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BIOMECHANICAL PROPERTIES OF WOLFBERRY PLANT ORGANS

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KEYWORDS

binding force, biomechanical characteristics, constitutive equation, dynamic model, vibrating wolfberry harvesting machinery.

ABSTRACT

To improve the picking rate and reduce the wrong picking rate of the existing wolfberry harvesting machinery, in this study, the binding force and physical appearance of the immature fruit stalk, mature fruit stalk, flower, and leaf were studied to guide the designing of new-generation wolfberry harvesting machinery and lay theoretical foundation for further studies on biomechanical properties of wolfberry. By preprocessing the experimental data with the Pauta criterion, the distribution range of the binding force and physical appearance of stalk were obtained; the binding force was not influenced by the picking temperature, mass of the fruit, and location of the branch of the fruit. The length-diameter ratio of mature fruit was confirmed by image processing. The constitutive equations for immature fruit stalks and mature fruit stalks were established. The breaking strength of the mature fruit stalk was obviously higher than that of the immature fruit stalk; moreover, the breaking strength of the mature and immature fruit stalk of the four wolfberry varieties differed obviously. The experimental results obtained in this study can provide detailed data for the parameter design of a new-generation wolfberry harvesting machinery.

INTRODUCTION

For hundreds of years, mechanized picking of wolfberry has been a difficult problem; fresh wolfberry was picked manually, resulting in low efficiency and high costs (Zhang et al., 2015; Ma, 2017; He et al., 2017; Cheng et al., 2013; Harunobu & Farnsworth, 2011; So, 2003). There are some problems with vibrating wolfberry harvesting machinery such as low picking rate, high wrong picking rate, and so on. Therefore, it's of vital significance to study the biomechanical characteristics of the organs of wolfberry, which can be used for parameter designing of the vibrating wolfberry harvesting machinery.

In recent years, increasing attention is being paid to the biomechanical characteristics of plants. Qin et al. (2015), and Luo et al. (2018) studied the factors affecting the binding force of tomato; they found that there is a significant influence of the binding force among different varieties and different masses of the fruits. Sun et al. (2016) studied the binding force of cerasus humilis and conducted regression model analysis; He et al. (2019) studied the relationship between the binding force and content of endogenous hormones and discovered that the binding force was influenced by the content of endogenous hormones in the fruit but not the stalk. There are many studies on the mechanical characteristics of plants, but few studies on the biomechanical characteristics of the organs of wolfberry. The biomechanical characteristics of each organ play a decisive role in determining the parameters of the vibrating wolfberry harvesting machinery, namely the amplitude and frequency.

In this study, the binding force and physical appearance of the immature fruit stalk, mature fruit stalk, flower, and leaf of four wolfberry varieties were tested; the distribution range of the binding force was obtained after preprocessing the data. Next, we determined the constitutive equation between the breaking strength and cross-sectional area, established the dynamical model of the vibrating wolfberry harvesting machinery. Finally, we confirmed the influence factors using orthogonal experiments. The technical route followed in this study is in Figure 1.

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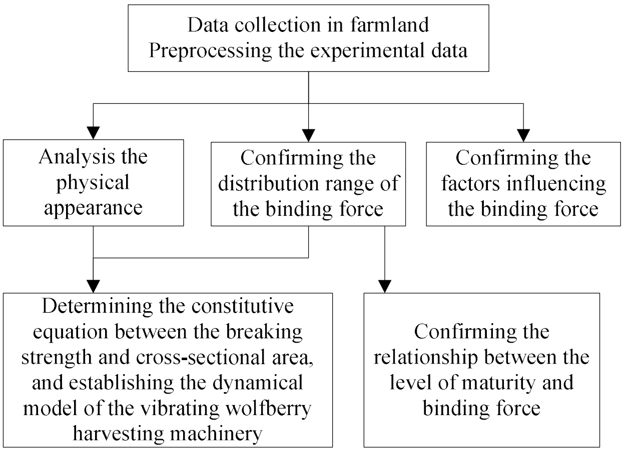


FIGURE 1. Research technical route.

MATERIAL AND METHODS

Materials and equipment

In this study, to comprehensively research the biomechanical characteristics of the immature fruit stalk, mature fruit stalk, flower, leaf of wolfberry, the four wolfberry varieties were studied, which were Ningqi No.1, Ningqi No.5, Ningqi No.7, and Ningqi No.9. These wolfberry trees were planted in Hongbao Group, Zhongning County, Zhongwei City, and Ningxia Province, China and the tests were conducted during the harvest season from May to October every year from 2016 to 2018.

FIGURE 2. Wolfberry planting base.

The following were the instruments used in the experiments: HF-2 tension meter with accuracy of 0.01 N, Vernier calipers with accuracy of 0.02 mm, HTC-1 temperature and humidity measuring instrument with accuracies of 0.1°C and 1%, respectively, and balance with accuracy of 0.1 g. The wolfberry planting base is shown in Figure 2.

Experimental scheme

Experiment for determining the relationship between binding force and physical appearance

To confirm the distribution range of binding force and physical appearance and study whether there is a relationship between the binding forces and the physical appearance of the stalks. In the experiment, the following data of the four varieties were tested: the binding force of the immature fruit stalk, mature fruit stalk, flower, and leaf, diameter of the fruit stalk, mass and length-diameter ratio of the mature fruit. The experimental process was shown in Figure 3. The length-diameter ratio were confirmed by image processing (the algorithm flow chart was shown in Figure 4). The data processing procedure was shown in figure 5.

