest time was determined by considering number of days after full bloom (135-145 days) for 'President'. MeJA was performed 2 weeks before optimal harvest period. This period is the period of ripening plums. In the study, it was aimed to determine the changes in the mechanical properties within the period of ripening plum-week intervals. Plums were completely harvested after 3 weeks of MeJA application. All spray solutions contained 0.077% v/v Triton X–100 (octoxynol, Aldrich). Each fruit was sprayed to drip. In addition, some trees served as a non-treatment (control) of MeJA (0 mg L^{-1} MeJA, MeJA-0). In addition, one tree in each block was only sprayed with 0.077% Triton X-100 and served as a non-treatment (control) of MeJA

Experimental design consisted three blocks each with three trees. In each block, one tree was selected for control treatment, one tree for 1,120 mg/L MeJA treatment and one tree for 2,240 mg/L MeJA treatment. Plum fruits were randomly harvested from a tree in each block for each treatment at three harvesting time (28 August, 4 September (optimal harvest time) and 11 September, 2012). Second harvesting time studied was the optimal harvesting of plum fruits. Harvested fruits were transferred to the laboratory in polyethylene bags to reduce moisture content during transportation.

A biological materials test device (Instruction Manual for Materials Testing Machines, BDO-FB 0.5 TS) (Zwick-Roell, Ulm, Germany) was used to determine the mechanical behaviour of the plum fruits tested. This device consists of three main components: a moving platform, a driving unit and a data acquisition (load cell, PC card and software) system (Altuntas and Yildiz, 2007). The fruit sample was placed on the moving platform and loaded at constant compression speed (1.06 mm/s) and pressed with a plate fixed on the load cell until to rupture the plum fruit. The plum fruits were measured with callipers (Model No; CD-6"CSX, Mitutoyo, Japan) to determine the length, width and thickness of the samples before analysis.

The specimens were axially loaded in an Instruction Manual for Materials Testing Machines equipped with a 500 N compression load cell. Whole plum samples were used for this experiment. Axial displacement (strain) and lateral deflections of the plum sample along compression orientations (X-, Y- and Z- axes) were measured and recorded by using the Testing Machine at the rupture limit of compression load. A digital vernier calliper was used for the size measurement of plum. Data on the mechanical strength properties (force, deformation and modulus of elasticity) were measured directly from the plotted force-deformation curve. The force-deformation curves were obtained at each loading orientation for each plum fruit at the different harvesting time. X, Y, and Z- compression axes of a plum fruits were used to determine the rupture force, specific deformation, rupture energy, toughness and rupture power. Three replications for each test and ten samples were used. The X-axis (force Fx) is the longitudinal axis through the length measured as X-axis, while the Y-axis (force Fy) is transverse axis containing the minor dimension (width) at right angles to the X-axis, Z-axis is the transverse axis containing the minor dimension (thickness).

The specific deformation was obtained from the following Equation (1):

$$\varepsilon = \left[1 - \frac{L_d}{L_{un}}\right] \times 100 \tag{1}$$

where, ε is the specific deformation (%); L_{un} (mm) is the undeformed plum fruit length measured in the direction of the compression axis and L_d (mm) is the deformed plum fruit length measured in the direction of the compression axis (Braga et al., 1999).

Energy absorbed (E) of plum fruits at the moment of rupture was determined by calculating the area under the force-deformation curve (Braga et al. 1999).

Toughness (T_o, mJ mm^{-3}) in this study is the ratio of the energy absorbed by the plum fruit to the point of rupture per unit volume of the plum fruit which was calculated using the following Equation (2) (Gupta and Das, 2000; Ozturk et al., 2009).

$$T_o = \frac{E_a}{V} \tag{2}$$

where, E_a is the energy absorbed in mJ and V is the volume of plum fruit tested in mm^3, which is obtained by analogy with a triaxial ellipsoid using the following Equation (3):

$$V = \frac{\pi}{6}(LWT) \tag{3}$$

The rupture power was calculated as Equation (4):

$$P_r = \left[\frac{E_a V_c}{60000D}\right] \tag{4}$$

where, P is required power for rupture in W; E_a is absorbed energy in mJ; V_c is compression speed in mm min^{-1} and D is deformation up to rupture point in mm (Khazaei et al., 2002). In this experiment, a total sample of 270 plum fruits were used, the data was analysed using a randomized complete block design with split block. In this design, the main factor was MeJA doses and sub-factor was harvesting time and compression axis. Results were analysed using analysis of variance and the means were compared using LSD test as described by Gomez and Gomez (1984).

