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Characterizing apple picking patterns for robotic harvesting

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ABSTRACT

Fruit detachment is one of the essential tasks in apple harvest. The resistance of detaching an apple from the tree is largely influenced by picking patterns. This research aimed at gaining an understanding of fruit detachment process under different picking patterns, focused on characterizing those processes using a few key detaching parameters. It also aimed at identifying an effective robotic picking pattern using a three-finger gripper. To accomplish this goal, one manual and three robotic apple checking patterns were studied, by measuring and analyzing the minimal grasping pressure required to remove a fruit from the tree. The corresponding damage level on removed fruit was also analyzed. The results revealed that manual picking could create a bending moment which helped to reduce the required grasping pressure for fruit detachment, and resulted in no picking-induced fruit bruising on all collected samples. Results obtained from all three robotic picking patterns indicated that the use of a three-finger gripper required higher grasping pressure to detach apples, which resulted in higher percentages of picking-induced fruit bruising. It was found that one of the studied robotic patterns could offer a more manual-like performance than the other two robotic picking patterns. Further investigation assessing potentials and limitations of this identified robotic picking pattern on a more comprehensive scale to gain a deeper understanding of how this pattern works is recommended before it can be used as the base pattern for developing effective and efficient apple picking robots.

1. Introduction

Fruit detachment is one of the essential tasks in robotic harvesting of apple and other tree fruit crops. Detachment force necessary for removing fruit from a branch is influenced heavily by stem-branch characteristics and detachment patterns. Based on their studies, Alper and Foux (1976) found that axial tension was the dominant parameter in the fruit detachment process. It was also found that the tension component of detachment force is heavily affected by loading rate applied to fruit stems. In comparison, stem diameter had less influence on the force required to pull fruit from the tree (Gilman, 2003). Parameswarakumar and Gupta (1991) observed that the ratio of detachment force to fruit weight decreased with the increasing fruit maturity. Due to the elastic nature of fruit stem-branch systems, any change in bending angle will make the stem-branch system react with a bending moment on the stem-branch joint (Allotta et al., 1990).

Robotic fruit harvesting technologies have been studied extensively around the world over the past a few decades. Through those efforts, many novel ideas for end-effector design, control and motion planning of robotic devices have been reported (Baeten et al., 2007; Zhao et al., 2011; Li et al., 2013; Bac et al., 2014; Eizicovits and Berman, 2014). Robotic picking requires fruit detachment motions planned and performed with sufficient grasping forces applied to the target fruit (Tillett, 1993). Many picking end-effectors use either two or more fingers to grasp the fruit to detach it (Burks et al., 2005). Pulling or snapping the fruit may achieve highly efficient apple picking (Sarig, 1993), but requires a robotic end-effector to have sufficient grasping force to detach the fruit. To minimize grasp-induced bruising on harvested fruit, some robotic picking devices accomplish this process through grasping a fruit and cutting the stem to lower the require grasping force in picking (Ceccarelli et al., 2000).

Excessive grasping force will induce bruising damage on harvested fruit and results in an economic loss. Lewis et al. (2008) studied apple contact areas and stresses under static loading to determine the thresholds of grasping force under which fruit damage could be controlled within an acceptable level. They also found

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Nomenclature

b	brix of fruit sample (%)	L/D	ratio of fruit length to fruit diameter
f	firmness of fruit sample (kg·f)	T_d	detachment moment of stem-branch joint (N·m)
F_d	detachment force of stem-branch joint (N)	$T_s(\theta)$	elastic torque of stem-branch joint (N·m)
F_s	elastic force of stem-branch joint (N)	$T(\theta)$	bending moment of stem-branch joint (N·m)
F_t	tension force (N)	θ_b	bending angle of stem (°)
G	gravity of fruit sample (N)	θ_d	detachment angle of stem-branch joint (°)

that there are many factors, such as fruit temperature, ripeness and the radius of curvature that could affect the formation of bruises. Van Zeebroeck et al. (2007) found that a smaller radius of contact surface curvature could lead to more bruise damage because of increased peak stress. They also found that bruise damage during robotic picking was related to the impact level caused by static or dynamic grasping force, and the picking pattern and the stem-branch joint characteristics could affect such an impact (Van Zeebroeck et al., 2006). Javad and Najarian (2005) found that properly controlling the grasping force and end-effector motion could help to reduce the needed grasping force and therefore reduce bruising damage during robotic picking.

Therefore, it is desirable to gain a better understanding of required grasping force to support the development of robotic picking manipulations capable of minimizing harvest-induced fruit damage. Special attention should be paid to selecting suitable robotic picking patterns by taking both picking efficiency and picking-induced fruit damage into consideration. This reported study was to characterize the effect of commonly used picking motions and picking patterns on the harvest effort required for fruit detachment and resultant bruise damage during the picking process. The physical parameters of stem-branch joint including the detachment force, detachment angle and detachment moment were measured to obtain a prefer picking motion. Effect of a manual picking process with a finger pushing the stem (pattern 1) and three different robotic picking patterns using an instrumented glove (patterns 2, 3 and 4) on fruit detachment process was evaluated. The effect was evaluated in terms of grasping force and grasping pressure at contact points as well as corresponding levels of fruit bruising. This study aimed to provide the baseline information for determining an optimal robotic picking pattern from among the four patterns studied, which will help design a suitable robotic end-effector that would help keep the damage level in robotically picked apples at an acceptable level.