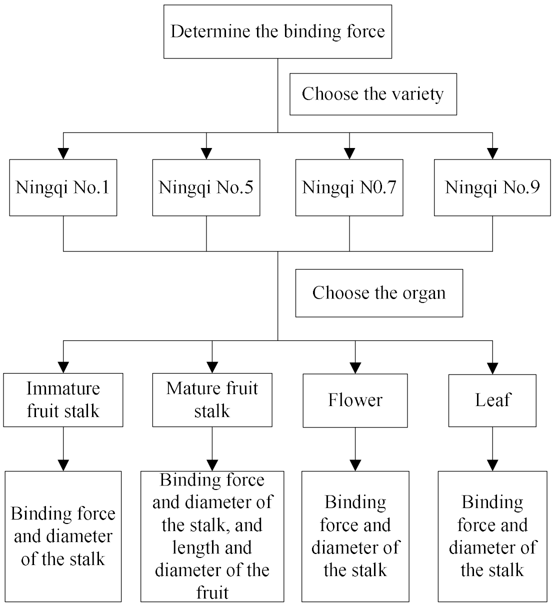


FIGURE 3. Experimental process.

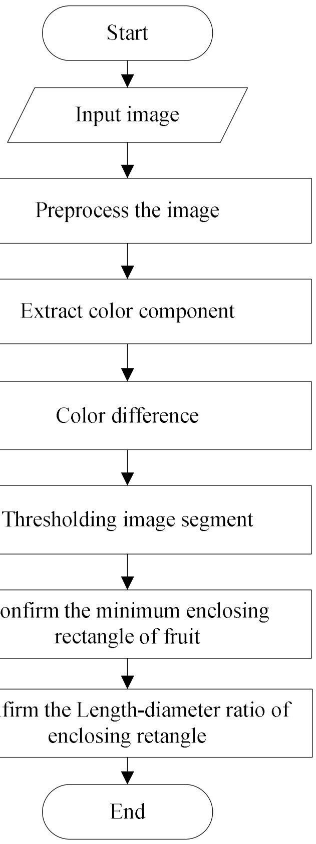


FIGURE 4. The algorithm flow chart of the calculation of length-diameter ratio of fruit.

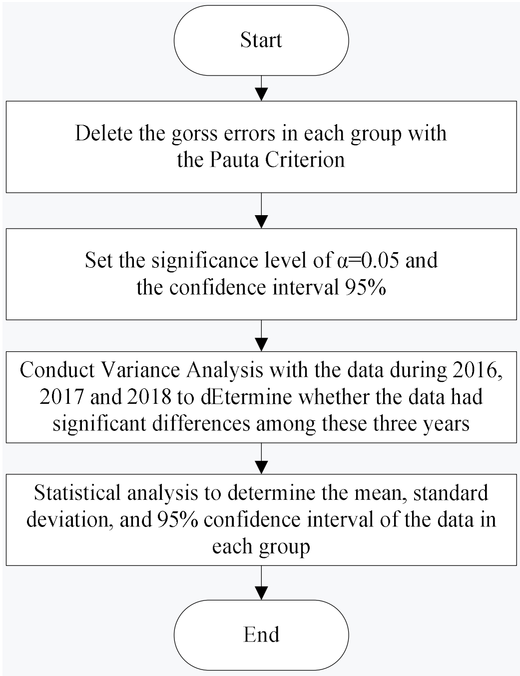


FIGURE 5. The data processing procedure.

To eliminate the influence caused by the season, the experimental time were selected from 8:00 to 18:00 each day, for two days after every ten days in a month, from June to October every year (Qin et al., 2015; Luo et al., 2018).

To study the effect of the fruit position on the branch, fruit quality, and picking temperature on the binding force, the temperature and position were recorded.

The relevant images of the experimental process are shown in Figure 6.

(a) Measured the binding force

(b) Recorded mass, temperature, and humidity data

(c) Size measurements

FIGURE 6. Images of the experimental processes.

Experiment for determining the relationship between binding force and maturity

The main cause of a high wrong picking rate in existing wolfberry harvesting machinery is the use of unreasonable design parameters; that is, there is no clear demarcation regarding the binding force of immature and mature fruits. Therefore, to establish a difference in the binding force between the immature and mature fruit stalks and to obtain data for designing new-generation vibrating wolfberry harvesting machinery, we set a significance level of $\alpha = 0.05$ to conduct independent sample t-tests (Zhang et al., 2019b).

Experiment for determining factors influencing binding force

The picking temperature, position of the fruit on the branches, and quality of the fruit may have an effect on the binding force of the mature fruit stalk in the mechanical picking process, thus influencing the harvesting process. Therefore, it was important to ascertain how these factors influenced the binding force and the extent of their influence. We performed orthogonal experiments to study these factors (Gao et al., 2018). Because the temperature varies widely from day to night and the picking of wolfberry varies during the day, it was necessary to study the influence of the temperature on the binding force. If the gravity acting on the fruit is higher than the binding force, then quality is a factor influencing the binding force. When the wind reaches the branch, different parts of the branch swing differently; therefore, studying the differences in the binding force at different positions was important. Hence, orthogonal experiments based on three factors and three levels were designed for the mature fruit stalk. The experimental factors and levels are given in Table 1.

TABLE 1. Orthogonal experiments on factors influencing binding force of mature fruit stalk.

Factors		A (The picking temperature)	B (The fruit mass)	C (The position on the branch)
Levels	1	20°C–25°C	0.1g-0.6 g	Tip
	2	25°C–30°C	0.6g-1.1 g	Middle
	3	30°C–35°C	1.1g-1.5 g	Bottom

The positions of the fruit on the branch were denoted as the shoot, middle, and root using the proportional quantification method. As shown in Figure 7, starting with the first fruit at the root of the branch, the branch was segmented into units of 5 cm until the end of the branch. The first 3/10 segments were designated as the shoot, the middle 2/5 as the middle, and the last 3/10 as the root; the proportional quantification method is shown in Figure 7.

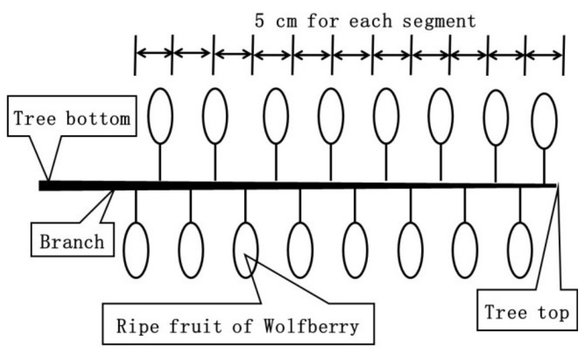


FIGURE 7. Proportional quantification method for determining the position of the fruit on the branch.

