Effects of maturity of citrus fruits on their stalks cutting force

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Abstract: When the citrus harvesting robot harvests citruses, the mechanical properties of citrus stalks have an important influence on the success rate of the citrus harvesting robot. During the harvesting, the maturity of citrus fruits not only determined the harvesting time of citrus fruits but also affected the mechanical properties of citrus fruit stalks. In this study, the changes in the cutting force of citrus fruit stalks were described during the maturity of citrus fruits, and the effect of the maturity on the cutting force of stalks was clarified, so as to determine the harvesting time with the minimum cutting force required for harvesting citrus fruits by the harvesting robot. During the maturity, the relevant parameters of fruit maturity, such as the hardness, pH, and solid solution content of citrus fruits, were monitored. The results showed that there is a significant correlation between the hardness, pH, the solid solution content of citrus fruits, and the cutting force of citrus fruit stalks during maturity. The single-factor mechanical model of hardness, pH, solid solution content of citrus fruits, and the cutting force of citrus fruit stalks were established based on the data of 2019, which were verified through tests in 2020. The test results are as follows: during the ripening period of citrus fruits, the fruit hardness varies in the range of 0.13-0.31 MPa, the hardness changes by 0.02 MPa, and the cutting force changes by about 2.0-6.0 N; the pH of the citrus fruits changes in the range of 2.8-4.0, and the cutting force changes by about 1.5-2.2 N for every 0.1 change in the pH; the variation range of fruit solid solution content is 6.5%-9.0%, and for every 0.2% change in solid solution, the cutting force of citrus fruit stalks changes by about 1.25-2.0 N. The mechanical models can predict the cutting force required to cut off citrus fruit stalks according to the relevant parameters of citrus fruit maturity and can provide a reference for effectively evaluating the required cutting force.

Keywords: citrus fruit harvesting, cutting force of citrus fruit stalks, citrus fruit maturity, mechanical regression model

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1 Introduction

Citrus is grown widely all over the world as one of the most productive fruits[1]. During the production of citrus fruits, because the growth of branches and fruits of citrus fruit trees is random, the harvesting of citrus fruits is a more complex process, and manual harvesting is generally used nowadays[2,3]. Manual harvesting has such problems as high labor cost, low efficiency, and high labor intensity. In recent years, many scholars carried out many researches and explorations on the intelligent automatic harvesting robot[4-9]. According to the method of manually harvesting citrus fruits, the method of automatically harvesting citrus fruits by means of cutting off citrus fruit stalks has the advantages such as little damage to fruits, a high success rate of separating fruits and stalks, and less consumption time, which is one of the important research directions of the end-effector of harvesting robots[10-13].

Fruits are connected to the fruit tree through stalks, which serve for the growth and development of fruits. It is necessary to keep the nutrient exchange between fruits and the fruit tree smooth and ensure that fruits do not fall during the growth cycle. Some studies have found that the poor structure of the apple stalk will cause the fruit to develop abnormally and fall off[14]. Croes et al.[15] found that the developing tobacco fruit is directly related to the senescence of the fruit stalk tissue. After the tobacco flower fades, the fruit stalk begins to enter the senescence process, which is regulated by the maturity of the fruit. In the natural environment, stalks of citrus trees will naturally dry and fall off within a few months after citrus fruits mature and fall off. Since the success rate of cutting stalks is directly affected by the mechanical properties of stalks, it is necessary to study the mechanical properties of citrus fruit stalks and their influencing factors[16-19].

The peak cutting force required to cut off citrus fruit stalks is not only an important factor affecting the success rate of stalk cutting but also an important mechanical parameter of citrus fruit stalks. The study of Wang et al.[16] indicated that the diameters of stalks, the water content of stalks, and the weight of citrus fruits have a great influence on the cutting force of citrus fruit stalks. Some studies showed that the cutting forces of some crop stalks were related to the maturity of crops[20-22]. However, as far as the author knows, there are few researches reported on the effect of citrus fruit maturity on the mechanical properties of citrus fruit stalks.

The maturity of citrus fruits is obviously related to the developing time of fruits, and also closely related to the hardness, sugar content, acid content, soluble solids, and aromatic gases released by fruits[23-25]. Since the growth cycle and fruit harvesting time of most crops are relatively fixed, it is relatively common for the studies of crop maturity to estimate maturity through the growth and developing time of crops. When studying the changes

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in phenolic compounds and carotenoids in citrus fruits, Multari et al.[26] divided the ripening process of citrus fruits into four maturity stages according to different months, and found that the color, solid solution content, pH, and other characteristics of citrus fruits at four different maturity stages changed significantly. Therefore, this paper takes the Ponkans (*Citrus poonensis*) grown in Chongqing, China as the research object, and divides the maturity of citrus fruits by time during maturity. The maturity of citrus is from 190-250 d after flowering[27], taking 7 d (a week) as a cycle, the hardness, solid solution content, acidity, and cutting force of citrus fruit stalks were measured, so as to determine the maturity of citrus fruits and the mechanical properties of citrus fruit stalks during harvesting, and the relationship between the maturity of citrus fruits and the cutting force of citrus fruit stalks was analyzed.