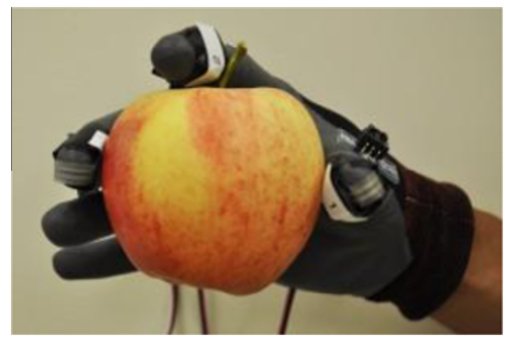

Fig. 1. Instrumentation glove used for evaluating picking motions (Sensor Model: GripTM, Tekscan, USA).

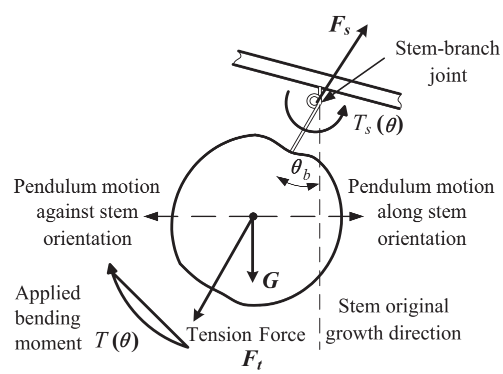

Fig. 2. Diagram of fruit-stem-branch system in equilibrium under various forces and moments.

2. Materials and methods

2.1. Apple picking motion

Apple picking motions (including bend-and-pull and pendulum motions) were investigated experimentally in this study using an instrumentation glove shown in Fig. 1.

Illustrated in Fig. 2, the fruit-stem-branch system is in equilibrium under the effect of gravity G, elastic force F_s, elastic torque of stem-branch joint $T_s(\theta)$, tension force F_t and the bending moment $T(\theta)$ exerted by the grasping fingers. The variable θ_b is the bending angle of stem during picking with respect to its natural growth direction. The stem-branch joint is assumed to be a torsional spring representing the lumped elasticity of the stem during detachment (Cooke and Rand, 1969).

One way of detaching fruit is to pick with only a pendulum action. In this process, the fruit stem was bent around stem-branch joint by exerting a bending moment without any tension on the stem. In picking experiments with bend-and-pull motion, apples were pulled along stem axial direction by exerting tension force while also bending the stem around stem-branch joint. The picking process involves a combination of pulling and pendulum actions. In this picking process, the detachment angle is the critical bending angle at which the fruit is detached from the branch.

Because the stretched branches and leaves often present obstacles to perform desired fruit picking actions accurately, it is very difficult to measure and record actual picking motion paths and fruit detachment angles accurately. To minimize the effect of such disturbances in measurement, tree branch specimens were cut from the orchard, and transported to a laboratory setup. Then, all leaves around the test fruit were removed before performing detachment experiments. The entire procedure was completed within four hours after the branch specimen was cut from the tree to avoid a big change in fruit-stem junction characteristics. To support the study of quantifying grasping force and detachment angle for different picking motions, a branch-grip test stand was designed and fabricated for holding a tree branch firmly at a required test position (Fig. 3). The test stand facilitated a consistent procedure for performing stem bending, fruit pulling and all other

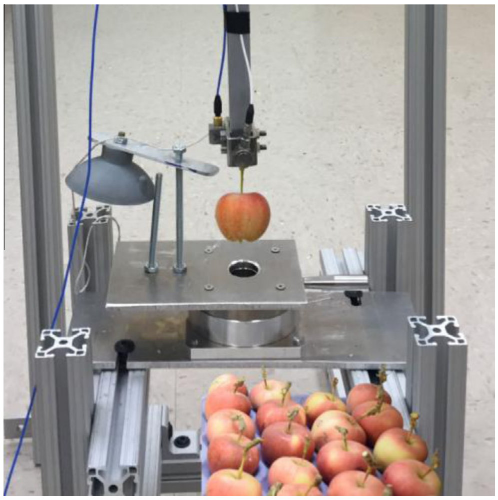

Fig. 3. Branch-grip stand for picking motion and picking pattern test.

picking motions leading to accurate and reliable measurements (Fig. 3). This branch-grip test stand used a square metal tube padded with rubber to avoid damaging the branch during the test. The branch was inserted into the grip and firmly fixed under the same orientation and angle as it was growing on the tree to simulate the branch natural growth condition as closely as possible. Fruit rotation was performed using an instrumentation glove to grasp and tilt the sample in a vertical plane around an axis passing through the fruit stem-branch joint.

Fig. 4 illustrates the natural growth orientations of apple stems at the abscission layer. Based on the growth orientation, apple stems can be divided into left-oriented and right-oriented groups (Tong et al., 2014). In the typical way of picking fruit with pendulum motion, the fruit is rotated either along or opposite to the stem's natural growth orientation.

2.2. Apple picking patterns

This research studied four patterns of apple picking, including one manual picking pattern as the baseline to compare three robotic picking patterns. All picking patterns were studied using an instrumentation glove. In manual picking, people use two fingers to grasp the apple and use the index figure to apply a force on the stem which creates a moment around the stem-branch joint to ease the picking effort (defined as pattern 1; Fig. 5a). Support provided by the index finger on the stem, which is commonly used by human pickers in harvesting varieties with longer stems (Bulanon and Kataoka, 2010), creates a pendulum motion for detaching apples from the branch.

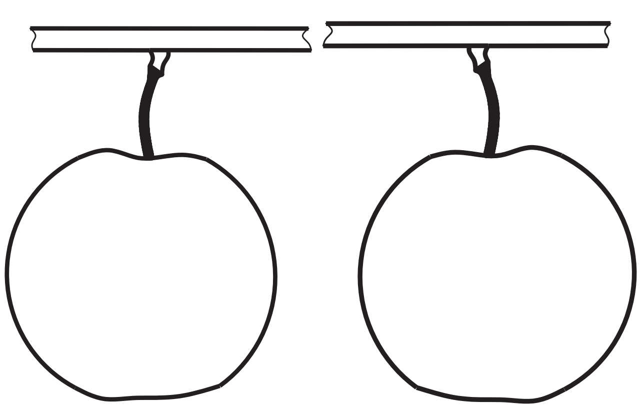

Fig. 4. Orientation of apple stems at the abscission layer; (a) left-oriented, (b) right-oriented.