RESULTS AND DISCUSSION

Study on vibration picking mechanism of wolfberry

Determination of the distribution range of binding force in each part of four varieties

The distribution range of binding force of each organ was an important factor to conduct the parameter design for the vibrating wolfberry harvesting machinery. To judge whether there was an obvious difference in the binding force of each organ during the different years, we conducted a one-way analysis of variance (ANOVA). The results are presented in Tables 2, 3, 4, and 5. From the results, it can be inferred that the probability obtained via one-way ANOVA for each organ was higher than 0.05, which indicated that there was no significant difference in the binding force between different years; that is, the binding force of each organ did not change with the age of the plant. This feature considerably reduces the difficulty in designing new-generation vibrating wolfberry harvesting machinery.

TABLE 2. Analysis of variance of binding forces of various organs in Ningqi No.1 during different years.

Organs	Years	Means	Standard deviation	*[a]	Confidence intervals (95%)
Immature fruit stalk	2016	1.60	0.48	0.066	[1.45, 1.75]
	2017	1.37	0.37		[1.25, 1.49]
	2018	1.44	0.49		[1.28, 1.59]
Mature fruit stalk	2016	1.69	0.58	0.678	[1.51, 1.89]
	2017	1.63	0.48		[1.47, 1.78]
	2018	1.73	0.58		[1.55, 1.92]
Flowers	2016	0.86	0.22	0.173	[0.79, 0.93]
	2017	0.81	0.25		[0.73, 0.89]
	2018	0.92	0.31		[0.82, 1.02]
Leaves	2016	1.33	0.50	0.193	[1.17, 1.49]
	2017	1.16	0.74		[0.92, 1.39]
	2018	1.40	0.60		[1.21, 1.60]

[a] *=The result of one-way analysis of variance(Sig.)

TABLE 3. Analysis of variance of binding forces of various organs in Ningqi No.5 during different years.

Organs	Years	Means	Standard deviation	*[a]	Confidence intervals (95%)
Immature fruit stalk	2016	1.28	0.39	0.081	[1.16, 1.41]
	2017	1.44	0.44		[1.30, 1.59]
	2018	1.49	0.44		[1.35, 1.63]
Mature fruit stalk	2016	1.51	0.46	0.563	[1.36, 1.66]
	2017	1.53	0.52		[1.33, 1.72]
	2018	1.63	0.53		[1.46, 1.80]
Flowers	2016	0.90	0.31	0.09	[0.80, 1.00]
	2017	1.04	0.40		[0.92, 1.17]
	2018	1.05	0.28		[0.96, 1.14]
Leaves	2016	1.14	0.54	0.089	[0.88, 1.39]
	2017	0.96	0.48		[0.73, 1.18]
	2018	1.30	0.40		[1.11, 1.48]

[a] *=The result of one-way analysis of variance(Sig.)

TABLE 4. Analysis of variance of binding forces of various organs in Ningqi No. 7 during different years.

Organs	Years	Means	Standard deviation	*[a]	Confidence intervals (95%)
Immature fruit stalk	2016	1.21	0.40	0.103	[1.08, 1.33]
	2017	1.00	0.40		[0.87, 1.12]
	2018	1.07	0.51		[0.91, 1.23]
Mature fruit stalk	2016	1.25	0.58	0.474	[1.06, 1.43]
	2017	1.25	0.49		[1.09, 1.40]
	2018	1.11	0.64		[0.91, 1.31]
Flowers	2016	0.87	0.30	0.073	[0.77, 0.96]
	2017	0.74	0.29		[0.64, 0.83]
	2018	0.87	0.29		[0.78, 0.96]
Leaves	2016	1.37	0.49	0.135	[1.22, 1.53]
	2017	1.13	0.39		[1.10, 1.35]
	2018	1.28	0.48		[1.02, 1.33]

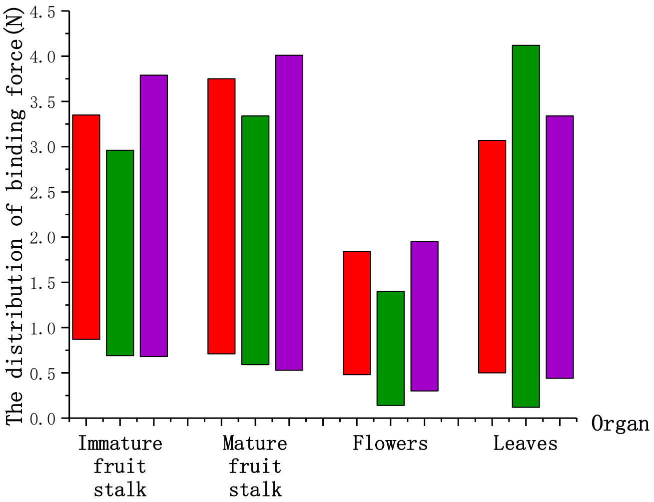
[a] *=The result of one-way analysis of variance(Sig.)

TABLE 5. Analysis of variance of binding forces of different organs in Ningqi No.9 during different years.

