Assessment of Grasp Ability for An End-effector with Fin-ray Structure

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Abstract. In this article, a flexible three-finger end-effector based on fin ray effect (FRE) was performed to evaluate the ability to resist dynamic loads during apple picking. A finite element method (FEM) simulation was performed to predict the FRE gripper’s tensile force using Abaqus software. The results of response surface analysis (RSM) showed the significant effects of TPU stiffness, grasp distance and fruit size on the vertical tension of the end-effector. Moreover, there is a good correlation between the test results and the regression model. The findings in the present study provide a reference for the application of the FRE gripper in fruit harvesting.

1. Introduction
As the world’s biggest apple producer, according to China Agricultural Yearbook of 2019, the apple planting area in China covered 1.94 million hectares, accounting for 16.3% of the national total planting area. Furthermore, apple production reached 39.233 million metric tons, accounting for 22.3% of the total. Apple harvesting is both time- and labor-intensive, with workers requiring experience and skill. Since the 20th century, the reduction of agricultural employment population is a serious challenge in many countries. Mechanization could make a great significance in tackling the problem in the fruit industry. In recent years, Apple harvesters have become a research hotspot. Interaction control between the robot end-effector and the fruit is crucial to reduce the mechanical damage of fruit and successfully picking during the picking process.

With the integration of finite element software algorithm and the enhancement of visualization function, finite element analysis has become an effective method to predict damage and analyze dynamic response process [1]. The drop test simulation was used to optimize the receiving material, height and direction for the fruit collection units [2]. Compression and impact are used to simulate dynamic and static load states during fruit transport [3]. In particular, Dintwa et al. pointed out that the viscoelastic properties obtained by stress relaxation experiments are not applicable to describe the transient behavior of fruits, needing deeply accurate theoretical evaluation [4]. Ji et al. analyzed the viscoelastic response of each parts of the fruit at different velocities of the grasp and estimated the equivalent stress when plastic damage occurred [5]. Ahmadi et al. considered a nonlinear time-dependent contact in the modeling of fruit-plane collision and fruit-fruit collision, and analyzed the influence of mechanical properties, shape size and relative velocity of object on kinetic energy loss of fruit collision [6].

In terms of end-effector interaction with fruit, direct contact force detection in real-time is an important method to avoid bruise for rigid fingers using press sensors [7]. On the contrary, a simpler
and more effective way to eliminate the effects of ‘hard contact’ is the performance of flexible gripper. In this article, a flexible three-finger end-effector based on fin ray effect (FRE) was performed to evaluate the stability of grasping apples using experimental and simulation analysis.

2. Materials and methods

2.1. End-effector structure

Robotic hand need the ability to resist external interference and avoid bruise when completing the task of picking and placing fruits. Soft robotic hand has excellent performance to deal with deformed and fragile objects due to its passive compliance and adaptability [8]. In this study, we use a flexible adaptive gripper as an end-effector (EasyGripper robot technology co., LTD, Dongguan, China). As shown in Figure 1(a), the end-effector consists of a pneumatic cylinder, a moving plant, links, finger mounts, soft fingers and a base frame and the reciprocating motion of the moving plate controls the release and grasp of the gripper. Soft fingers are designed based on the fin ray effect (FRE) with a V-shaped skeleton structure embedded in a series of supports, bending and deforming to be closely attached to the grasped object while one side is subjected to a force [9, 10], as shown in Figure 1(b).

![Figure 1](image-url)

**Figure 1.** Schematic drawing of end-effector structure (a) and the soft finger (b): (1) base frame, (2) moving plant, (3) links, (4) pneumatic cylinder, (5) finger mounts and (6) soft fingers.

2.2. Finite element simulation of grasp process

2.2.1. Finite element model. Although the FRE gripper has been used in agriculture and medicine, there is still a lack of understanding of its grasp properties. To predict the grasp ability of the FRE gripper, Shan and Birglen [11] proposed a kinetostatic model to identify the best parameters for the equivalent stiffness in its joints combining both shape and force estimation. In our previous work, the simulation and experimental results showed that the three-finger FRE gripper would not cause damage during the grasp process of fruit, but would lead to a slip. Therefore, the purpose of this work is to study the influence of three factors of TPU stiffness, the distance from fruit’s center of mass to the palm, and fruit size on the grasp stability of the three-finger FRE gripper through simulation test. The Box-Behnken design was implemented using Design-Expert 8.0 and the factor codes were listed in Table 1.