In terms of three-finger pinching grasp, Lim et al. (2000) proposed the prefer-three-finger grasp posture and fingertip arrangement for a circular object. Mangialardi et al. (1996) also found that an isosceles triangle formed using three figures could create an optimal grasp for circular objects. Therefore, a parallel pinching grasp with two fingers in opposition to the thumb and a centripetal pinching grasp with three fingers centripetally positioned are feasible configurations to effectively grasp a circular object (Li et al., 2011). Based on the mentioned pinching grasps, this study aims to find a feasible three-finger grasp pattern that corresponds to the fruit geometry, kinematic rotation and detaching orientation during picking process. Three robotic picking patterns (as defined in Fig. 5b–d) were proposed and the corresponding grasping forces were analyzed. More specifically, in robotic picking pattern 2, fruit sample was grasped using the parallel pinching grasp. Three fingers flex in parallel to the fruit stem-calyx axis, with two on the top close to the stem approximately the same distance as the stem cavity width and the other one on the bottom as illustrated in Fig. 5b. Pattern 3 (illustrated in Fig. 5c) is a three-finger centripetal grasp in which three fingers acting on an equatorial plane of the fruit are located approximately 120° apart. In experiments with Pattern 4 (illustrated in Fig. 5d), fruit samples were grasped also using the parallel pinching grasp. However, three fingers flex in perpendicular to the fruit stem-calyx axis, with two on one side and one on the other side, just a 90° turning to acting points of Pattern 2. All robotic picking patterns exerted tension on the fruit stem during the picking process, which resulted in a combination of pulling and pendulum motions during the fruit detachment process. To quantify the required grasping forces for detaching an apple, the grasping pressures applied by every fingers were obtained from all robotic picking patterns and were compared with that recorded during manual picking.

2.3. Experimental methods and data acquisition

In this study, the grasping force and associated bruising potentials were measured for individual fruit samples harvested with different picking patterns. The effects of picking motion and fruit maturity on detaching parameters were assessed for *Gala* variety whereas the effects of picking patterns on grasping pressure and fruit bruising damage potential were assessed for *Pink Lady* variety. The average fruit dimensions were determined using the measurements from 300 fruit samples for each variety. Table 1 presented the means and standard deviations of various physical properties of *Gala* and *Pink Lady* apple samples including fruit diameter, length, length to diameter ratio, and mass. In this study, all fruit samples were randomly picked from commercial apple orchards located in Eastern Washington during the harvest season of 2014. In all cases, the picking pattern test was conducted within four hours after the samples were collected from orchards. The pendulum picking tests used 25 *Gala* apples each to determine the critical bending moments and angles corresponding to clockwise and counter-clockwise pendulum motion. Bend-and-pull picking tests were completed with 20 *Gala* apples for each bending angle level evaluated. The effects of picking patterns were investigated using 30 *Pink Lady* apples for each pattern tested. Considering the effect of fruit maturity on grasping force, the firmness and brix of fruit samples were measured immediately after each picking test. The recorded *Gala* fruit firmness was 7.35 ± 0.99 kg/cm^2 and fruit brix was 10.76 ± 1.13%.