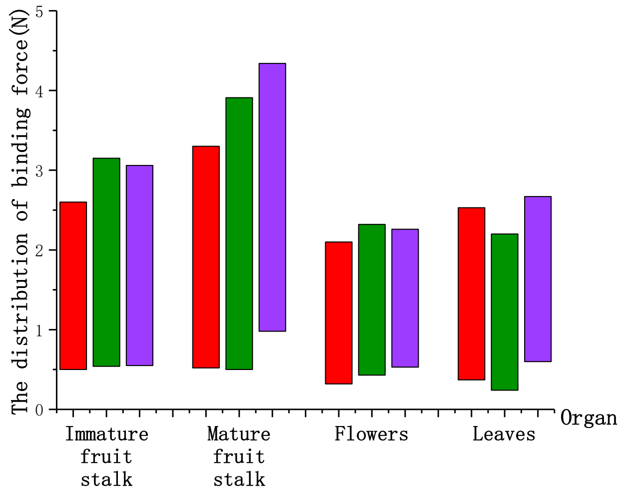
Organs	Years	Means	Standard deviation	*[a]	Confidence intervals(95%)
Immature fruit stalk	2016	1.21	0.40	0.103	[1.08, 1.33]
	2017	1.00	0.40		[0.87, 1.12]
	2018	1.07	0.51		[0.91, 1.23]
Mature fruit stalk	2016	1.82	0.53	0.255	[1.65, 1.99]
	2017	1.78	0.50		[1.62, 1.94]
	2018	1.98	0.64		[1.77, 2.18]
Flowers	2016	0.91	0.20	0.1789	[0.84, 0.97]
	2017	0.97	0.29		[0.87, 1.06]
	2018	0.86	0.23		[0.79, 0.94]
Leaves	2016	1.41	0.47	0.733	[1.26, 1.56]
	2017	1.35	0.49		[1.19, 1.51]
	2018	1.33	0.50		[1.17, 1.49]

[a] *=The result of one-way analysis of variance(Sig.)

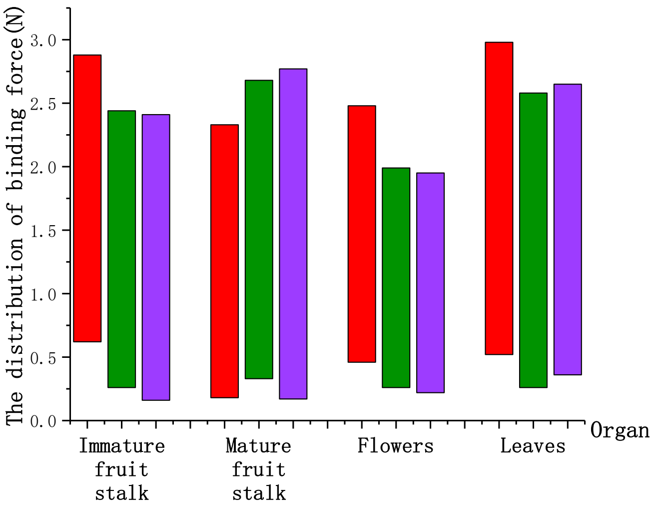
From the results presented in Figure 8, it can be seen that there are obvious differences among the various organs of the four wolfberry varieties. Except for Ningqi No.5, the other three varieties had the highest binding forces in the mature fruit stalk and the lowest binding forces in the flowers. Additionally, there were some differences among the four varieties in the same organs because of small differences in their internal structures. Therefore, to enhance the picking rate and reduce the wrong picking rate, it was necessary to consider the difference in the binding forces among the four varieties when designing the parameters of the vibrating wolfberry harvesting machinery.



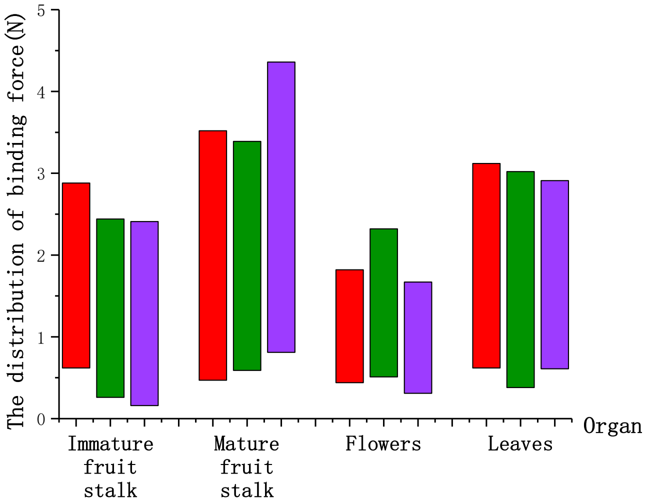
(a)Distribution of binding force of each organ during different years in Ningqi No.1



(b) Distribution of binding force of each organ during different years in Ningqi No.5



(c) Distribution of binding force of each organ during different years in Ningqi No.7



(d) Distribution range of binding force of each organ during different years in Ningqi No.9

FIGURE 8. Distribution of binding forces of each organ during different years.

Physical and morphological analysis of mature fruit of each variety

Fruit quality is one of the decisive physical quantities required for designing the parameters of the vibrating wolfberry harvesting machinery. It can be calculated of the inertia force according to Newton's second law of motion-force and acceleration after determining the mass of the fruits; if the inertia force is higher than the binding force, the fruits would move away from the branch.

TABLE 6. Statistical analysis results of mature fruit quality of different wolfberry varieties in each year.

Varieties	Years	Means	Standard deviations	One-way ANOVA result (Sig.)	Confidence intervals (95%)
Ningqi No.1	2016	1.39	0.21	0.098	[1.33,1.46]
	2017	1.31	0.25		[1.23,1.39]
	2018	1.30	0.22		[1.22,1.36]
Ningqi No.5	2016	1.10	0.37	0.063	[0.98,1.22]
	2017	1.10	0.41		[0.97,1.23]
	2018	1.30	0.48		[1.14,1.45]
Ningqi No.7	2016	1.01	0.27	0.088	[0.93,1.10]
	2017	0.87	0.26		[0.79,0.96]
	2018	0.91	0.35		[0.80,1.02]
Ningqi No.9	2016	1.02	0.29	0.340	[0.92,1.11]
	2017	1.04	0.45		[1.00,1.28]
	2018	1.10	0.37		[0.98,1.21]

One-way ANOVA for the mass of each variety during different years was conducted to judge whether there was any obvious difference in fruit quality during the different years to determine whether the parameters of the harvesting machinery need to change with the age of the plant. The results are presented in Table 6. According to these results, the two-tail probability of single-factor ANOVA of each variety was higher than the set significance level of 0.05. Therefore, the age of the plant had no significant effect on the fruit quality. This characteristic considerably reduces the complexity in the design of the picking machine.