3 Results and Discussion

The mean length, width and thickness, geometric mean diameter and unit mass of plum fruits were found to be 56.76 mm, 46.54 mm, 46.00 mm, 49.33 mm and 70.86 g for MeJa-0, respectively. The mean length, width and thickness, geometric mean diameter and unit mass of plum fruits ranged from 54.48 mm to 54.40 mm, 44.37 mm to 45.67 mm, 44.24 mm to 44.96 mm, 47.26 mm to 47.96 mm and 65.10 g to 69.02 g with an increase MeJA dose from 1,120 to 2,240 mg L^{-1}, respectively.

Rupture force

The effect of MeJA doses, compression axes and harvesting time on rupture force was significant ($p<0.01$). The force required to initiate plum fruit rupture in samples with varying MeJA doses and harvesting time at the three different compression axes is presented in Table 1. The force required to initiate plum fruit rupture on the X-axis decreased as MeJA doses increased from 0 to 2,240 mg L^{-1}. The rupture forces required when loading along the Y- axis were found to be 243.6–228.2 N and 140–129.6 N as the MeJA doses increased through the three harvesting times categories. The results indicated that the rupture force along all three axes is highly dependent on harvesting time over the MeJA doses ranges investigated. Greater force was required to rupture plum fruits with low MeJA 0 values being tested for each loading orientation. Y-axis recorded the highest resistance to rupture force during loading. The rupture force measured when loading along the lateral axis (Y-axis) was found to be 243.6 N to 228.2 N, 225.2 N to 174.6 N and 202.6 N to 171.0 N for plum fruits harvested on 28 August, 4 September and 11 September, respectively.

The maximum compressive force for cherry tomatoes were found as 22.66 N, 15.93 N and 23.81 N for ‘Zucchero’, ‘Mosaica’ and ‘1018 F1’ varieties, respectively by Kabas and Ozmerzi (2008). Similarly, the average rupture force and fruit hardness was determined as 23.04 N to 39.59 N and 9.87 N mm^{-1} to 13.74 N mm^{-1} between ‘Deveci’ and ‘Santa Maria’ cultivars of pear fruits (Ozturk et al., 2009). The rupture force of *Jatropha curcas* L. fruits were reported as 135.39 N by Sirisomboon et al. (2007). The rupture force required to initiate Oak marble galls along the Y- and X-axis were as 236.44 N and 201.78 N, respectively (Bahrami et al., 2012). Kilickan and Guner (2008) reported that the rupture force of the olive fruit increased in magnitude with an increase in deformation rate and size. The rupture force values along X- and Y-axis were found as 94.45 N and 57.38 N, respectively. The values of rupture force were obtained to be about 26.75 N, 37.36 N and 63.26 N for apple cvs. ‘Golden Delicious’, ‘Starking Delicious’ and ‘Granny Smith’, respectively (Ozturk et al., 2010). Akinoso and Raji (2011) reported that rupture force of date palm fruits, for ‘Tenera’ and ‘Dura’ cultivars were 806.1 N and 3,924.6 N at 5% wet basis and 40℃ heat temperature, respectively.

Table 1 Effects of methyl jasmonate, harvesting time and compression axes on rupture force of plum fruits (N)

MeJA applications /mg L^{-1}	Compression axes	Harvesting time			Mean
		28 Aug.	4 Sept.	11 Sept.	
0	X - axis	180.0	171.5	165.4	172.3
	Y - axis	243.6	236.0	228.2	235.9
	Z - axis	200.8	181.7	184.5	189.0
	Mean	208.0	196.0	193.0	199.0 a[a]
1120	X - axis	164.2	156.6	142.6	154.5
	Y - axis	225.2	180.8	174.6	193.5
	Z - axis	187.4	160.3	169.0	172.2
	Mean	192.0	166.0	162.0	173.0 b
2240	X - axis	140.0	135.2	129.6	134.9
	Y - axis	202.6	161.8	171.0	178.5
	Z - axis	162.4	185.8	142.8	163.7
	Mean	168.3	160.9	147.8	159.0 c
	Mean	189.4 a[a]	174.3 ab	167.6 b	
	X mean	161.4	154.5	145.9	154 c[a]
	Y mean	223.8	192.9	191.3	203 a
	Z mean	189.0	175.9	165.4	177 b

Note: [a] The means in the same group not followed by the same letter (within same line and column) are not significantly different according to Fisher protected LSD test ($P = 0.01$).

