Tomato’s Mechanical Properties Measurement Aiming for Auto-harvesting

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Abstract. Freshly-eating tomato’s auto-harvesting is urgently needed to replace labor-costly manual harvesting. And a feasible picking end-effector is a key part for mechanical harvesting, as the irregular-sized and soft fruits should be reliably separated from the plant. In this paper, the mechanical properties of “Jiali 14” tomato was measured and analysed to support the design of picking end-effector. The methods and devices for measuring a series of force parameters were researched, including fruit/stalk friction coefficient, fruit pressure resistance, stalk cutting force, and abscission-layer breakage force. Through measuring the pressure and maximum static-friction force between the fruit/stalk and the contrast material, the friction coefficients between fruit/stalk and stainless steel, PVC and rubber was calculated. The pressure resistance of fruit also was evaluated by measuring the extreme pressure on the test samples, and the influences from the fruit’s maturity and the pressure direction also were analysed. The stalk cutting force, with the single and double blade, both was measured and compared. The breakage force of the calyx abscission-layer and the tie abscission-layer also was measured, and the force value variation with its anisotropy and the fruit maturity was analysed. The measurement and analysis result in this paper was supposed as a necessary reference for developing the tomato’s auto-harvesting machine.

1. Introduction

Freshly-eating tomato is largely produced and consumed in China, where its plant area reaches about 732,600 hm² [1] and the annual per-person consumption is 21kg [2]. The propose has been widely concerned these years [3], to develop the automatic harvesting machine for replacing or assisting manual labour on harvesting tomato. To hold tomato’s fruit and stalk, then separate fruit at the calyx, the picking method is widely accepted for both manual and mechanical harvesting, because the fruit without stalk left is expected to avoid breaking by other’s stalk during transporting and storing.

However, the mature tomato fruit is soft and easily-broken, which is one of challenges limiting the tomato’s automatic harvesting [4, 5]. So understanding the mechanical properties of tomato fruit, is important for automatic harvester’s developing. In view the need for automatic harvesting, the present research on fruit’s mechanical properties mainly focused on fruit’s damaging force, stalk’s cutting force and the relativity between the force and fruit’s maturity [6], and the measuring objects involved tomato [6,7], aonla [8], litchi [9], kiwi [10] and bayberry [11]. The limited properties could not cover all the force parameters related to the fruit’s (stem’s) holding, stem’s cutting and calyx’s separating. What's more, the research on measuring the fruit’s (stem’s) frictional characteristic and abscission layer’s broken force has not been reported.

Aiming at accurately obtaining the tomato’s mechanical properties to support the automatic harvester’s design, the measuring methods for fruit (stalk) friction coefficient, fruit pressure resistance,
stalk cutting force and abscission-layer breakage force, were introduced in this paper, and the relationships between the fruit’s maturity and the properties also were analysed.

2. Measurement Instrument and Object

2.1. Measurement Instrument
MTS E43 electronic universal testing machine was adapted as the measuring instrument. Its force sensor could real-timely communicate with PC under 1000 HZ sampling frequency to insure the measuring data could be accurately set and monitored. And the two types of sensor with 100 N (±0.30%) and 10,000 N (±0.20%) measurement range were available. Besides, its standardized mechanical connector makes it convenient to install various customized measuring tool.

2.2. Measurement Sample

![Figure 1. Tomato fruits (1. Main stem 2. Fruit body 3. Fruit shoulder 4. Fruit Stalk 5. Stalk tie 6. Fruit calyx)](image)

The “Jiali14” tomato is selected as test sample, which is widely cultivated in north China. The tomato bunch of three fruits is shown in figure 1. The fruit-stalk is the stem linking fruit and plant’s main stem, and the length is averagely 20mm long. The stalk-tie exists about 9.53mm from the fruit-calx. 100 fruit samples picked in the greenhouse of Beijing Special Food Garden in May, 2016, was sorted into four grades as Table 1, according to the fruits’ maturity [12]. Every grade contained the fruits of the same number and similar size-range.

| Table 1. Tomato samples grades |
|-------------------------------|
| Maturity stage | Green Mature | Color Change | Maturation | Entire Maturation |
| Color state |
| ![Image of different maturity stages](image) |

3. Frictional Property

3.1. Maximum Static-friction Force Measurement
Static-friction coefficient, as the intrinsic property between the materials contacting with each other, is the critical parameter to determine the grasping force on fruit/stalk to overcome the external force sliding them off. In this paper, the stainless steel (Ra0.8), PVC and rubber were selected as the contrast material, and the static-friction coefficients between the fruit/stem and contrast materials were calculated through measuring a series of maximum static-friction force under different pressure.