2 Materials and methods

2.1 Samples

According to the author's field survey statistics, the fruit sizes of Ponkans that grow naturally in Chongqing, China are normally distributed. As shown in Figure 1, the weight of 80% of citrus fruits is between 100-200 g. The investigation also showed that there is a significant correlation between fruit sizes and stalk diameters. As shown in Table 1, the average stalk diameter of citrus fruits weighing less than 50 g is only 1.65 mm, while the stalk diameter of citrus fruits weighing more than 200 g can reach 2.5-3.30 mm. Normally, the stalks of small citrus fruits are more slender than the stalks of big citrus fruits. Wang et al.[16] studied the effects of cutting parameters on cutting citrus fruit stalks and found that the cutting force of stalks becomes greater as the weight of citrus fruits increases. Obviously, there is a certain connection between the maturity of citrus fruits and the tissue structure of citrus fruit stalks, which will inevitably cause changes in the mechanical properties of citrus stalks.

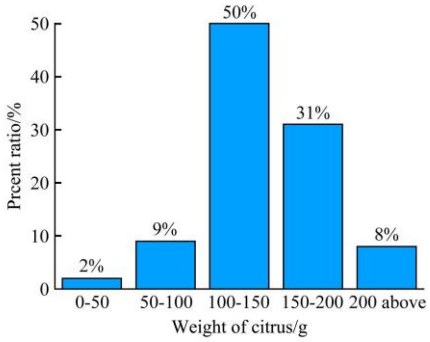


Figure 1 Weight distribution of the citrus fruits

Table 1 Size parameters distribution of stalks with different citrus fruit weight

Size parameters	Weight of the citrus fruits/g			
	0-50	50-100	100-150	≥150
d_1/mm	1.40	1.90	2.20	2.50
d_2/mm	1.80	2.45	2.70	3.30
d_3/mm	1.65	2.32	2.50	2.70
A/mm^2	2.14	4.23	4.91	5.73
L/mm	81.00	69.00	52.00	46.00

Note: d_1, d_2, and d_3: the minimum, maximum and average diameters of the stalks; A: the cross-sectional areas of the stalks; L: the average length of the stalks.

The experiment was carried out in a citrus planting base in Chongqing, China (Figure 2a). The climate in this region is mild and belongs to a subtropical monsoon temperature and humidity climate, with an average annual temperature of 16℃-18℃, annual precipitation of 1000-1450 mm, warm winters and early springs, and abundant precipitation[28]. Ponkan, a popular citrus species widely planted in China, is also the sample studied in this paper. The ripening period of Ponkans in Chongqing, China is generally from mid-to-late October to mid-December. According to the local production experience of Ponkans, Ponkan usually blooms in mid-March, and the flowering period (from identifiable flower buds to withering) lasts about 30 d, and the fruit set is basically completed. Ponkans enter the mature period 190 d after flowering, and the mature period lasts about 60 d from mid-October to mid-to-late December. Therefore, Ponkans become mature 240-250 d after flowering.

In 2019, the citrus in this citrus plantation finished blooming on April 14, and the test started on October 21. Due to the individual differences of naturally grown citrus fruits, as many representative fruits as possible were selected for tests in the case of limited resources. First, since the color of a citrus fruit largely reflects the maturity level of a citrus fruit[29,30], the citrus fruits with the most representative color in the orchard at the current growth stage were selected as the test samples. Second, since the diameter is an important parameter affecting the mechanical properties of fruit stalks[16], in order to reduce the influence of the stalk diameter on the shearing force, the stalk diameters of 2.4-2.7 mm that were the most concentrated in the citrus stalk diameters were selected for the test. In order to make the diameter of the selected citrus stalks the most representative, the tested stalk diameters were divided into 3 groups, (2.45±0.05) mm, (2.55±0.05) mm, and (2.65±0.05) mm respectively. Third, since the weight of citrus fruits reflects the development of fruits[31], based on the citrus fruit samples initially selected according to the color and stalk diameter, the primary samples were weighed and the fruits in the range of most concentrated weight of 100-150 g were selected as the test samples instead of too large or too small, so that the selected experimental samples could be fully representative.