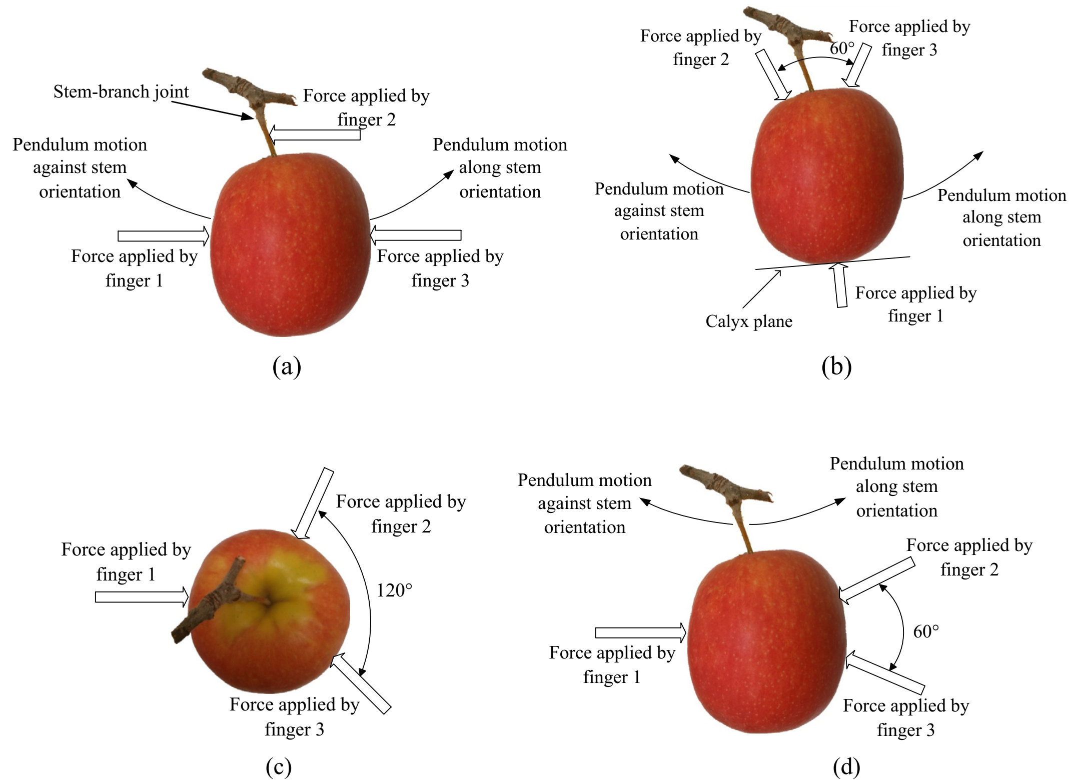

Fig. 5. Various picking patterns evaluated in this study; (a) Pattern 1: manual picking with one finger pushing the stem and two fingers holding the apple and applying a pendulum motion; (b) Pattern 2, grasping the fruit with three fingers acting in a parallel direction to the stem-calyx axis; (c) Pattern 3, centripetal grasping with three fingers acting on the equatorial plane of the fruit; and (d) Pattern 4, grasping with three fingers acting in a perpendicular direction to the stem-calyx axis.

Table 1
Mean and standard deviation of physical properties for *Gala* and *Pink Lady* apples.

Measurement	*Gala*		*PinkLady*	
	Mean	SD[b]	Mean	SD[b]
Diameter (mm)	71.37	4.45	77.08	3.50
Length (mm)	64.99	4.55	79.49	4.10
L/D[a]	0.91	0.04	1.03	0.03
Mass (g)	152.78	28.24	216.51	28.41

[a] L/D, ratio of fruit length to fruit diameter; fruit length was measured along the stem-calyx axis. Fruit diameter is the diameter of equatorial plane of fruit.
[b] SD, Standard deviation.

The grasping force applied to apple samples by each finger was measured using a 3D force sensor (OMD-10-SA-10N, OptoForce Ltd., Hungary) mounted on each contact surface of the instrumentation glove used in this study (Fig. 1). A wrist-mounted inclinometer (SQ-SI2X-360DA, SignalQuest LLC, USA) was used to measure the stem bending angle. The contact pressure of a finger on test fruit surface was measured using a high precision pressure film (Prescale LLLW, Fujifilm, Japan). Geometric dimensions of all apple samples were measured using a digital Vernier caliper with accuracy of ±0.01 mm. As indirect indicators of fruit maturity, apple firmness was measured using a Wagner fruit ripeness tester (FT30, Wagner Instruments, USA) and apple brix was measured using a refractometer (MA871, Milwaukee Instruments, USA).

For pendulum picking experiments, the fruit stem was bent around the stem-branch joint. After a test branch was fixed firmly on the branch-grip stand designed for this study, the fruit specimen was rotated in a consistent and slow speed of approximately $5°\cdot s^{-1}$ to creating a smooth bending motion. In preliminary tests of fruit picking with bend-and-pull motion, the required detachment force at 0° bending angle from the natural growth direction was beyond the range of 3D force sensor (Nominal capacity of the compression force is 10 N) and may cause fruit damage. To ensure the robotic grasping force is within the apple fruit damage threshold, the experiments with bend-and-pull motion were conducted with stem bending angles of 10°, 20° and 30°, which was then used to estimate the regression equation representing the relationship between bending angle and detachment force.

3. Results and discussion

3.1. Effect of picking motion on fruit detachment

In pendulum picking experiments, the fruit stem was bent from its natural growth direction at a very low velocity of approximately $5°\cdot s^{-1}$ in order to apply a close-to-static load to the stem during picking. Fig. 6 presents a typical curve of change in bending moment corresponding to the increasing stem bending angle during a pendulum picking process. This curve indicates that the stem bending moment increases as the bending angle increases until it reached the value required to break the stem-branch joint. The bending stiffness of stem-branch joint represents the lumped flexibility of the stem, which means that the stem will exert a resisting moment on the joint while the stem is bent. The ratio between the reaction bending moment and the bending angle is the coupling bending stiffness. The changes in the bending angle with varying bending moment plotted in Fig. 6 indicated that the elastic behavior of a fruit stem-branch system can be assumed to be linear. Such a finding makes it possible to estimate the bending stiffness of stem-branch joint and use it to indicate the stem stiffness related to the detachment moment (namely the critical bending moment at the time of fruit detachment) needed to pick an apple.

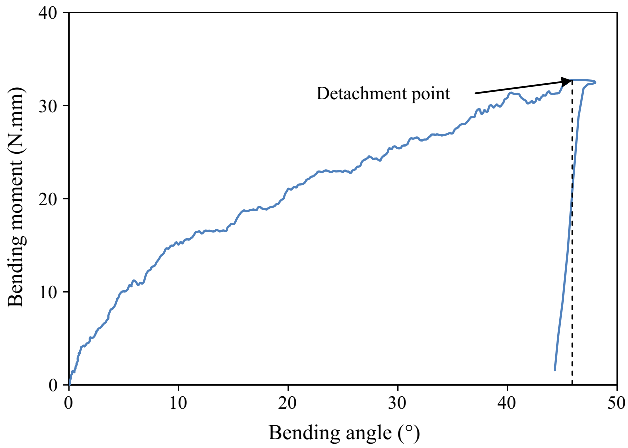

Fig. 6. A relationship between bending angle and bending moment during the detachment of apple fruit from a branch with pendulum motion.