The measuring device for maximum static-friction force is shown as figure 2. The contract material is pasted on the presser and the base of MTS E43 and contacted with measured fruit/stalk. After
setting the pressure, which the presser presses on the fruit/stalk, a pulling-force instrument is adapted to pull the fruit until moving it. The maximum value showed on the pulling-force instrument is noted as the double maximum static-friction force under the setting pressure, including the frictions both on the above and below sides of fruit (or stem).

![Diagram of fruit and pulling-force instrument]

**Figure 2.** Maximum static frictional force measurement (1. Electronic universal tester 2. Contrast material 3. Test material 4. Push belt 5. Base 6. Pulling-force instrument)

### 3.2. Maximum Static-friction Coefficient Calculation

The test samples are classified into 5 groups, 20 fruits every group. And the pressure $F_{Ni}$ on fruit of each group respectively is 2N, 4N, 6N, 8N and 10N. $F_i$ mean the max-value tested by the pulling-force instrument, so the actual value $F'_{i}$ of the max static-friction force between fruit and contract material is $F_i/2$.

The relationship of the max static-friction coefficient $f_g$ and the ideal value $F_\text{fi}$ of the max static-friction force between the fruit and the contract material, is show as equation (1).

$$F_\text{fi} = f_g F_{Ni} \quad (1)$$

According to the least squares principle [13], the optimal estimated value of the max static-friction coefficient $f_g$ could minimize the deviation $\sum_{i=1}^{5}(F_{fi} - F'_{i})^2$ between the ideal value $F_\text{fi}$ and the actual value $F'_{i}$, and make the derivative of the deviation to be zero as equation (2).

$$\sum_{i=1}^{5}(2f_g F_{Ni} - F_i)F_{Ni} = 0 \quad (2)$$

According to equation (2), $f_g$ the max static-friction coefficient could be calculated as equation (3).

$$f_g = \frac{\sum_{i=1}^{5} F_i F_{Ni}}{2 \sum_{i=1}^{5} F_{Ni}} \quad (3)$$

### 4. Fruit Press-resistance Property

The fruit’s press-resistance property is another important factor to consider, when designing the flexible picking grasper. The measurement device is shown in figure 3. The fruit is pressed between the presser and the base of MTS E43. The presser moves down, until the pressure on fruit increased to the extremity, when the resistance force from fruit begins to sharply decrease. The max pressure value measured is noted as the fruit’s crushed-pressure.
In view of the spoke-cavity structure of tomato as shown in figure 4, the fruit’s press-resistance extremity is various with the different direction of pressure. So in this paper, the fruit samples were classified into 4 groups, 24 fruits every group, and among which 6 fruits were at the same maturity stage. The fruits from the 4 groups were pressed respectively along the spoke-spoke, spoke-cavity, cavity-cavity of radial direction and the axial direction. Each sample fruit was crushed for once without repetition.

5. Stalk Cutting Property

The device of measuring stalk’s cutting force is show as figure 5. The blades made of T12 steel are installed with the presser and the base of MTS E43, and the stalk is fixed on base by the stalk platen. Then the presser is moved down until the stalk is cut off, and the max-value of press force is noted as the stalk’ cutting force. In this paper, the cutting modes of double blade and single blade both were tested through installing or removing the static blade.

6. Stalk Abscission-layer Breakage Property

As the tomato fruit getting mature, the abscission-layer formed at stalk-tie and stalk-calyx becomes easy to been separated [14], which is the candidate point for picking fruit from the plant. So to obtain its breakage property is important for designing the mechanical harvesting device. The method for measuring breakage force is shown in figure 6.
Figure 6. Abscission layer breakage force measurement (1. Stalk grasper 2. Annular groove 3. Slider 4. Pin 5. Fruit container 6. Stalk 7. Stalk tie 8. Cushion 9. Fruit 10. Stalk fixer)

The tested fruit is hold by cushion in the container, and the stalk, pulled out from the stalk fixer at the top of the container, is grasped by the grasper of MTS E43. When measuring the breakage force of stalk tie, the grasper would hold the stalk above the stalk tie. When measuring the breakage force of calyx, the grasper would hold the stalk below the stalk tie. In view of the structure anisotropy of abscission layer, its breakage force value varies with the pull force direction. So the sliders fixed with fruit container, which could slid along the annular groove fixed with the MTS E43 base, are adapt to adjust the fruit container’s rotating angle around the center of annular groove. And the rotating angle is noted as the breakage force direction.

The samples are classified into 4 groups according to the breakage force direction of 0º, 30º, 60º and 90º, 24 ones every group. Among the 24 fruit, every 6 fruits are at the same maturity stage. The breakage force of the calyx’ abscission layer is measured after the stalk tie, so as to keep the sample complete.