According to the test conditions, each group of tests consisted of 20 citrus fruits, and the stalk length of the sample citrus fruits was kept at 30-50 mm. The sample fruits and stalks were numbered (Figure 2b), and the experiment was completed within 6 h after harvesting. During the experiment, the stalk was first removed from the fruit sample, the shear test was performed and the cutting force of the stalk was recorded, and then the citrus fruit was measured for hardness, pH, and solid solution content, and finally, the measured data were used for fitting analysis.

a. Citrus planting base b. Samples

Figure 2 Citrus planting base and experimental samples

2.2 Test equipment

This study aimed to find out the relationship between the hardness, solid solution content, and acidity of citrus fruits that reflect the maturity of citrus fruits and the force of cutting off citrus stalks. Therefore, it is necessary to determine the hardness, solid solution content, acidity, and a peak force of cutting off citrus stalks. The Aipu GY-3 Fruit Hardness Tester (Figure 3a) produced by Aipu Measuring Instrument Co., Ltd. (Quzhou, China) with a range of 0.1-1.5 MPa and a resolution of 0.001 MPa was used to measure the hardness of citrus fruits. Nohawk-HP-TD1 fruit sugar content meter (Figure 3b) produced by Tianjin Liaowang Optoelectronics Technology Co., Ltd. (Tianjin, China) with a resolution of 1% and a range of 0-55% was used to measure the solid solution content in fruits. The AZ 8601 hand-held acid-base tester (Figure 3c) produced by Taiwan Hengxin Co., Ltd. (Taiwan, China) with a resolution of 0.01 was used to determine the pH of citrus fruits.

a. GY-3 fruit hardness tester b. Fruit sugar content measuring instrument c. Hand-held acid-base tester

Figure 3 Apparatuses used in the experiment

The peak cutting force required to cut off the citrus stalks was measured by the fruit stalk cutting force test experimental system, which was composed of the WDM-500 electric level test platform and WD-500 digital push-pull force meter produced by Weidu Electronics Co., Ltd. (Wenzhou, China), as shown in Figure 4. The right side of the test platform is a movable part composed of a screw rod and a push-pull force gauge, which can provide the platform with a moving speed of 40-240 mm/min. On the left side of the test platform, there is a fixed platform whose height can be adjusted vertically. Two straight-edged cutting blades with a blade material of 45# steel are respectively installed on the front end of the thrust gauge and a fixed platform through a special fixture. According to the research of Wang et al.[32], the edge angle of the cutting blade was set to 25°.

Figure 4 Experimental system for fruit stalk cutting force

2.3 Test method

2.3.1 Determination of the hardness of citrus fruits

In this study, the method based on the study of Chen et al.[33] was used to determine the hardness of citrus fruits, and the measurement was carried out by using Aipu GY-3 with a cylindrical probe with a diameter of 8 mm. First, the citrus fruit samples were picked, washed, dried, weighed, and numbered. Second, the fruit hardness meter was set to zero, and then the samples were peeled about 3-5 cm^2. The peeled sample was held in the left hand, the hardness meter was held in the right hand, the hardness tester was made perpendicular to the surface of the tested sample, and the indenter was pressed into the sample with the action of uniform force. For the same sample, the measurement was repeated 3 times at different parts, and the average value was used as the hardness of the sample.

2.3.2 Determination of the solid solution content and the pH of the citrus fruits.

For the method of measuring the solid solution of citrus fruits, cut the citrus fruits to be measured for hardness into two pieces, squeezed the juice with a juicer, filter through two layers of clean gauze, and placed in a beaker. Finally, the sac after the juice was squeezed, peeled, and put into the clean gauze, and all of the juice was pressed out and mixed in the beaker. After shaking, the glue-head dropper was used to suck 1-2 drops of juice on the prism panel of the fruit brix meter. After repeating the measurement 3 times, recorded the average value.

For the method of measuring the pH of citrus fruits, the probe of the AZ 8601 acid-base tester was put into the beaker containing the juice, and the value was recorded after it was stable.

2.3.3 Determination of the cutting force of the citrus fruit stalks

According to the study of Wang et al.[16], the diameter of the stalk is an important parameter that affects its mechanical properties of the stalk. In order to reduce the impact of the diameter, the cutting diameters of the citrus fruit stalks were limited to three groups, which were 2.45 mm, 2.55 mm, and 2.65 mm, and the deviation of the diameters of each group was ±0.05 mm, and the cutting force test was carried out on the different maturity of the fruit stalks (every week after entering the mature period). In order to reduce the influence of cutting parameters, referring to the parameter setting of the cutting test of Wang et al.[16], the cutting speed of the movable knife of the test bench was set to 240 mm/min, and the gap between the movable knife and the fixed knife was set to 0.75 mm. When cutting, the stalk was held by a hand and the stalk was kept perpendicular to the blade, and then the experimental system was controlled to complete the cutting of the stalk of the citrus fruit through the cooperation of the movable knife and the fixed knife, and the peak cutting force was determined, as shown in Figure 5.