3.1.1. Pendulum picking

Pendulum motion generated by bending the stem from its natural growth orientation towards the branch results in fruit detachment after a certain bending angle was achieved. Fig. 7 shows an example of experimental results obtained from pendulum picking experiments in which fruit samples with stem fixed on the branch-grip stand were rotated at a slow and consistent velocity of approximately $5° \cdot s^{-1}$. Obtained results showed that the critical detachment moment for *Gala* apples varied from 16.9×10^{-3} to 70.8×10^{-3} N·m, corresponding to detachment angle from 30.5–70.9°. On average, a $43.0 \pm 16.0 \times 10^{-3}$ N·m of moment was needed to detach a fruit from the tree with pendulum picking along its natural growth direction, and $36.6 \pm 10.4 \times 10^{-3}$ N·m with pendulum picking against the growth direction. The relationship between detachment moment and detachment angle in pendulum picking against stem orientation was similar with pendulum picking along stem orientation as shown in Fig. 7. The corresponding regression curves between detachment moment and detachment angle are expressed by the following linear regression equations with R^2 value of 0.77 and 0.73 for pendulum motion against (Eq. (1)) and along stem orientation (Eq. (2)), respectively.

$$T_d = 1.31 \cdot \theta_d - 22.19 \quad (1)$$

$$T_d = 1.35 \cdot \theta_d - 24.89 \quad (2)$$

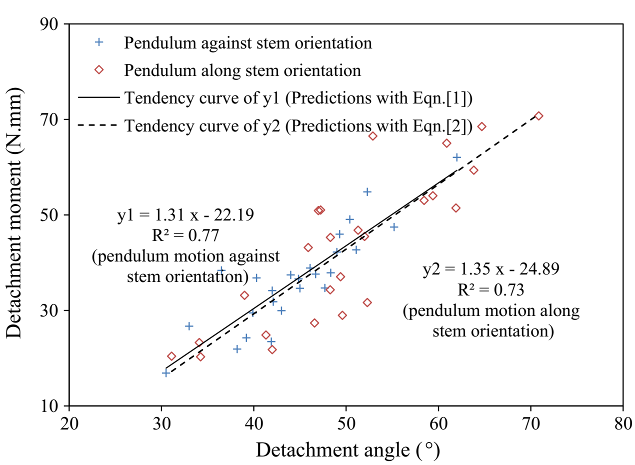

Fig. 7. Variation in fruit detachment moment at harvest with varying detachment angle achieved during a pendulum motion.

It was also found that the average bending angle needed for fruit detachment was higher for pendulum picking along its natural growth direction ($50.1 \pm 10.1°$) than against it ($44.7 \pm 6.9°$). The ranges of detachment angles varied from 31.1–70.9° for pendulum picking along the natural growth direction and 30.5–62.0° for against the direction. Based on the *t*-test analysis, a statistically significant difference was found in detachment angle between two pendulum directions (the *p*-value was found to be $0.03 < \alpha = 0.05$).

Regardless of the pendulum direction, the detachment moment generally increased with the detachment angle. There was no significant difference in detachment moment between two pendulum directions (*p*-value was 0.10). Higher detachment moment or detachment angle implies a larger level of harvesting energy required to remove the fruit. As the fruit removal energy is an integral determined by detachment moment and angle, and the detachment angle was noticeably larger for pendulum picking along the growth direction, it implies that more energy is required to detach a fruit when using pendulum picking along stem orientation than against it.

3.1.2. Bend-and-pull picking

Bend-and-pull picking involves pulling fruit along the stem while bending it. It was found that the detachment force required to pick fruit using a purely pulling motion is at least twice as much as when using bend-and-pull picking with a bending angle of 45° (Torregrosa et al., 2014). The increased detachment force requires a higher level of grasping force, which has potential to result in a higher level of fruit damage (Parameswarakumar and Gupta, 1991). To assess the effect of bending angle on detachment force for removing fruit from branches required for bend-and-pull picking, the detachment force at the stem branch joint was measured by pulling the fruit stem from the branch with 10.0°, 20.0° and 30.0° bending angles from the natural growth direction. Detachment forces recorded in the experiment were regressed against bending angle for different pendulum orientations as follows (Fig. 8). Eq. (3) represents the regression for bend-and-pull against stem natural orientation ($R^2 = 0.79$) whereas Eq. (4) represents the same along stem natural orientation ($R^2 = 0.78$)

$$F_d = 0.02 \cdot \theta_b^2 - 1.32 \cdot \theta_b + 26.03 \quad (3)$$

$$F_d = 0.01 \cdot \theta_b^2 - 0.99 \cdot \theta_b + 26.15 \quad (4)$$

The results showed that the detachment force in the bend-and-pull picking process would decrease noticeably as bending angle increased either against or along stem orientation. So (2003) found that fruit detachment is a combined effect of tension force, bending stress, and shear stress. Under small bending angle, the tension

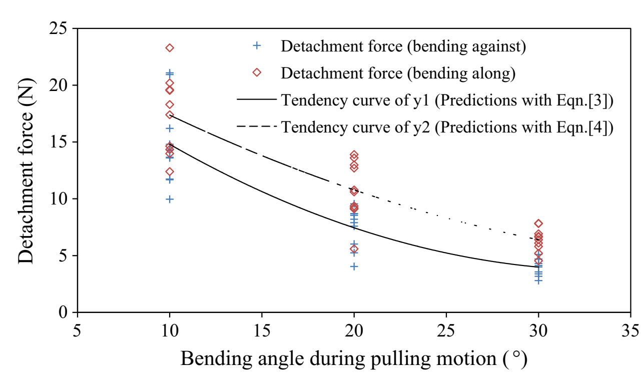

Fig. 8. Variation in fruit detachment force at harvest with varying bending angle achieved during a pulling motion.

would be the biggest contributor as the bending stress and shear stress in this case were small. As the bending angle increases, the stress combination would boost and result in a noticeable decrease in required tension force to break a stem from a branch.

Bend-and-pull picking requires smaller detachment force than with a straight pulling process. The result implies that this fruit picking method could reduce fruit bruising damage during picking. Accordingly, bend-and-pull picking motion was considered as the basic form of picking motion for designing robotic end-effectors for fruit picking.