From the results shown in Figure 9, we can see that Ningqi No. 5, Ningqi No.7, and Ningqi No.9 have much larger distribution ranges in terms of the mature fruit quality than Ningqi No.1. Therefore, the picking rate will be far lower than that for Ningqi No.1.

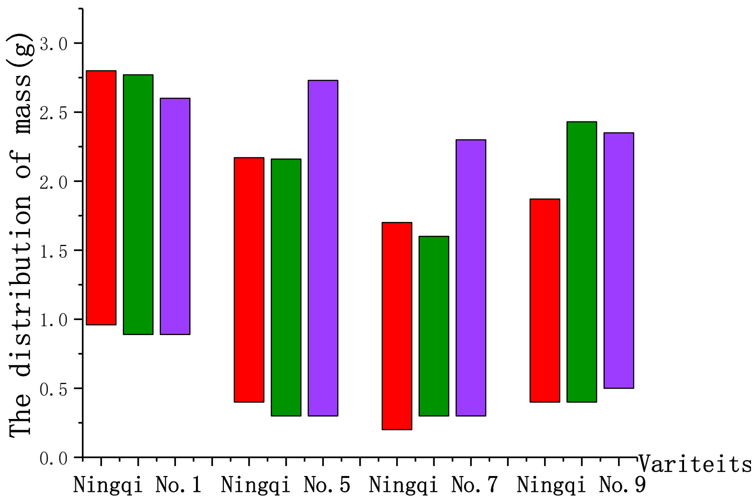


FIGURE 9. Statistical analysis results of the mass of mature fruit in each variety during each year.

For the mature fruits of four varieties of wolfberry, the image processing was used to confirm the length-diameter ratio, whose accuracy and efficiency were higher than the result by Vernier Caliper. In the progress, the initial image of wolfberry were shown in Figure 10. Since the red component dominates the area of wolfberry and the rest were the background object, the R component and the G component were subtracted to increase the difference between the foreground and the background, which facilitates the segmentation of wolfberry. The color difference image were shown in Figure 11. Segmented the foreground and background with thresholding method and the result were shown in Figure 12. Finally, the minimum enclosing rectangle of the foreground portion were determined and were shown in Figure 13.

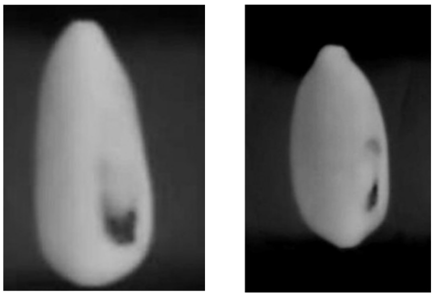
Using the image processing, the length-diameter ratio of 100 mature fruits of wolfberry of Ningqi No.1, Ningqi No.5, Ningqi No.7, Ningqi No.9 were analyzed, respectively. The result was shown in Table 7.

TABLE 7. The length-diameter ratio of four varieties of wolfberry.

Varieties	Means	Standard deviations	Confidence intervals (95%)
Ningqi No.1	1.89	0.407	[1.81，1.97]
Ningqi No.5	1.63	0.843	[1.46，1.79]
Ningqi No.7	2.05	0.473	[1.95，2.14]
Ningqi No.9	2.10	0.348	[2.03，2.16]

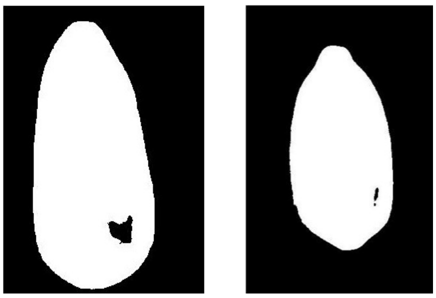
(a) (b)

Figure 10. The initial image of wolfberry.



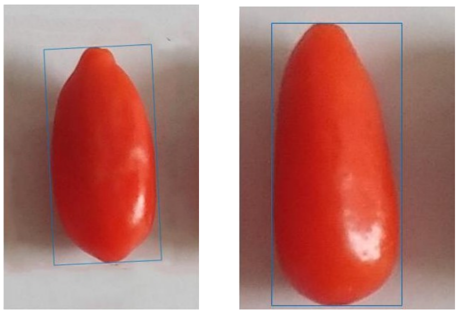
(a) (b)

Figure 11. The color difference image.



(a) (b)

Figure 12. The binary image segmented by thresholding.



(a) (b)

Figure 13. The minimum enclosing rectangle

Dynamic model of vibration picking

The harvesting mechanism of the vibrating wolfberry harvesting machine is that the machine provides vibration to a position on the branch, and then the parts in other positions will provide a vibration response after receiving energy from the vibration source. There will be an acceleration associated with each part and the inertia force can be calculated using Newton’s second law of motion-force and acceleration. If the inertia force is higher than the binding force, the fruit parts will break away from the branch. Therefore, the binding force and mass of the mature fruit can be determined.

The inertia force of the mature fruit at distance d during vibration can be expressed using formula (1). It can be inferred from formula (1) that the higher the distribution range of the fruit mass, the higher is the requirement in terms of the vibrational frequency and amplitude. Moreover, this is also the reason why the existing vibrating wolfberry harvesting machinery has a low picking rate and high wrong picking rate.

$$F(d) = 4\pi^2 * m(d) * [f(d)]^2 * A(d) \quad (1)$$

In which:

F(d) - inertia force N;

d - distance mm;

m(d) - the mass g;

f(d) - the vibrational frequency Hz,

A(d) - the amplitude mm.

The vibrational frequency and amplitude would be attenuated by the transmission in the branches owing to the properties of the branch. This attenuation could lead to incorrect picking, causing an immature fruit, flower, or leaf to be picked. To avoid the reduction in the picking rate caused by vibration attenuation, we propose a new picking program named 'Multipoint accurate grasp'. This provides new vibration, which is the same as that provided by the vibration source, at the position where the vibration attenuates to an improper value to strengthen the vibration so that mature fruits can be picked properly. Therefore, it was necessary to establish the dynamic model of the vibrating branch and then determine the position for providing the vibration.