Specific deformation

The effect of MeJA applications on specific deformation was not significant; whereas, the effects of compression axes and harvesting time at specific deformation was significant ($p<0.05$; $p<0.01$, respectively). The specific deformation generally decreased along the X-, Y-, and Z-axis as MeJA doses increased. The highest specific deformation was obtained for plum fruits loaded along the Y-axis, whereas the least specific deformation was obtained along the Z-axis. The specific deformation values ranged from 28.13% to 16.84% as the harvesting time increased through the three test compression axes for plum fruits. The results show that the specific deformation along any of the X-, Y- and Z-axes is highly dependent on the MeJA doses over the range of harvesting time investigated (Table 2).

Table 2 Effects of methyl jasmonate, harvesting time and compression axes on specific deformation of plum fruits (%)

MeJA applications /mg L^{-1}	Compression axes	Harvesting time			Mean
		28 Aug.	4 Sept.	11 Sept.	
0	X - axis	21.40	22.66	27.13	23.73
	Y - axis	27.22	22.51	24.17	24.63
	Z - axis	23.86	20.42	22.37	22.22
	Mean	24.16	21.86	24.56	23.53 ns
1120	X - axis	26.10	21.10	17.71	21.64
	Y - axis	30.93	20.22	19.49	23.55
	Z - axis	23.70	19.77	19.52	21.00
	Mean	26.91	20.36	18.91	22.06 ns
2240	X - axis	29.67	20.55	16.07	22.10
	Y - axis	29.07	19.23	19.09	22.46
	Z - axis	25.66	15.41	15.37	18.81
	Mean	28.13	18.40	16.84	21.12 ns
	Mean	26.40 a[a]	20.21b	20.10 b	
	X mean	25.73	21.44	20.30	22.50 ab[b]
	Y mean	29.07	20.65	20.92	23.50 a
	Z mean	24.41	18.53	19.09	20.70 b

Note: [a] The means in the same group not followed by the same letter (within same line) are not significantly different according to Fisher protected LSD test ($P = 0.01$).

[b] The means in the same group not followed by the same letter (within same column) are not significantly different according to Fisher protected LSD test ($P = 0.05$).

The rupture force values were observed to be 27.27% to 24.17% (MeJA-0); 30.93% to 19.49% (MeJA-1); and 29.07% to 19.09% (MeJA-2) when loading along the Y-axis. Z-axis yielded the least specific deformation among other loading orientations. The specific deformation measured while loading along the lateral axis (Z-axis) was found to be 23.86% to 22.37% (MeJA-0); 23.70% to 19.52% (MeJA-1); and 25.66% to 15.37% (MeJA-2) for the three MeJA applications examined. The specific deformation was measured as 21.40% to 27.13%, 26.10% to 17.71% and 29.67% to 16.07% when loading along the X-axis as the MeJA doses increased from 0 to 2,240 mg L^{-1} for plum fruits. The specific deformation values for president plum fruits compressed along the Y- axis were higher than those compressed along the X-axis and Z-axis.

Likewise, the maximum specific deformation values for cherry tomatoes were found as 9.35%, 5.52% and 13.92% for 'Zucchero', 'Mosaica' and '1018 F1' varieties, respectively. The specific deformation values were found to be statistically significantly different at $p<0.01$ for all varieties. The tomato variety '1018 F1' has the higher mean of specific deformation value than the other varieties as elucidated by Kabas and Ozmerzi (2008). The average deformation values determined as 2.96 mm and 2.38 mm for 'Deveci' and 'Santa Maria' pear cultivars (Ozturk et al., 2009). Akinoso and Raji (2011) reported that deformation of date palm fruits, for 'Tenera' and 'Dura' cultivars were 11.7 mm and 8.7 mm at 5% wet basis and 40℃ heat temperature, respectively. Kilickan and Guner (2008) reported that the specific deformation of the olive fruit increased in magnitude with an increase in deformation rate and size. The highest specific deformation of the olive fruit among the axes at all deformation rates and sizes were obtained for X-axis except for specific deformation for olive fruit. The specific deformation values along X and Y-axes were reported as 20.2% and 22.6%, respectively. The values of deformation at rupture were found to be about 2.90 mm, 3.03 mm, and 3.14 mm for apple cvs. 'Golden Delicious', 'Starking Delicious' and 'Granny Smith', respectively (Ozturk et al., 2010).