3.2. Effect of picking patterns on grasping pressure and bruising damage

The effect of picking patterns on grasping force, pressure and fruit bruising was experimentally studied using an instrumentation glove representing a three-finger gripper removing fruit using different picking patterns. Table 2 lists the average grasping force and pressure on each finger, mean grasping force and pressure over all three fingers, and critical stem bending angle at which fruit was detached under various picking patterns. It could be found that pattern 1 (manual picking pattern) requires the smallest average grasping force (5.05 ± 0.79 N) and grasping pressure (0.24 ± 0.05 MPa) on all grasping fingers when harvesting *PinkLady* apple. Average critical stem detachment angle in this case was 25.6 ± 15.1°. There existed significant differences between pattern 1 and patterns 2–4 (three different robotic picking patterns) in terms of average grasping pressure. Results showed that the mean grasping force, grasping pressure and critical stem detachment angle for pattern 2 were 6.77 ± 0.95 N, 0.27 ± 0.04 MPa and 42.0 ± 14.4° respectively, which were the lowest among the three robotic picking patterns. To limit the grasping force and grasping pressure in robotic picking, it is reasonable to recommend pattern 2 as the base pattern for robotic picking of apples based on these experimental results.

To evaluate bruise damage caused by grasping force in a picking process, fruit samples were stored at 26 °C environment for 7 days and then inspected for injury according to the protocols defined by United States Standards for Grading of Apples (USDA, 2002). According to this standard, a fruit is considered injured if any bruise greater than 3.18 mm deep or 15.88 mm wide is detected. Table 3 gives the fruit bruising injuries corresponding to forces applied to fruit samples under different picking patterns.

Apples picked using pattern 1 (manual picking) did not show any detectable bruising damage whereas all three robotic picking patterns resulted in some levels of bruising. A significance analysis indicated that the percentages of bruised fruit and fruit with more than one bruised spot were significantly increased from samples picked using patterns 3 and 4 than using pattern 2, with an exception for fruit with more than one bruised spot when picked using pattern 4. It could be attributed to the fact that the mean grasping pressure for pattern 2 was less than those when using patterns 3 and 4 as shown in Table 2. It was also noticed that there was no significant difference in average grasping pressure applied on damage spots among all those robotic picking patterns. The results indicated that the contact points on the surface of *PinkLady* apple could be bruised when the grasping force surpasses 11.23 N or grasping pressure surpasses 0.29 MPa, which can be used to predict the tensile pressure threshold.

Although manual picking (pattern 1) requires a minimal grasping force and results in no picking-induced bruising damage, it should be noted that the realization of two-finger grasp with another finger pushing on the stem is difficult for low DOF (Degree Of Freedom) robotic end-effectors to accomplish. Robotic picking pattern 2, which achieved a good harvesting efficiency with relatively a simple picking mechanism and the best fruit quality from all three robotic picking patterns tested, is recommended to be the base pattern in designing robotic picking end-effectors.

3.3. Effect of fruit maturity on detachment parameters

Fruit firmness and sugar content are two measurable parameters indicating fruit ripeness. The degree of ripeness is an important factor affecting fruit picking performance, especially the allowable grasping force and potential for bruising damage of the fruit during physical interaction (Wang and Sheng, 2005; Berardinelli et al., 2006; Lu and Tipper, 2009). The prediction of detachment parameters based on the firmness and sugar content

Table 2
Comparison of grasping force, grasping pressure and bending angle of fruit stem at detachment for four different picking patterns.

Picking pattern	Grasping force (N)			Grasping pressure (MPa)			Mean grasping force over all fingers (N)	Mean grasping pressure over all fingers (MPa)	Bending angle (°)
	Finger 1	Finger 2	Finger 3	Finger 1	Finger 2	Finger 3			
Pattern 1	4.76 ± 0.86[a]	7.16 ± 1.59[a]	3.23 ± 0.64[a]	0.25 ± 0.05[a]	N/A	0.23 ± 0.05[a]	5.05 ± 0.79[a]	0.24 ± 0.05[a]	25.6 ± 15.1[a]
Pattern 2	5.39 ± 1.24[a]	8.65 ± 1.42[b]	6.28 ± 0.81[b]	0.25 ± 0.06[a]	0.28 ± 0.05[a]	0.26 ± 0.03[b]	6.77 ± 0.95[b]	0.27 ± 0.04[b]	42.0 ± 14.4[b]
Pattern 3	14.47 ± 1.14[b]	9.48 ± 1.03[b]	8.53 ± 1.37[c]	0.30 ± 0.02[b]	0.28 ± 0.03[a]	0.28 ± 0.05[c]	10.83 ± 0.70[c]	0.29 ± 0.02[c]	64.6 ± 16.0[c]
Pattern 4	15.87 ± 1.70[c]	11.28 ± 1.63[c]	6.04 ± 1.00[b]	0.30 ± 0.03[b]	0.30 ± 0.04[b]	0.26 ± 0.04[b]	11.06 ± 0.98[c]	0.29 ± 0.03[c]	45.5 ± 11.2[b]

Note: Significance of the difference between mean within columns was tested using Duncan's multiple range test at $\alpha = 0.05$. Different letters denote statistically significant differences. The contact type between finger 2 and fruit for picking pattern 1 is a point-to-point contact compared to the surface-to-surface contact for other picking patterns.

Table 3
Comparison of fruit damage for different picking patterns.