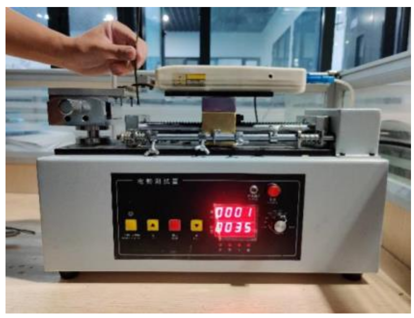


Figure 5 Determination of the peak cutting force of the citrus fruit stalk

3 Results and discussion

3.1 Changes in the related parameters of the maturity of the citrus fruits

In 2019, starting from 190 d after the citrus tree bloomed (October 17), the maturity of Ponkans was monitored for eight weeks. The changes every week in the parameters related to the citrus fruit maturity- the hardness, pH, and solid solution content are listed in Table 2.

Regarding the hardness of the citrus fruits, when citrus fruits entered the first week of maturity (experiment on October 22), the hardness of the fruits was 0.301 MPa (experiment on October 22). As the citrus fruits were fully matured, the hardness of the citrus fruits dropped to 0.120 MPa. About 190-220 d after blooming

(1-4 weeks of maturity), the hardness of the citrus fruits decreased drastically, and then decreased gradually until full maturity. The test results were consistent with the compression test of citrus fruits with different maturity by Jiang et al.[34]. The Student's *t*-test[35] was performed on the hardness values of the citrus fruits detected every week, and the significant results were all less than 0.05 (p=0.01), indicating that the hardness values of the citrus fruits measured every week have good differences.

Table 2 Changes in parameters related to citrus fruit maturity at the immature stage in 2019

Week	Hardness			pH			Solid solution content		
	n	A/MPa	SD	n	A	SD	n	A/%	SD
1	59	0.301	0.002	59	2.95	0.08	59	7.12	0.93
2	60	0.271	0.003	60	3.08	0.09	60	7.59	0.26
3	58	0.255	0.003	58	3.34	0.06	58	7.95	0.83
4	60	0.201	0.003	60	3.62	0.09	60	8.52	0.22
5	60	0.166	0.003	60	3.75	0.09	60	8.83	0.34
6	60	0.147	0.002	60	3.86	0.11	60	9.06	0.12
7	60	0.132	0.003	60	3.92	0.08	59	9.23	0.32
8	60	0.120	0.002	58	3.98	0.09	58	9.32	0.94

Note: Week is the number of weeks after the start of the first experiment; n is the number of samples; A is the average value; SD is the standard deviation.

Regarding the pH of the citrus fruits, from October 21 to December 16, the pH value rose from 2.95 to 3.98. About 190-220 d after blooming (1-4 weeks of the maturity), the pH value rose about 0.8, accounting for 77% of the total increase; afterwards, the rising trend of pH gradually slowed down until fully matured. The Student's *t*-test was performed on the pH values of the citrus fruits detected every week, and the significant results were all less than 0.05 (p=0.01), indicating that the pH values of the citrus fruits measured every week have great differences, and can better reflect the changes in the pH values of the citrus fruits.

Regarding the solid solution content of the citrus fruits, after testing, the solid solution content in the citrus fruits increased significantly during maturity, and the highest solid solution content value of 9.32% was obtained when fully matured. About 190-230 d after blooming (1-5 weeks of the maturity), the solid solution content of the citrus fruits increased rapidly. The closer to full maturity, the slower the increase in solid solution content of the citrus fruits. The Student's *t*-test was performed on the solid solution content of the citrus fruits detected every week, and the significant results were all less than 0.05 (p=0.01), indicating that the solid solution content of the citrus fruits measured every week have good differences, and can better reflect the changes in the solid solution content of the citrus fruits.

3.2 Changes in the cutting force of citrus fruit stalks

The average values of the cutting force required to cut off the citrus stalks for the 3 different types of diameters are shown in Table 3. In Table 3, the standard deviation of the cutting force of the stalks at the same maturity stage was all less than 1.5, and the cutting force of the stalks at each maturity stage changed significantly (p=0.01). With the increase in maturity of citrus fruits, the cutting force showed a trend of first increasing and then slowly decreasing, and the fluctuation range was between 0-34% (p=0.02). Within 190-210 d after blooming (1-2 weeks of the maturity), the cutting force of the fruit stalks rose rapidly by 16%-34% (p=0.03), and about 220 d after blooming (3-4 weeks of the maturity) the cutting force of the fruit stalks reached the peak. Subsequently, the cutting force of the citrus fruit stalks began to decrease slowly, with a decreased range of 10%-16% (p=0.02).

Table 3 Cutting forces of stalks with different diameters at different fruit maturities in 2019

Week	r=2.45 mm			r=2.55 mm			r=2.65 mm		
	n	Mean/N	SD	n	A/N	SD	n	A/N	SD
1	20	29.5	0.95	19	41.2	1.08	20	50.4	0.93
2	20	34.7	1.23	20	45.0	1.15	20	53.9	1.26
3	19	42.9	1.49	18	49.9	0.87	21	57.8	0.83
4	21	43.7	0.88	21	51.3	1.05	18	59.0	1.22
5	20	40.5	0.81	20	47.8	0.81	20	60.4	1.34
6	20	41.0	0.93	19	47.2	0.98	21	55.5	1.02
7	19	36.9	0.95	22	45.5	1.43	20	54.4	1.32
8	20	35.5	1.13	21	42.7	1.13	20	53.6	0.94

Note: Week is the number of weeks after the start of the first experiment; r is the diameter; n is the number of samples; SD is the standard deviation.

