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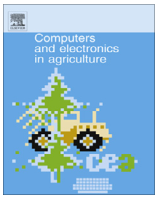

Original papers

# Effect of catching surface and tilt angle on bruise damage of sweet cherry due to mechanical impact

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ABSTRACT

Fruit bruise damage induced by mechanical impact is the most critical obstacle for the application of mechanical harvesting on fresh-market sweet cherries. One of main sources of fruit bruise is the mechanical impact by fruit catching surfaces occurring in fruit collection during mechanical harvesting. The goal of this research was to investigate the effect of cushion material, fruit drop height, and tilt angle of catching surface on fruit bruise damage. Three catching surfaces with five tilt angles from 0° to 60° were used to catch fruits freely dropped from heights of 0.3–2.1 m. The impact force and deformation of cushion materials was measured by a force sensing unit and a high speed camera, respectively. Results showed that maximum impact force increased linearly with drop height and was reduced by cushion materials with sufficient thickness. The fruit damage percentages of cushion material 1 and 2 were 25.0–89.0% and 72.0–100.0% less than that of non-cushion material at drop height of 0.3–2.1 m at 0° tilt angle, respectively. Results also shown catching surfaces with tilt angle reduced bruise damage substantially. Damage percentage of catching surfaces at 60° tilt angle was around 75.0% less than that at 0° non-cushion and cushion material when fruit were dropped from 1.5 m. The results show that catching surfaces with cushion materials at a tilt angle of 60° might be a promise for mechanical harvesting of fruits with low fruit bruise damage.

## 1. Introduction

The consumption of fresh market sweet cherry (*Prunus avium* L.) has been increasing rapidly around the world in recent years (USDA-ERS, 2012). In U.S, good return and profit margin has led to a substantial increase in planting acreage from 24,300 ha in 2000 to 34,400 ha in 2009 (USDA-ERS, 2012). Currently, all the fresh-market sweet cherry is harvested by seasonal pickers. However, decreasing labor availability and increasing labor cost have been one of the most critical challenges for sweet cherry growers. Especially, the increased labor cost is decreasing the return to growers, making it difficult for them to remain competitive and sustainable. Development and adoption of mechanical harvesting technologies is becoming essential to address these labor-related issues in sweet cherry and other tree fruit production.

Mechanical harvesting of tree fruit crops, including sweet cherry, has been investigated for many decades (Adrian et al., 1965; Pellerin et al., 1982; Peterson and Brown, 1996; Erdoğan et al., 2003; Polat et al., 2007; Zhou et al., 2013), but the commercial adoption for fresh market fruit is still lacking. One of the obstacles for adopting mechanical harvesting to fresh market sweet cherry and other tree fruit is the harvest-induced fruit damage. In an early trail of mechanical harvesting of sweet cherry, Halderson (1966) used a commercial nut shaker and found that the damage percentage of machine harvested fruit was three times higher than that of hand picking. More recently, Peterson et al. (2003) developed a new limb knocker to harvest fresh-market tree fruit including cherry and apple. The authors reported that only 58.0–64.0% of fruit achieved marketable quality in the trail of harvesting "Bing" sweet cherries. Chen et al. (2012) reported an average fruit damage percentage of 23.9% in a field test using a handheld vibratory harvester to harvest sweet cherry. Zhou et al. (2014) found that the mechanical harvester could remove more than 90.0% of fresh cherries from tree branches if suitable excitation positions were selected, but around 29.0% fruit were bruised during harvesting. These reports indicated that the high fruit damage percentage of sweet cherry using mechanical harvesting technologies is still the key issue that needs to be addressed.

Harvest-induced fruit damage is mainly caused by mechanical impact of fruit-to-fruit or limb-to-fruit contacts, which happens in detaching process and/or during fruit catching (Norton et al.,

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1962; Markwardt et al., 1964; Opara and Pathare, 2014). Trees in sweet cherry orchards of Northwest Pacific region of U.S. are usually 3–5 m in height, and 2–5 m in width (Ampatzidis and Whiting, 2013). Fruits mechanically detached from these trees will fall down from the height of up to 2 m before caught by catching surfaces. To reduce fruit damage, fruit catching surfaces are padded with various impact absorbing materials (cushion materials) during harvesting (Erdoğan et al., 2003). Erdoğan et al. (2003) found that fruit damage reduced 30.0% when 20-mm canvas material was put on the ground during mechanical harvesting of apricots. Xu et al. (2015) also found that mechanical impact of blue berries was reduced significantly by using cushion materials on packing lines. The basic principle of using cushion materials is to absorb the kinetic energy, which can result in bruise damage when exceeds a threshold for tissue failure (Van linden et al., 2006a). Different cushion materials have different firmness, density and elasticity and will perform differently in reduction of fruit bruise damage (Jarimopas et al., 2007; Ahmadi et al., 2010). Clark (1971) used two types of polyurethane foam to form low-impact fruit cushion surfaces to reduce the mechanical impact in catching falling peaches, and found that catching surfaces with a wedge shape had low impact force and less rebound height. Through a theoretical analysis of extended Hertz contact theory, Horsfield et al. (1972) found that a material with a low modulus of elasticity could more effectively reduce the impact-induced peach bruise damage while using the material to catch the falling fruit.