Picking pattern	Percentage of bruised samples (%)	Percentage of samples with more than one bruised spots (%)	Average grasping force applied on damage spots (N)	Average grasping pressure applied on damage spots (MPa)
Pattern 1	0.0[a]	0.0[a]	/	/
Pattern 2	7.1[a]	0.0[a]	11.23 ± 1.13[a]	0.29 ± 0.03[a]
Pattern 3	46.7[b]	26.7[b]	12.65 ± 2.91[a]	0.30 ± 0.07[a]
Pattern 4	60.0[b]	6.7[a]	13.66 ± 4.23[a]	0.30 ± 0.09[a]

Note: Significance of the mean difference within columns was tested using Duncan's multiple range test at $\alpha = 0.05$. Different letters denote statistically significant differences.

of apple fruit is useful for the determination of robotic grasping force. Therefore, a basic understanding of the relationships between fruit firmness or sugar content and fruit detachment strength at stem-branch joint will be meaningful. The effect of fruit maturity on detaching parameters was experimentally studied with pendulum picking. Fig. 9 shows a positive correlation between fruit stem detachment angle and fruit firmness for *Gala* apple. The relationship was given by the following equation (Eq. (5)) with a coefficient of determination R^2 of 0.58. A similar relationship was also found between detachment moment and fruit firmness as given by Eq. (6) ($R^2 = 0.74$).

$$\theta_d = 7.06 \cdot f - 4.56 \tag{5}$$

$$T_d = 12.16 \cdot f - 49.65 \tag{6}$$

where f is the firmness of fruit sample, kg·cm^{-2}.

The sugar content, often measured by brix, is another important indicator for evaluating the ripeness of apple fruits. This study found that there exists a negative effect of fruit brix on required detachment angle to remove a fruit from the branch as shown in Fig. 10, with an R^2 value of 0.43 for the regression equation of average detachment angle with certain brix level for *Gala* apples:

$$\theta_d = -531.50 \cdot b + 104.46 \tag{7}$$

where b denotes the brix of fruit sample, %.

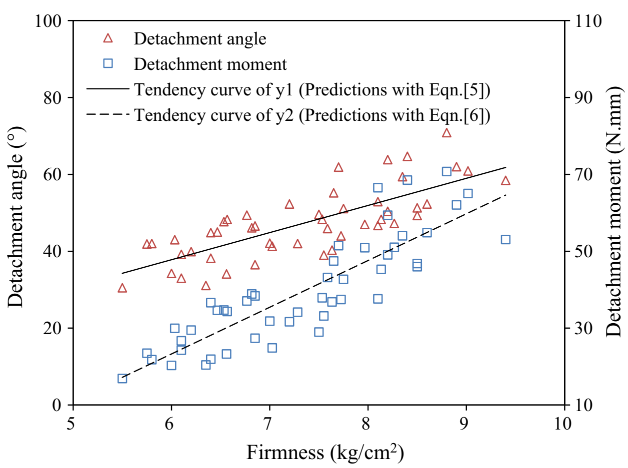

Fig. 9. Variations in fruit detachment angle and moment with varying fruit firmness.

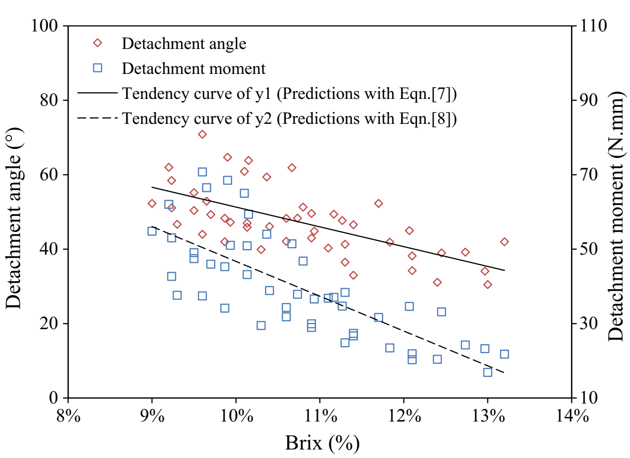

Fig. 10. Variations in fruit detachment angle and detachment moment during apple picking with varying brix levels.

Similar to detachment angle, results presented in Fig. 10 also reveal that the detachment moment is also negatively correlated with fruit brix with an R^2 value of 0.58 for corresponding regression equation as follows:

$$T_d = -935.94 \cdot b + 140.32 \tag{8}$$

Comparing the R^2 for Eqs. (5)–(8), apple firmness is a relatively better indicator for the prediction of detachment parameters with higher estimation accuracy.

The results showed that it requires relatively less effort to pick mature fruit, but mature fruit are also bruised relatively easily due to its lower firmness value. Lower impact picking pattern in terms of required grasping force is therefore always helpful in minimizing picking effort while keeping bruising potential at low level.

4. Conclusions

This study experimentally investigated the effects of picking patterns, as well as the picking motions, on required grasping pressure and resulting bruise damage. The results showed that it requires more energy to break apple stem-branch joint using a pendulum picking along the stem growth direction than against it. To remove a fruit from the branch, bend-and-pull picking will require less energy than straight pulling along stem growth direction. This result indicated that bending the stem in fruit picking could substantially reduce the required detachment force to remove the fruit from a branch.

This experimental investigation also found that the typical manual picking used by local fruit pickers (pattern 1 of fruit picking in this study) applies the least grasping pressure and bends the stem by the smallest angle to complete a picking process. Further study also indicated that robotic picking pattern 2 (a grasp using three fingers acting in a parallel direction to the stem-calyx axis of the fruit) requires less grasping pressure than robotic patterns 3 (a three-finger centripetal grasp with fingers acting on the equatorial plane of the fruit) and 4 (a grasp using three fingers acting in a perpendicular direction to the stem-calyx axis of the fruit). Such a difference resulted in significantly smaller bruising damage on the fruit picked using pattern 2 than patterns 3 and 4. It is difficult for the low DOF robotic picking mechanisms (preferable for low cost machine) to complete the complicated picking action of manual picking (like pattern 1 which uses one finger pushing the stem and two other fingers holding the fruit for pendulum-pulling motion). Hence it is recommended to further investigate the potentials and limitations of adopting robotic pattern 2 as the baseline for developing robotic picking mechanisms for fresh market apple and other tree fruit harvest.