Rupture energy

The energy of rupture decreased along the X, Y and Z-axis as increased MeJA doses through the three harvesting time categories. The results show that the rupture energy along any of the test axes (Table 3) is generally highly dependent on the MeJA application and harvesting time of the plum fruits tested. The highest rupture energy was obtained for plum fruits loaded along the Y-axis, while those loaded along the Z-axis required the least energy to rupture. The effects of MeJA applications, compression axes and harvesting time on rupture energy were significant ($p<0.01$). Loading along the Z-axis required the least amount of energy to rupture the skin fruit, relative to other orientations. The rupture energy values for plum fruits compressed along the Y-axis were higher than those compressed along the X- and Z-axis.

Table 3 Effects of methyl jasmonate, harvesting time and compression axes on rupture energy of plum fruits (mJ)

MeJA applications /mg L^{-1}	Compression axes	Harvesting time			Mean
		28 Aug.	4 Sept.	11 Sept.	
0 mg L^{-1}	X - axis	1800.0	1745.0	1725.9	1757.0
	Y - axis	2744.2	2446.1	2618.6	2603.0
	Z - axis	2296.1	1925.7	1783.2	2001.7
	Mean	2280.1	2039.0	2042.6	2120.5 a[a]
1120	X - axis	1621.5	1589.5	1454.5	1555.2
	Y - axis	2390.5	1861.7	1647.4	1966.5
	Z - axis	1755.0	1536.0	1535.4	1608.8
	Mean	1922.3	1662.4	1545.7	1710.2 b
2240	X - axis	1260.0	1365.5	1142.4	1256.0
	Y - axis	2099.9	1450.5	1624.5	1725.0
	Z - axis	1334.1	1678.7	1204.5	1405.8
	Mean	1564.7	1498.3	1323.8	1462.3 c
	Mean	1922.4 a[a]	1733.2 b	1637.4 b	
	X mean	1560.5	1566.7	1441.0	1522.7 b[a]
	Y mean	2411.5	1919.5	1963.5	2098.2 a
	Z mean	1795.1	1713.5	1507.7	1672.1 b

Note: [a] The means in the same group not followed by the same letter (within same line and column) are not significantly different according to Fisher protected LSD test ($P = 0.01$).

The rupture energy values were 2,744.2 mJ to 2,618.6 mJ (MeJA-0), 2,390.5 mJ to 1,647.4 mJ (MeJA-1) and 2,099.9 mJ to 1,624.5 mJ (MeJA-2) when loading along the Y-axis. The rupture energy measured when loading along the lateral axis (X-axis) was found to be 1,800 mJ to 1,725.9 mJ, 1,621.5 mJ to 1,454.5 mJ and 1,260 mJ to 1,142.4 mJ for samples with MeJA application doses of 0, 1,120, 2,240 mg L^{-1}, respectively. The rupture energy values were determined to be 2,296.1 mJ to 1,783.2 mJ, 1,755 mJ to 1,535.4 mJ and 1,334.1 mJ to 1,204.5 mJ when loading along the Z-front axis as MeJA doses increased through the three harvesting time test categories.

Failure energy values of 'Redspar' and 'Delbarstival' apple cultivars resulted in different means 127.59 N mm and 51.06 N mm (Kheiralipour et al., 2008). The average energy absorbed values for rupture determined as 58.64 N mm and 28.65 N mm for 'Deveci' and 'Santa Maria' cultivars (Ozturk et al., 2009). Energy absorbed of apple cultivars were recorded as 39.14 N mm ('Golden Delicious'), 56.97 N mm ('Starking Delicious') and 100.02 N mm ('Granny Smith'), respectively. The deformation energies of cherry tomatoes were 74.32 N mm, 85.28 N mm and 71.67 N mm for 'Zucchero F1', 'Mosaica F1' and '1018 F1', respectively. The deformation energy of 'Mosaica F1' was significantly higher than 'Zucchero F1' and '1018 F1' (Kabas and Ozmerzi, 2008). Similarly, Akinoso and Raji (2011) reported that rupture energy of palm fruits for 'Tenera' and 'Dura' cultivars to be 4.2 N m and 4.9 N m at 5% wet basis and 40℃ heat temperature, respectively. Kilickan and Guner (2008) reported that the rupture energy of the olive fruit increased in magnitude with an increase in deformation rate and size. The highest rupture energy of the olive fruit among the axes at all deformation rates and sizes were obtained for X-axis. The rupture energies of olive fruits were 0.32 N m and 0.26 N m along X- and Y-axis, respectively.