The dynamic model of the vibrating branch is given in formula (2).

$$\frac{F_c(i)}{m(d)\cdot A_c(d)\cdot[2\pi\cdot f_c(d)]^2}=-\sin[2\pi\cdot f_c(d)\cdot t+\alpha] \qquad (2)$$

In which:

I - the number of mature fruits based on the vibration source;

d - distance mm;

t - the vibration time seconds;

α -the starting phase angle radians;

Ac(d) - the amplitude from from the vibration source; Ac(d)=ψ(d)·A; A is the amplitude of the vibration source and ψ(d) is the attenuation function of the amplitude;

fc(d) - the vibration frequency from the vibration source whose distance is d and its unit is Hz; fc(d)=2π·f·φ(d); f is the frequency of the vibration source and φ(d) is the attenuation function of the vibration frequency.

Determination of the range of breaking strength

To further reveal the breaking mechanism of the fruit and branch and confirm whether there was a relationship between the breaking strength and diameter of the stalk, we analyzed the stress of the stalk when breaking. Breaking strength is an important parameter for studying breaking behavior. Breaking strength is the ratio of the stress and cross-sectional area when breaking. In this study, the breaking strength was calculated using formula (3). The breaking strength values of the immature fruit stalk and mature fruit stalk (Lei et al., 2016; Yao et al., 2015) are given in Tables 7 and 8.

TABLE 8. Regression equations for breaking strength of immature fruit stalk.

Varieties	Regression equations	R^2	Means of the cross-sectional area (mm^2)	Means of the breaking strength (N/mm^2)
Ningqi No.1	$y=-2.019+\frac{1.477}{x}$	0.822	0.12	23.48
Ningqi No.5	$y=19.19\cdot e^{-4.36x}$	0.379	0.15	11.11
Ningqi No.7	$y=2.075+\frac{0.999}{x}$	0.721	0.15	13.16
Ningqi No.9	$y=1.615\cdot x^{-0.967}$	0.881	0.14	36.73

From Table 8, it can be inferred that the mean breaking strength of the immature fruit stalk of the four varieties differ obviously. The sizes have the following order starting from the highest value: Ningqi No.9, Ningqi No.1, Ningqi No.7, and Ningqi No.5. This may be because of the different internal microstructures of the immature fruit stalk. Moreover, this property is necessary to confirm the parameters of the vibrating harvesting machinery for picking different varieties of wolfberry. From Figure 14, it can be also inferred that the breaking strength decreases with the increase in the cross-sectional area. As shown in Figures 14(a) and 14(c), the breaking strengths of Ningqi No.1 and Ningqi No.7 decrease with the inverse function owing to the increase in the cross-sectional area. It can be inferred from Figure 14(b) that the breaking strength of Ningqi No.5 decreases with the exponential function owing to the increase in the cross-sectional area. Finally, Figure 14(d) shows that the breaking strength of Ningqi No.9 decreases with the power function owing to the increase in the cross-sectional area. Additionally, the breaking strengths of Ningqi No.1, Ningqi No.5, and Ningqi No.7 increase with the maturity of fruits, while Ningqi No.9 shoed the opposite characteristics.

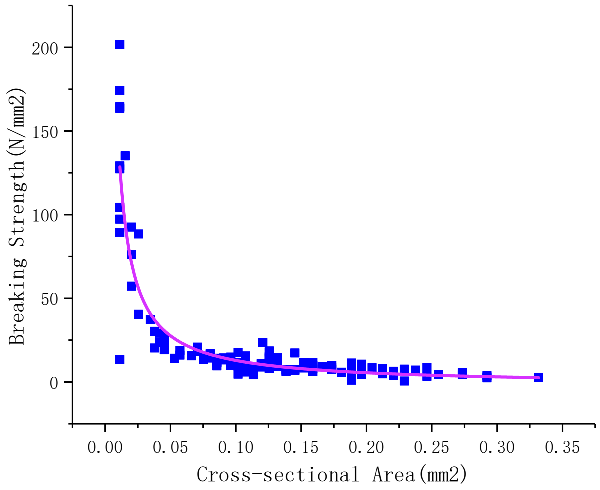
$$P = \frac{4F}{\pi D^2} \quad \text{(Zhu et al., 2009)} \qquad (3)$$

In which:

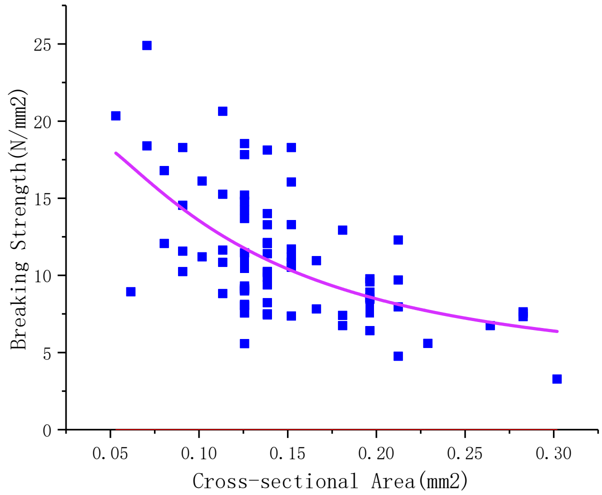
P - Breaking strength N/mm^2;

F - Breaking force N,

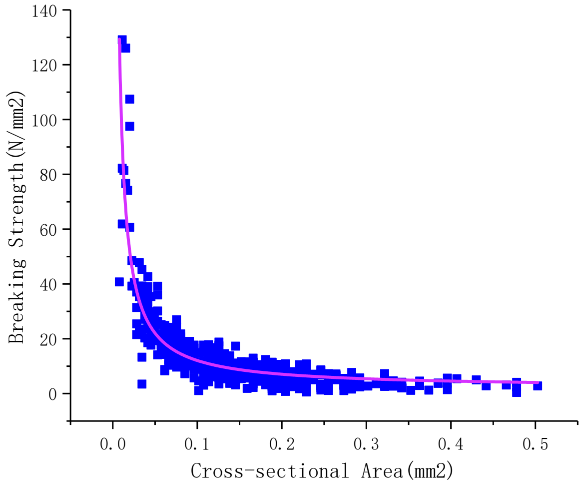
D - Cross-sectional area mm^2.