3.3 Effect of related parameters of the maturity of citrus fruits on the cutting force of citrus fruit stalks

3.3.1 Effect of fruits hardness on the cutting force of the citrus fruit stalks

For citrus fruit stalks with diameters of 2.45 mm, 2.55 mm, and 2.65 mm, the influence of citrus fruit hardness on the cutting force of the citrus fruit stalks during citrus maturity is shown in Figure 6.

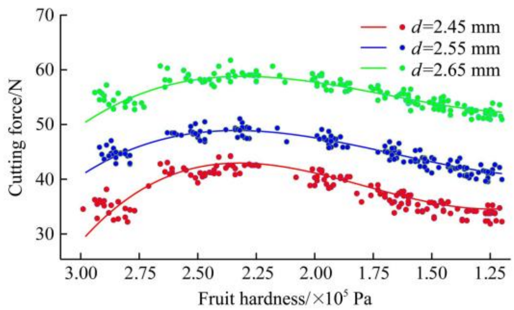


Figure 6 Relationship between the fruit hardness and the peak cutting force

The Curve Fitting Toolbox in Matlab software (R2020a, The Math Works Inc., Natick, MA, USA) was used to obtain the regression equations of the three curves according to the measured data, as shown in Equations (1)-(3):

$$F_{2.45} = -13.68x_1^3 - 73.31x_1^2 - 119.2x_1 + 9574 \quad x_1 \in [1.25, 3] \ (R^2 = 0.822) \tag{1}$$

$$F_{2.55} = -7x_1^3 + 35x_1^2 - 48.93x_1 + 261.54 \quad x_1 \in [1.25, 3] \ (R^2 = 0.863) \tag{2}$$

$$F_{2.65} = -7.4x_1^3 + 37.68x_1^2 - 55.71x_1 + 77.64 \quad x_1 \in [1.25, 3] \ (R^2 = 0.863) \tag{3}$$

where, x_1 represents the fruit hardness; $F_{2.45}$, $F_{2.55}$ and $F_{2.65}$ represent the peak cutting force with the fruit stalk diameters of 2.45 mm, 2.55 mm and 2.65 mm, respectively.

In order to avoid overfitting that makes the model lose its universality, according to the requirement that the goodness of fitting should be greater than 75% (R^2>0.75)[18], the mechanical model was fitted with a cubic polynomial. Regression analysis showed that with the decrease in citrus fruit hardness, the cutting force of the stalks increased first and then decreased slowly. When the hardness of citrus fruits was within the range of 0.25-0.32 MPa, the cutting force increased to 3-6 N for every 0.02 MPa reduction in hardness; when the hardness was in the range of 0.12-0.25 MPa, the cutting force decreased by about 2-3 N for every 0.02 MPa reduction in hardness.

3.3.2 Effect of the solid solution content in the citrus fruits on the cutting force of citrus fruit stalks

For citrus fruit stalks with diameters of 2.45 mm, 2.55 mm, and 2.65 mm, the influence of the solid solution content in the citrus fruits on the cutting force of the citrus fruit stalks during the citrus maturity is shown in Figure 7.

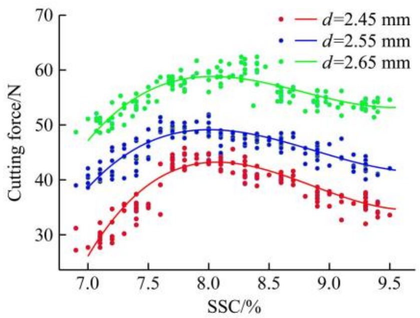


Figure 7 Relationship between the solid solution content and the cutting force

The Curve Fitting Toolbox in Matlab software (R2020a) was used to obtain the regression equations of the three curves according to the measured data, as shown in Equations (4)-(6):

$$F_{2.45} = 4.343x_2^3 - 115.46x_2^2 + 1015x_2 - 2911 \quad x_2 \in [7, 9.5] \ (R^2 = 0.823) \tag{4}$$

$$F_{2.55} = 2.882x_2^3 - 76.76x_2^2 + 674.9x_2 - 1913 \quad x_2 \in [7, 9.5] \ (R^2 = 0.815) \tag{5}$$

$$F_{2.65} = 3.352x_2^3 - 88.3x_2^2 + 769.7x_2 - 2163.8 \quad x_2 \in [7, 9.5] \ (R^2 = 0.791) \tag{6}$$

where, x_2 represents the solid solution content in the citrus fruits.