Toughness

Generally, the toughness of plum fruits decreased along the X, Y and Z- axis as increased MeJA doses through the three harvesting time categories. The effects of MeJA applications, compression axes and harvesting time on toughness of plum fruits were significant ($p<0.01$). Toughness along the X, Y and Z-axis (Table 4) is highly dependent on MeJA doses over the range of harvesting time investigated. Toughness values determined along the Y-axis were higher than those observed for other two axes. This indicated that higher force was required to rupture plum fruits along the Y-axis. The toughness observed when testing plum fruits oriented along the Y-axis were greater than that of the other axes tested at the lower MeJA-0 dose.

The loading orientation with the lowest values of firmness was the X-axis. Toughness measured while loading along the lateral axis (X-axis) was 0.324 mJ mm^{-3} to 0.293 mJ mm^{-3}, 0.278 mJ mm^{-3} to 0.215 mJ mm^{-3} and 0.253 mJ mm^{-3} to 0.233 mJ mm^{-3} for MeJA application doses of 0, 1120 mJ mm^{-3} and 2,240 mg L^{-1}, respectively. The toughness values were determined to be 0.428 mJ mm^{-3} to 0.402 mJ mm^{-3} (MeJA-0), 0.408 mJ mm^{-3} to 0.305 mJ mm^{-3} (MeJA-1) and 0.371 to 0.302 mJ mm^{-3}

(MeJA-2) when loading along the Y- axis for the three MeJA doses categories tested. The toughness values observed were 0.365 to 0.310 N mm^{-3}, 0.330 to 0.296 mJ mm^{-3} and 0.281 to 0.250 mJ mm^{-3} when loading along the Z-axis for the three tested MeJA categories, respectively. The toughness values for plum fruits tested in the Y-axis were higher than plum fruits tested in the X- and Z-axis orientations.

Table 4 Effects of methyl jasmonate, harvesing time and compression axes on toughness of plum fruits (mJ mm^{-3})

MeJA applications /mg L^{-1}	Compression axes	Harvesting time			Mean
		28 Aug.	4 Sept.	11 Sept.	
0	X - axis	0.324	0.288	0.293	0.302
	Y - axis	0.428	0.422	0.402	0.418
	Z - axis	0.365	0.327	0.310	0.334
	Mean	0.372	0.346	0.335	0.351 a[a]
1120	X - axis	0.278	0.224	0.215	0.239
	Y - axis	0.408	0.311	0.305	0.341
	Z - axis	0.330	0.264	0.296	0.297
	Mean	0.339	0.267	0.272	0.292 b
2240	X - axis	0.253	0.212	0.233	0.233
	Y - axis	0.371	0.283	0.302	0.319
	Z - axis	0.281	0.329	0.250	0.287
	Mean	0.302	0.275	0.262	0.279 b
	Mean	0.338 a[a]	0.296 b	0.290 b	
	X mean	0.285	0.242	0.247	0.258 c[a]
	Y mean	0.402	0.339	0.337	0.359 a
	Z mean	0.325	0.307	0.285	0.306 b

Note: [a] The means in the same group not followed by the same letter (within same line and column) are not significantly different according to Fisher protected LSD test ($P = 0.01$).

The average toughness values for rupture determined as 0.46 mJ cm^{-3} and 0.30 mJ cm^{-3} for 'Deveci' and 'Santa Maria' cultivars (Ozturk et al., 2009). The toughness for cherry tomatoes were 0.67, mJ mm^{3}, 0.75 mJ mm^{-3} and 0.65 mJ mm^{-3} for 'Zucchero F1', 'Mosaica F1' and '1018 F1', respectively (Kabas and Ozmerzi, 2008). The values of toughness of apple cultivars were reported as 0.53 mJ cm^{-3} ('Golden Delicious'), 0.64 mJ cm^{-3} ('Starking Delicious') and 0.86 mJ cm^{-3} ('Granny Smith') by Ozturk et al. (2010).