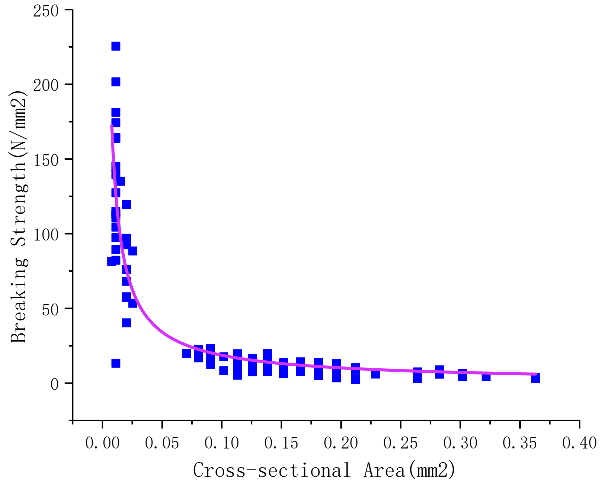
(a) Ningqi No.1



(b) Ningqi No.5

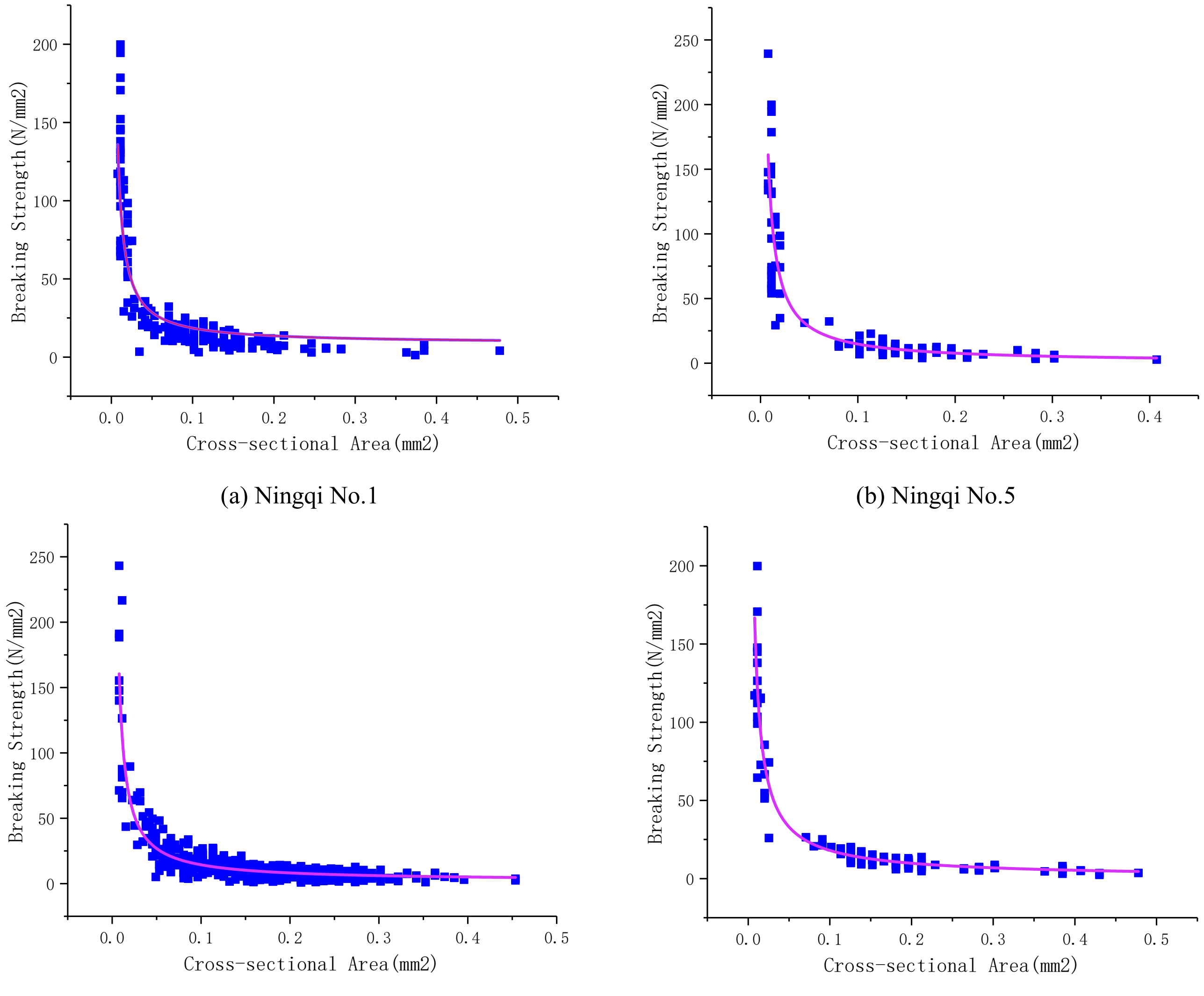


(c) Ningqi No.7



(d) Ningqi No.9

FIGURE 14. Regression equations between breaking strength and cross-sectional area of the immature fruit stalk.



(a) Ningqi No.1 (b) Ningqi No.5

(c) Ningqi No.7 (d) Ningqi No.9

FIGURE 15. Regression equations between breaking strength and cross-sectional area of the mature fruit stalk.

According to the results presented in Table 9, the average breaking strengths of the mature fruit stalk of the four varieties are obviously different; the order of the average breaking strengths from high to low is Ningqi No.5, Ningqi No.1, Ningqi No.9, and Ningqi No.7. The breaking strength of the mature fruit stalk of the four varieties decreased with the increase in the cross-sectional area, but the decreasing forms of the different varieties were different. Ningqi No.1 and Ningqi No.7 decreased in the form of an inverse function, as shown in Figures 15 (a) and 15 (c). Ningqi No.5, and Ningqi No.9 decreased in the form of power functions, as shown in Figures 15 (b) and 15(d).