Other than the cushion materials to absorb mechanical impact energy, there is also a potential to reduce mechanical impact by adjusting tilt angle of catching surface. In fully mechanical harvesting system of cherries, fruit catching devices were often made of a set of catching plates covered with cushion materials, with the catching surface usually tilted at an angle for collecting fruits (Peterson et al., 2003; Torregrosa et al., 2006). However, no researches were conducted to determine how tilt angle of fruit catching devices affects the fruit damage. In this research, a laboratory experiment was designed to study the aforementioned factors of cushion materials and tilt angle of catching surface affecting the bruise damage. A laboratory scale fruit catching system was developed to mimic the fruit catching process, and determine the effect of fruit drop height, cushion materials and tilt angle on bruise damage of sweet cherries. The specific objectives of this research are: (1) to develop a fruit impact sensing system to measure the impact force and deformation of cushion material in fruit catching process; and (2) to determine the effect of cushion material, fruit drop height, and tilt angle of catching surface on bruise damage of sweet cherries.

## 2. Materials and methods

### 2.1. Development of experimental system

In this study, a laboratory-scale fruit catching frame was designed and fabricated (Fig. 1). This research platform consisted of four functional parts: (i) a fruit guidance tube, (ii) a fruit catching plate, (iii) an impact force sensing unit, and (iv) an image acquisition unit. The guidance tube was adjustable in both vertical direction (from 0 to 3.0 m above the catching plate) and horizontal direction. The guide tube allowed cherry samples in one treatment to be dropped from exactly the same height and guided to same target zone of the fruit catching plate. The catching plate was made of aluminum material, where the sensing unit was mounted underneath (Fig. 1a). The tilting setup of the catching plate was shown in Fig. 1b, which shows that one end of the catching plate (aluminum material) was attached to the impact force sensor and another end was hinged to the frame. By adjusting the position of the hinge and sensor location, the catching frame could be adjusted from 0° to 90° from the ground level. The different foams (cushion materials hereafter) would be attached on the surface of the catching plate (non-cushion material hereafter) to reduce fruit bruise damage.

To study mechanical impact force on the fruit bruise damage, a pendulum impactor is commonly used for impact tests in many researches (Van linden et al., 2006b; Opara et al., 2007), where a fruit was attached to the end of a pendulum arm and hits on a sensing unit to measure impact force. This method is suitable for measure the impact force, but it is difficult to detect the force of a fruit falling on a tilting catching surface. In this test, a mechanical impact sensing system was developed, which included an impact force sensing unit (208C02, PCB Piezotronics, Depew, NY), a signal conditioner (482A21, PCB Piezotronics, Depew, NY), an analog signal acquisition module (NI 9205, National Instruments, Austin, TX) and associated software. The impact force unit is a calibrated ICP® force sensor with upper frequency response of 36 kHz and non-linearity of less than 1.0%. The NI signal acquisition module is a high resolution analog input module with 16-bit resolution and 250 kHz sample rate. The impact force was sampled at a rate of 10 kHz in this study. At same time, a high speed camera (HiSpec 1, Fastec Imaging, San Diego, CA) was used to record the impact process of cherry fruits hitting on catching surface at the rate of 1500 frames per second (fps). The high speed images were used to quantify the deformation of cushion materials and tracking the impact position of fruits.

### 2.2. Sample preparation and experimental design

Fruit samples were manually picked from 11-year-old "Skeena" cherry trees at commercial harvesting time in an orchard near Sunnyside, WA, USA. Samples were selected with a cherry color chart (Cerise, Centre Technique Interprofessionel des Fruit et Légumes, Paris, France) and only those with skin color of approximate six grade were chosen. All fruits were carefully picked in the morning time when they were firm to avoid bruise damage and were processed timely in the same day. Approximate 1200 visually selected defect-free fruit samples were selected from those hand-picked fruits and were randomly divided into 45 groups with 25 fruits in each group. Each fruit sample was weighted, labeled and followed by firmness test with a firmness tester (Firm Tech 2, Bio Works, Wamego, Kansas). The firmness tester measures the fruit firmness using the force–deformation response from a cherry fruit compressed across fruit cheeks with deformation of 1 mm. This firmness tester is a widely used non-destructive instrument for testing the firmness of soft fruit (such as cherry, berry) in quality assessment research (Hampson et al., 2014; Mezzetti, 2013). The tester was also used to monitor the change of fruit firmness continually (Yang et al., 2008; Schrader, 2005) and no report indicated significant quality change in the test fruits. The average firmness and average weight of fruits in a group was listed in Table 1. With the ANOVA test described in Section 2.5, it is found that there was no difference in average firmness and weight of fruits among those test groups. All the prepared samples were kept in the preparation room with room temperature of 21.0 °C and relative humidity (RH) of around 60.0%. The same room condition was also applied to the room of experiment. To avoid the development of further damage, the prepared fruit samples were tested in the same day as they were sampled.

In this study, three external factors related to mechanical induced fruit damage were investigated, i.e. drop height, cushion material and tilt angle. The test drop height in this study was selected from 0.3 to 2.1 m according to the potential falling height in orchard condition of Washington State. The used cushion materials were two off-the-shelf foams, which were commonly used as