7. Measurement Result and Analysis

7.1. Frictional Property

The average actual value $F_{f1}$ of the max static friction force under different pressure between fruit and the contrast materials, and the friction coefficient calculated are listed in Table 2.

| Material  | Pressure $F_{N1}$(N) | Friction Coefficient $f_s$ |
|-----------|----------------------|-----------------------------|
|           | 2  | 4  | 6  | 8  | 10 |                 |
| Fruit-Steel| 3.4 | 4.9 | 7.1 | 11.8 | 15.1 | 0.71           |
| Fruit-PVC | 8.0 | 11.2 | 12.8 | 20.0 | 25 | 1.24           |
| Fruit-rubber | 14.2 | 26.2 | 31.1 | 36.4 | 47.1 | 2.46           |

With the same measurement method, the frictional property of the stalk also is determined. And the measurement result is shown in Table 3.

| Material   | Pressure $F_{N1}$(N) | Friction Coefficient $f_s$ |
|------------|----------------------|-----------------------------|
|            | 5   | 10  | 15  | 20  | 25           |
| Stalk-Steel| 3.2 | 5.2 | 7.5 | 9.8 | 12.4         |
| Stalk-PVC  | 5.5 | 7.7 | 10.0 | 13.2 | 17.2 | 0.34        |
| Stalk-rubber | 6.8 | 11.0 | 16.0 | 18.0 | 22.8 | 0.48        |
7.2. *Fruit Press-resistance Property*

The average crushed-pressure value of the fruit samples of same maturity in each group is listed in Table 4.

**Table 4.** Fruit crushing pressure measurement result

| Pressure direction | Maturity stage          | Green mature | Color change | Maturation | Entire maturation |
|--------------------|-------------------------|--------------|--------------|------------|------------------|
| Radial             | Spoke-spoke             | 197.00       | 155.19       | 134.25     | 130.82           |
|                    | Spoke-cavity            | 252.27       | 139.68       | 110.55     | 101.70           |
|                    | Cavity-cavity           | 233.93       | 150.88       | 115.25     | 106.73           |
| Axial              |                         | 384.18       | 269.52       | 224.85     | 194.14           |

7.3. *Stalk Cutting Property*

The stalk samples are classified into 4 groups according to their diameter size, 25 ones every group. The average cutting force of different diameter range is listed as Table 5. The result showed that the stalk of bigger diameter size needed stronger force to cut. The cutting force with double blade was about 50% less than the force with single blade.

**Table 5.** Stalk cutting force measurement result

| Cutting mode        | Stalk diameter (mm) | 2.0~2.9 | 3.0~3.9 | 4.0~4.9 | 5.0~5.9 |
|---------------------|---------------------|---------|---------|---------|---------|
| Double Blade        |                     | 11.10   | 14.17   | 15.54   | 17.52   |
| Single blade        |                     | 19.42   | 23.87   | 31.48   | 35.59   |

7.4. *Abscission-layer Breakage Property*

The measuring result of the abscission-layer breakage force at the stalk tie is listed in Table 6. The stalk tie is more easily broken when pulled along 0° direction than other angle, and the variation of the breakage force along 30°, 60° and 90° is not obvious. Besides, as the fruit gets more mature, the breakage force value all decreases, which reduces by about 44% when the maturity stage gets to Entire Maturity from Green Maturity.

**Table 6.** Stalk tie breakage force measurement result

| Maturity stage      | Pull force angle |
|---------------------|------------------|
|                     | 0° | 30° | 60° | 90°  |
| Green Mature        | 11.90 | 13.64 | 15.57 | 17.35 |
| Color Change        | 9.158 | 12.52 | 10.83 | 14.75 |
| Maturation          | 8.38 | 9.87 | 9.81 | 12.36 |
| Entire Maturation   | 6.66 | 9.66 | 8.81 | 8.90  |

8. **Conclusion**

In order to obtain the mechanical property for freshly-eating tomato’s auto-harvesting, the force parameters, including fruit (stalk) friction coefficient, pressure resistance, cutting force, and abscission-layer breakage force, are measured with the methods and devices introduced in this paper. The main result and analysis is listed as below.

1) Max static-friction coefficients between the tomato fruit and the contrast materials, such as stainless steel (Ra0.8), PVC and rubber, are respectively 0.71, 1.24, and 2.46, and the values between the stalk and the contrast materials are respectively 0.25, 0.34, and 0.48.

2) Tomato fruit’s pressure resistance property is related with its maturity and the pressing area. The performance on resisting pressure declines greatly when the maturity stage gets into Color Change stage, and fruit pressed along the radial direction will be more easily crushed than the axial direction, especially, most easily crushed in the spoke-cavity radial direction.
(3) The abscission-layer at the stalk tie is more easily separated than the one at the stalk calyx, and the breakage force of both parts decreases when the fruit getting maturity. Besides, the breakage force value also related with the force direction, the stalk tie is most easily broken when pulled along 0°, and the calyx is most easily broken when pulled along 90°.

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