TABLE 9. Regression equations for breaking strengths of mature fruit stalk.

Varieties	Regression equations	R^2	Means of the cross-sectional area (mm^2)	Means of the breaking strength (N/mm^2)
Ningqi No.1	$y = -1.574 \cdot \frac{0.931}{x}$	0.846	0.10	33.53
Ningqi No.5	$y = 1.678 \cdot x^{-0.905}$	0.912	0.12	39.20
Ningqi No.7	$y = 1.932 + \frac{1.246}{x}$	0.830	0.17	15.90
Ningqi No.9	$y = 2.105 \cdot x^{-0.901}$	0.942	0.17	30.75

Relationship between binding force and maturity

Because of the characteristics of wolfberry fruits, disordered inflorescence and continuous flowers, the mechanized picking of wolfberry is extremely difficult. The study on the relationship between the binding force and maturity was of considerable significance for the rational design of picking parameters. We conducted independent sample t-test using the data of the binding force of the immature and mature fruit stalks with no gross errors; the results are given in Table 10.

TABLE 10. Results of independent sample t-tests for determining the relationship between binding force and maturity.

Varieties	Ningqi No.1	Ningqi No.5	Ningqi No.7	Ningqi No.9
Independent samples t-test with two-tail probability	0.010	0.493	0.015	0.634
Average binding force of immature fruit stalk (N)	1.47	1.40	1.09	1.09
Average binding force of mature fruit stalk (N)	1.68	1.56	1.20	1.86

According to the results presented in Table 9, the binding forces in the immature fruit stalk and mature fruit stalk of Ningqi No.1 and Ningqi No.7 are obviously different, and the binding force of the mature fruit stalk is higher than that of the immature fruit stalk; this might be related to the internal microstructures of the fruit stalks. This characteristic provides a theoretical foundation for automatic classification during wolfberry picking. According to the results given in Table 9, the binding forces of the mature fruit stalks in Ningqi No.1 and Ningqi No.7 are 0.21 N and 0.11 N higher than that of the respective immature fruit stalks. The relationship between binding force and maturity of wolfberry is different from that of Lingwu Long Jujube (Gao et al., 2018), this maybe caused by that the quality change of wolfberry from immature fruit to mature fruit was more than that of Lingwu Long Jujube.

Determination of the factors influencing the binding force

The picking rate was essential for determining the factors influencing the binding force. Orthogonal experiments comprising three factors and three layers were designed to study the picking temperature, mass of the fruit, and the location of the fruit on the branch with the data for mature fruits obtained in 2018 (Voltarelli et al., 2018; Noronha et al., 2018; Zhang et al., 2019a; Du et al., 2019; Feng et al., 2019; Zhang et al., 2019; Jin et al., 2019).

TABLE 11. Orthogonal experiment results.

Experimental factors		Picking temperature (°C)	Fruit mass (g)	Site on the branch	Binding force (N)
Number	1	20–25	0.1–0.6	1	1.11
	2	20–25	0.6–1.1	2	1.20
	3	20–25	1.1–1.5	3	1.12
	4	25–30	0.1–0.6	2	0.93
	5	25–30	0.6–1.1	3	1.26
	6	25–30	1.1–1.5	1	1.37
	7	30–35	0.1–0.6	3	1.86
	8	30–35	0.6–1.1	1	1.61
	9	30–35	1.1–1.5	2	1.55

TABLE 12. Analysis of orthogonal experiment results.

Source	Sum of squares of Type III	df	Mean square	F	Sig.
Correction model	0.543[a]	6	0.090	1.349	0.484
nodal increment	16.018	1	16.018	238.715	0.004
A	0.005	2	0.003	0.041	0.961
B	0.515	2	0.258	3.841	0.207
C	0.022	2	0.011	0.164	0.859
Error	0.134	2	0.067		
Total	16.695	9			
Total corrected	0.677	8			

The experimental scheme was presented in Table 1. The data satisfying the experimental parameters given in Table 11 were extracted from the data pertaining to the binding forces of the different wolfberry varieties. The significance level was 0.05, the orthogonal experiments were carried out. According to the results presented in Table 12, the P values of factors A, B, and C are 0.961, 0.207, and 0.859, respectively, which are much higher than the significance level of 0.05. Therefore, the effects of these three factors on the experimental results were not significant; that is, the picking temperature, quality of the fruit, and position of the target fruit on the branch had no significant effect on the binding force of the mature fruit stalk.

CONCLUSIONS

In this study, the binding force and related physical appearance of the immature fruits, mature fruits, flowers, and leaves of four wolfberry varieties, namely Ningqi No.1, Ningqi No.5, Ningqi No.7, and Ningqi No.9, were studied. The characteristics of the binding force and mass of the fruit were obtained, which can provide data and a theoretical basis for designing new-generation vibrating wolfberry harvesting machinery. We established the dynamic model of the vibrating branches that can help determine the design parameters of the harvesting machinery. The constitutive equation for breaking of the immature fruit stalk and mature fruit stalk of the four varieties was determined. This can provide a theoretical foundation for further studies on the biomechanical properties of wolfberry. We determined the relationship between the fruit maturity and binding force of the four varieties using the independent sample t-test; there was a relationship between Ningqi No.1 and Ningqi No.7. It was confirmed that there were no influences of the picking temperature, fruit mass, and the location of fruits on the branches on the binding force. In conclusion, this study can provide a theoretical foundation and detailed data for the design of new-generation wolfberry harvesting machinery.

However, this study has some limitations. One limitation is that there was no experiment performed for confirming if the binding force is related to the angle between the branch and stalk of immature fruit, mature fruit, flowers, and leaves; the other one is that there was no experiment performed to analyze the biomechanical characteristics of the branch. In future, experiments will be conducted to study these biomechanical characteristics.

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