The results of regression analysis showed that the cutting force of citrus fruit stalks increased first and then decreased slowly with the increase of the solid solution content in the citrus fruits. The solid solution content in the citrus fruits rose from 7.0% to 8.0%, and the cutting force of the citrus fruit stalks increased by 10-15 N; then the solid solution content in the citrus fruits reached its peak, and the cutting force of the stalks began to decrease slowly.

3.3.3 Effect of the pH of the citrus fruits on the cutting force of the citrus fruit stalks

For citrus fruit stalks with diameters of 2.45 mm, 2.55 mm, and 2.65 mm, the influence of the pH of the citrus fruits on the cutting force of the citrus fruit stalks during the citrus maturity is shown in Figure 8.

The Curve Fitting Toolbox in Matlab software (R2020a) was used to obtain the regression equations of the three curves according to the measured data, as shown in Equations (7)-(9):

$$F_{2.45} = 40.46x_3^3 - 448x_3^2 + 1641x_3 - 1940 \quad x_3 \in [2.8, 4] \ (R^2 = 0.892) \tag{7}$$

$$F_{2.55} = 22.08x_3^3 - 249.7x_3^2 + 926.2x_3 - 1082 \quad x_3 \in [2.8, 4] \ (R^2 = 0.883) \tag{8}$$

$$F_{2.65} = 22.25x_3^3 - 250.8x_3^2 + 929.5x_3 - 1077 \quad x_3 \in [2.8, 4] \ (R^2 = 0.865) \tag{9}$$

where, x_3 represents the pH of the citrus fruits.

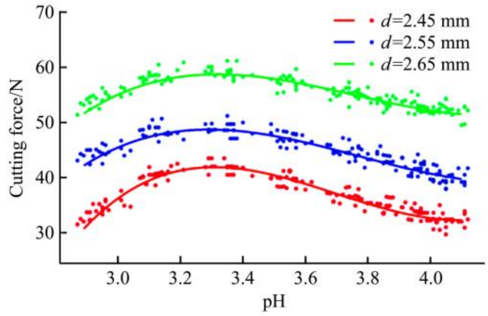


Figure 8 Relationship between the pH and the cutting force

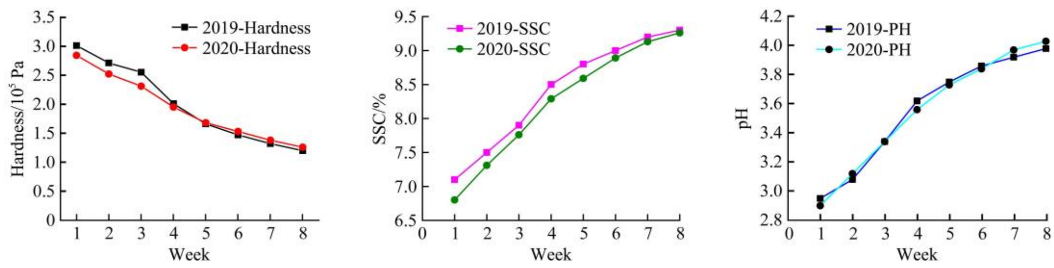
The results of regression analysis showed that the cutting force of the citrus fruit stalks increased first and then decreased with the increase of the pH of the citrus fruits. When the citrus fruit was in the early stage of maturity (around 190 d after blooming), the pH of the citrus fruits was low, and the cutting force of the citrus fruit stalks was at a lower position; when the pH of the citrus fruits reached 3.0, the cutting force of the citrus fruit stalks reached its highest peak, and then as the pH of the fruit reached 3.7, the cutting force of the citrus fruit stalks began to decrease slowly, with a decrease of 8-10 N.

4 Experimental verification

In 2020, a verification test on the relationship between the maturity of citrus fruits and the cutting force of citrus fruit stalks was conducted at the citrus planting base to verify the results of Section 3. The blooming date of the citrus fruit trees in the planting base was about April 20, 2020, and the mature time was around October 26, which was calculated based on the maturity 190 d after blooming.

4.1 Changes in the related parameters of the maturity of the citrus fruits in 2020

In 2020, the changes in the fruit hardness, pH of the fruits, and the fruit solid solution content of the citrus fruits grown in Chongqing during the maturity are shown in Figure 9.



a. Hardness b. Fruit Solid Solution Content c. pH

Figure 9 Comparison of related parameters of the maturity of citrus fruits hardness, fruit solid solution content, and pH

The hardness of citrus fruits in the first week of maturity was about 0.28 MPa, which was lower than that in 2019. About 230 d after blooming (the 6th week of the maturity), the hardness was about 0.17 MPa, which was almost the same as that of last year. After entering the maturity, the hardness of fruits decreased by 0.03 MPa per week on average, which is lower than the rate of decrease in 2019, as shown in Figure 9a

In 2020, 190 d after blooming (the first week of the maturity), the average solid solution content of citrus fruits was about 6.76%, a decrease of 0.36% from last year, and the average solid solution content 220 d after blooming was about 8.3%. The average rising rate of solid solution content of citrus fruits 190-220 d after blooming was about 0.5%, which was slightly higher than the average of 0.46% in 2019. 250 d after blooming (the eighth week of the maturity), the solid solution content was 9.1%, which was basically the same as that of the same period in 2019, as shown in Figure 9b.