Rupture power

Rupture power values determined along the Y- axis were higher than those observed for both the X- and Z-axis (Table 5). And also the power of rupture observed when a testing plum fruit along the Y- axis was greater than that of the other axes tested for all the harvesting time.

Table 5 Effects of methyl jasmonate, harvesting time and compression axes on rupture power of plum fruits (W)

MeJA applications /mg L^{-1}	Compression axes	Harvesting time			Mean
		28 Aug.	4 Sept.	11 Sept.	
0	X - axis	0.094	0.089	0.086	0.090
	Y - axis	0.127	0.123	0.119	0.123
	Z - axis	0.104	0.094	0.096	0.098
	Mean	0.108	0.102	0.100	0.104 a[a]
1120	X - axis	0.085	0.081	0.074	0.080
	Y - axis	0.117	0.094	0.091	0.101
	Z - axis	0.097	0.083	0.088	0.090
	Mean	0.100	0.086	0.084	0.090 b
2240	X - axis	0.073	0.070	0.067	0.070
	Y - axis	0.105	0.084	0.089	0.093
	Z - axis	0.084	0.097	0.074	0.085
	Mean	0.088	0.084	0.077	0.083 b
	Mean	0.099 a[b]	0.091 ab	0.087 b	
	X mean	0.084	0.080	0.076	0.080 c[a]
	Y mean	0.116	0.100	0.099	0.105 a
	Z mean	0.095	0.091	0.086	0.091 b

Note: [a] The means in the same group not followed by the same letter (within same line and column) are not significantly different according to Fisher protected LSD test ($P = 0.01$).

The effects of MeJA applications and compression axes on rupture power of plum fruits were significant ($p<0.01$); whereas, the effects of harvesting time on rupture power of plum fruits were significant ($p<0.05$). The loading axis with the lowest values for power of cracking was the X- axis.

Rupture power measured, while loading along longitudinal axis (Y- axis) ranged from 0.127 W to 0.119 W (MeJA-0), 0.117 W to 0.091 W (MeJA-1) and 0.105 W to 0.089 W (MeJA-2) applications, respectively. The lowest power of cracking values changed from 0.094 W to 0.086 W (MeJA-0), 0.085 W to 0.074 W (MeJA-1) and 0.073 W to 0.067 W (MeJA-2) when loading along the X- axis for the three harvesting time categories tested. The power of cracking values for almond cultivars tested in the Y- axis were higher than almonds tested in the X- and *Z*-axis.

Altuntas et al (2010) reported that rupture power measured while loading along longitudinal axis (X- axis) ranged from 0.20 W to 0.73 W ('Nonpareil'), 0.20 W to 0.67 W ('Picantili') and 0.18 W to 0.65 W ('Drake') cultivar, respectively. The power of cracking values for almond cultivars tested in the X- axis were higher than almonds tested in the Y- and Z-axes. Khazaei et al. (2002) reported the required rupture power increased with increasing almond dimension and the compression speed. The difference between power of rupture for big and medium almonds wasn't statistically significant. The power of rupture along the Y- axis was greater than that of the other axes tested for all the harvesting time. MeJA applications and compression axes affect the rupture power of plum fruits.

4 Conclusions

In this study, the effect of MeJA applications (1,120 mg L^{-1} and 2,240 mg L^{-1}) on mechanical behaviour of plum fruit 'cv. President' was determined. The results indicated that the rupture force, rupture energy and rupture power are highly dependent on MeJA doses at all three harvesting time and compression axes. Greater force was required to rupture plum fruits with high MeJA dose while being tested using all the compression axes. The specific deformation and rupture energy values observed for plum fruits compressed along the Y- axis were higher than the values obtained when testing plum fruits in the X- and Z- orientations. The toughness of plum fruits tested along the Z-axis was higher than those tested in the X- and Y-axes orientations. The effects of MeJA applications, harvesting time and compression axes on rupture force, rupture energy, toughness and rupture power were statistically significant. The rupture energy and rupture power for plum fruits were higher along the Y- axis than X- and Z- axis orientations. Selected mechanical properties of plum fruits (rupture force and rupture energy) were statistically affected by MeJA applications. For this reason, the harvest and postharvest production processing of plum fruits must be designed while taking these criteria into consideration such as mechanical parameters for plum fruits.

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