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References

Allotta, B., Buttazzo, G., Dario, P., Quaglia, F., Levi, P., 1990. A force/torque sensor-based technique for robot harvesting of fruits and vegetables. In: IEEE International Workshop on Intelligent Robots and Systems, pp. 231–235.

Alper, Y., Foux, A., 1976. Strength properties of orange fruit-stem joints. Trans. ASAE, 412–416.

Bac, C.W., van Henten, E.J., Hemming, J., Edan, Y., 2014. Harvesting robots for high-value crops: state-of-the-art review and challenges ahead. J. Field Robot. 31 (6), 888–911.

Baeten, J., Donne, K., Boedrij, S., Beckers, W., Claesen, E., 2007. Autonomous fruit picking machine: a robotic apple harvester. Springer Tracks Adv. Robot. 42, 531–539.

Berardinelli, A., Donati, V., Giunchi, A., Guarnieri, A., Ragni, L., 2006. Mechanical behavior and damage of Pink Lady apples. Appl. Eng. Agric. 22 (5), 707–712.

Bulanon, D.M., Kataoka, T., 2010. Fruit detection system and an end effector for robotic harvesting of Fuji apples. Agric. Eng. Int.: CIGR J. 12 (1), 203–210.

Burks, T., Villegas, F., Hannan, M., Flood, S., Sivaraman, B., Subramanian, V., Sikes, J., 2005. Engineering and horticultural aspects of robotic fruit harvesting: opportunities and constraints. HortTechnology 15 (1), 79–87.

Ceccarelli, M., Figliolini, G., Ottaviano, E., Mata, A., Criado, E., 2000. Designing a robotic gripper for harvesting horticulture products. Robotica 18 (1), 105–111.

Cooke, J.R., Rand, R.H., 1969. Vibratory fruit harvesting: a linear theory of fruit-stem dynamics. J. Agric. Eng. Res. 14 (3), 195–209.

Eizicovits, D., Berman, S., 2014. Efficient sensory-grounded grasp pose quality mapping for gripper design and online grasp planning. Robot. Auton. Syst. 62 (8), 1208–1219.

Gilman, E.F., 2003. Branch-to-stem diameter ratio affects strength of attachment. J. Arboric. 29 (5), 291–294.

Javad, D., Najarian, S., 2005. Advances in tactile sensors design/manufacturing and its impact on robotics applications – a review. Ind. Robot: Int. J. 32 (3), 268–281.

Lewis, R., Yoxall, A., Marshall, M.B., Canty, L.A., 2008. Characterising pressure and bruising in apple fruit. Wear 264 (1–2), 37–67.

Li, S., Yao, S., Zhang, Y., Meng, L., Lu, Z., 2011. Grasp planning analysis and strategy modeling for under actuated multi-fingered robot hand using in fruits grasping. Afr. J. Agric. Res. 6 (9), 2086–2098.

Li, Z., Li, P., Yang, H., Wang, Y., 2013. Stability tests of two-finger tomato grasping for harvesting robots. Biosyst. Eng. 116, 163–170.

Lim, M., Oh, S., Son, J., You, B., Kim, K., 2000. A human-like real-time grasp synthesis method for humanoid robot hands. Robot. Auton. Syst. 30, 261–271.

Lu, R., Tipper, N.C., 2009. A portable device for the bioyield detection to measure apple firmness. Appl. Eng. Agric. 25 (4), 517–523.

Mangialardi, L., Mantriota, G., Trentadue, A., 1996. A three-dimensional criterion for the determination of optimal grip points. Robot. Comput.-Integr. Manuf. 12 (2), 157–167.

Parameswarakumar, M., Gupta, C.P., 1991. Design parameters for vibratory mango harvesting system. Trans. ASAE, 14–20.

Sarig, Y., 1993. Robotics of fruit harvesting: a state-of-the-art review. J. Agric. Eng. Res. 54, 265–280.

So, J.D., 2003. Vibratory harvesting machine of boxthorn (*Lycium chinense* mill) berries. Trans. ASAE 46 (2), 211–221.

Tillett, N.D., 1993. Robotic manipulators in horticulture: a review. J. Agric. Eng. Res. 55 (2), 89–105.

Tong, J., Zhang, Q., Karkee, M., Jiang, H., Zhou, J., 2014. Understanding the dynamics of hand picking patterns of fresh market apples. American Society of Agricultural and Biological Engineers Annual International Meeting, vol. 3, pp. 2057–2063.

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 (3), 1–12.

USDA (2002). United States Standards for Grades of Apples.

Van Zeebroeck, M., Tijskens, E., Dintwa, E., Kafashan, J., Loodts, J., De Baerdemaeker, J., Ramon, H., 2006. The discrete element method (DEM) to simulate fruit impact damage during transport and handling: model building and validation of DEM to predict bruise damage of apples. Postharvest Biol. Technol. 41 (1), 85–91.

Van Zeebroeck, M., Van Linden, V., Darius, P., De Ketelaere, B., Ramon, H., Tijskens, E., 2007. The effect of fruit factors on the bruise susceptibility of apples. Postharvest Biol. Technol. 46 (1), 10–19.

Wang, J., Sheng, K., 2005. Variations in firmness and sugar content in 'Huanghua' pear (*Pyrus pyrifolia* 'Nakai'). J. Horticult. Sci. Biotechnol. 80 (3), 307–312.

Zhao, D., Lv, J., Ji, W., Zhang, Y., Chen, Y., 2011. Design and control of an apple harvesting robot. Biosyst. Eng. 110 (2), 112–122.