In 2020, the value and the rate of change of pH of the citrus fruits at various stages during maturity were almost the same as in 2019. The pH of the citrus fruits 230-245 d after blooming (the 7th-8th weeks of the maturity) was slightly higher than that of the same period in 2019, as shown in Figure 9c.

4.2 Changes in the cutting force of citrus fruit stalks in 2020

In 2020, the changes in the cutting force of the citrus fruit stalks during maturity are listed in Table 4. The trend of changes was to increase first and then decrease, which is basically the same as in 2019, but the magnitude of the change is different. In the first week of maturity, the average cutting force of the citrus stalks with a diameter of 2.45 mm was about 34 N, and the average cutting force of the citrus fruit stalks with a diameter of 2.55 mm was about 45 N, and the average cutting force of the citrus stalks with a diameter of 2.65 mm was about 54 N, so there is an increase of about 5%-7% compared to that in 2019. The maximum cutting force of the fruit stalks of different diameters appeared 205-215 d after blooming, and the value of maximum cutting force was basically the same as that in 2019. The cutting force gradually decreased by about 230 d after blooming, and the reduction rate was basically the same as that in 2019.

Table 4 Cutting forces of stalks with different diameters at different fruit maturities in 2020

Week	*r*=2.45 mm			*r*=2.55 mm			*r*=2.65 mm		
	n	*A*/N	*S-D*	*n*	*A*/N	*S-D*	*n*	*A*/N	*S-D*
1	20	34.1	0.87	19	44.56	0.96	20	54.35	0.93
2	20	40.5	1.01	20	48.32	1.05	20	58.39	1.06
3	19	41.6	1.21	18	49.35	0.87	21	58.93	0.83
4	21	39.54	0.98	21	47.19	1.21	18	57.49	1.02
5	20	36.74	0.86	20	44.97	0.92	20	55.49	1.25
6	20	34.85	0.93	19	43.27	0.74	20	54.02	1.02
7	19	33.43	0.95	22	41.64	1.13	19	52.69	1.32
8	20	32.08	1.14	21	39.72	1.02	20	52.01	0.94

Note: Week is the number of weeks after the start of the first experiment; *r* is the diameter of stalks; *n* is the number of samples; *A* is the average value; *S-D* is the standard deviation.

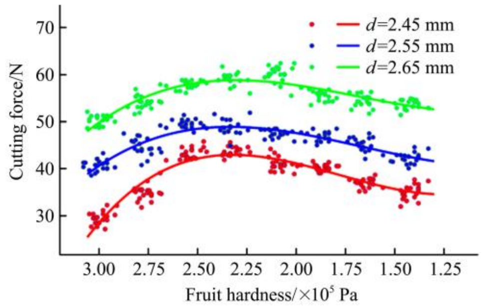
4.3 Verification of the influence of the related parameters of the citrus fruit maturity and the cutting force of the citrus fruit stalks

4.3.1 Verification of the relationship between the hardness of the citrus fruits and the cutting force of the citrus fruit stalks

Compared the cutting force of the citrus fruit stalks calculated by Equations (1)-(3) with the actual value corresponding to the hardness of the citrus fruits measured in 2020, as shown in Figure 10. The Root Mean Square Error (RMSE[36]) between the predicted value and the actual value of the cutting force required for the fruit stalks with a diameter of 2.45 mm was 1.37, and the goodness of fitting R^2 was 0.753. The *RMSE* between the predicted value and the actual value of the cutting force required for the fruit stalks with a diameter of 2.55 mm was 1.03, and the R^2 was 0.793. The *RMSE* between the predicted value and the actual value of the cutting force required for the fruit stalks with a diameter of 2.65 mm was 1.25, and the R^2 was 0.773. The experimental results showed that the values of R^2 between the predicted value and the actual value of the cutting force of the three types of diameters were greater than 0.75, which can effectively provide a reference for evaluating the required cutting force of the citrus fruit stalks[30].

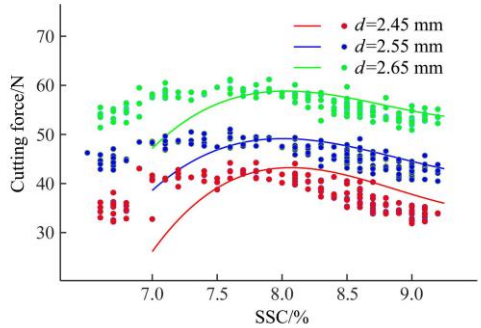
4.3.2 Verification of the relationship between the solid solution of the citrus fruits and the cutting force of the citrus fruit stalks

Compared the cutting force of the citrus fruit stalks calculated by Equations (4)-(6) with the actual value corresponding to the solid solution of the citrus fruits measured in 2020, as shown in Figure 11. The RMSE between the predicted value and the actual value of the cutting force required for the fruit stalks with a diameter of 2.45 mm was 1.37, and the goodness of fitting R^2 was 0.658. The RMSE between the predicted value and the actual value of the cutting force required for the fruit stalks with a diameter of 2.55 mm was 2.92, and the R^2 was 0.702. The RMSE between the predicted value and the actual value of the cutting force required for the fruit stalks with a diameter of 2.65 mm was 2.64, and the R^2 was 0.675.



Note: — Represents the predicted value of the mechanical model; • Represents the actual value.

Figure 10 Relationship between the hardness and the predicted value and the actual value in 2020



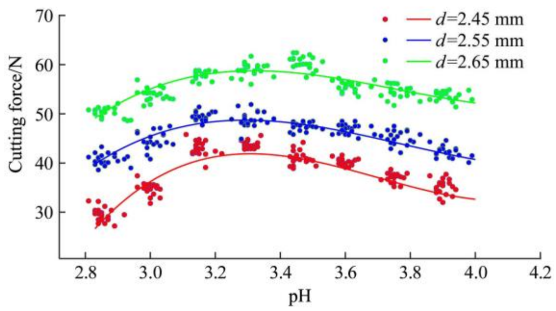
Note: — Represents the predicted value; • Represents the actual value.

Figure 11 Relationship between the solid solution and the cutting force in 2020

According to the analysis of the test results, there was a certain error between the predicted value and the actual value. When the solid solution content was less than 7.7%, the actual value of the solid solution content obtained in the experiment in 2020 was larger than the predicted value of the model; When the content was greater than 7.7%, the actual value was smaller than the predicted value of the model. According to the analysis of the reasons, the average temperature in Chongqing, China in October 2020 was 16.3℃, which was significantly lower than 18.1℃ in the same period in 2019, and the sunshine duration was also less than that in October 2019[37], resulting in the solid solution content of citrus fruits during maturity in 2020 was lower than that of the same period in 2019. At the same time, since the temperature decreased earlier in 2020 than it did in 2019, the change in solid solution content of citrus fruits in 2020 was earlier than that of 2019, but the trend was still basically the same.

4.3.3 Verification of the relationship between the pH of the citrus fruits and the cutting force of the citrus fruit stalks

Compared the cutting force of the citrus fruit stalks calculated by Equations (7)-(9) with the actual value corresponding to the pH of the citrus fruits measured in 2020, as shown in Figure 12. The RMSE between the predicted value and the actual value of the cutting force required for the fruit stalks with a diameter of 2.45 mm was 1.34, and the goodness of fitting R^2 was 0.768. The *RMSE* between the predicted value and the actual value of the cutting force required for the fruit stalks with a diameter of 2.55 mm was 1.17, and the R^2 was 0.781. The RMSE between the predicted value and the actual value of the cutting force required for the fruit stalks with a diameter of 2.65 mm was 1.25, and the R^2 was 0.786. The experimental results showed that the values of R^2 between the predicted value and the actual value of the cutting force of the three types of diameters were greater than 0.75, which can effectively provide a reference for evaluating the required cutting force of the citrus fruit stalks.



Note: — Represents the predicted value; • Represents the actual value.

Figure 12 Relationship between the pH and the cutting force in 2020

5 Conclusions

The cutting tests for citrus fruit stalks with different diameters showed that the cutting force of citrus fruit stalks increased significantly in the early maturity of citrus fruits (from the 190th day to the 210th day after blooming), the increase rate was about 16%-34%, and the maximum cutting force of citrus fruit stalks appeared 210-220 d after blooming. However, in the late maturity of citrus fruits (about 220 d after blooming), the cutting force of citrus stalks showed a steady downward trend, decreasing by 10%-16%. The harvesting time and the power of the end-effector of the harvesting robot can be selected or adjusted according to the maturity of citrus fruits. Some parameters such as the hardness, the solid solution, and the pH of citrus fruits were used to quantify the maturity of citrus fruits, a single factor regression model between the hardness, the solid solution, the pH of citrus fruits and the cutting force of citrus fruit stalks was established, and the relationship between the same parameters was obtained. During the ripening period of citrus fruits, the fruit hardness varies in the range of 0.13-0.32 MPa, the hardness changes by 0.02 MPa, and the cutting force changes by about 2-6 N. The pH of the citrus fruits changes in the range of 2.8-4.0, and the cutting force changes by about 1.5-2.2 N for every 0.1 change in pH. The variation range of fruit solid solution content is 6.5%-9.0%, and for every 0.2% change in solid solution, the cutting force of citrus fruit stalks changes by about 1.25-2.0 N. Validation experiments showed that the relevant parameters of citrus fruit maturity can be used to predict the cutting force, which can provide a reference for evaluating the cutting force of the harvesting robot.

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