| actors          | unit     | -1 | 0  | 1  |
|-----------------|----------|----|----|----|
| TPU stiffness   | HA       | 50 | 70 | 90 |
| distance (L)    | mm       | 65 | 75 | 85 |
| fruit size (D)  | mm       | 65 | 75 | 85 |
The finite element (FE) model was built in Abaqus software (version 2018, Dassault Systemes Simulia Corp., USA), as shown in Figure 2. Soft fingers were meshed into 6933, 6953 and 6884 elements respectively. Meanwhile, the mounts were meshed into 14183, 14374, and 14232 elements. For the 65-millimeter-diameter apple model, the number of the skin, cortex, core and stem were 11308, 41887, 8410, and 742, respectively; Moreover, in the 75-millimeter-diameter apple model, the number of elements of the skin, cortex, and core were 12359, 42089, 8530 and 1036, respectively. Furthermore, in terms of the 85-millimeter-diameter apple model, the number of the skin, cortex, core and stem were 19685, 66617, 10345, and 1352, respectively. All the elements are C3D4 (4-node linear tetrahedron) cells.

Figure 2. Finite element model of the end-effector and the apple.

2.2.2. Material properties. The soft fingers made of thermoplastic polyurethanes (TPU) material were 3D printed by WeiLaiGongChang Co., Shenzhen, Guangdong, as shown in Figure 1(b). In order to obtain the mechanical properties of TPU materials, uniaxial tensile tests were carried out on specimens with hardness of 50HA, 70HA and 90HA, respectively. Uniaxial tensile tests were conducted on an electronic universal testing machine (type: DDL.10, range: 0-10 kN; manufactured by Sino test Equipment Co., Ltd., China) following the ISO 37-2011 standard with a loading rate of 500 mm/min. The stress-strain response results of tensile tests were fitted using the Ogden 3N model [12], which provides a good fit to the test data within a strain of 700%. The strain energy density function is as follows:

\[
W = \sum_{i=1}^{N} \frac{H_i}{\alpha_i} (\lambda_{1}^{\alpha_1} + \lambda_{2}^{\alpha_2} + \lambda_{3}^{\alpha_3} - 3)
\]

Where \( \lambda_i \) (j=1,2,3) are the principal stretch ratio; N is a material parameter; \( \mu_i \) and \( \alpha_i \) are empirically determined material constants. The experimental data fitting of the mathematical model was performed using Abaqus software. The material parameters are reported in Table 2.

2.2.3. Simulation steps. To evaluate the ability to resist dynamic loads during apple picking, two steps were implemented in the simulation test: (1) The fingers rotate at 1 rad/s until the sum of the driving torque of the three fingers reaches 1000 N-mm which is the maximum torque that the pneumatic cylinder can provide; (2) The fruit was shifted upward at a speed of 100 mm/s and the maximum tension (N) that the end-effector could provide to the fruit was recorded. The normal behaviour of finger-skin contact was set to hard contact and the tangential friction coefficient (\( \mu \)) was 0.3 and the gravity was defined as -9.810 m·s\(^{-2}\).
2.3. Experimental procedures

Figure 3 presents the structure of the experimental device which contains a stereo camera (ZED Stereo Camera, STEREOLABS, San Francisco, USA), a manipulator (Xarm 5Lite, UFactory Technology, Hong Kong, China), a force sensor (ZLMB-102, Zhongcheng, Bengbu, China) and the FRE end-effector. A Jetson TX2 with Ubuntu 16.04 is used as the host computer and the software running in the Robot Operating System (ROS) controlled the motion of the manipulator, fruit detection and data recording.

![Schematic diagram of the test device.](image)

Figure 3. Schematic diagram of the test device.

3. Results and discussion

3.1. Stress-strain characteristics of TPU

The comparison of the tensile test results and the Ogden 3N model fitting is shown in Figure 4. The tensile test result shows that the stress increases nonlinearly with the strain. Compared with the experimental results, the fitting results of Ogden 3N model have a fairly good accuracy within the strain of 300%. The parameters of Ogden 3N are shown in Table 2.

![Strain-stress curve of the tensile tests and fitting using the Ogden N3 model.](image)

Figure 4. Strain-stress curve of the tensile tests and fitting using the Ogden N3 model.
Table 2. Mechanics parameters of the materials.

| Density [kg/m$^3$] | $\mu_i$  | $\alpha_i$ |
|---------------------|----------|------------|
| TPU (50 HA)         | 120      | 1.3196     | 2.7078 |
|                     |          | -1.0457    | 3.1595 |
|                     |          | 0.5655     | -7.0428|
|                     |          | 2.3136     | 2.3706 |
| TPU (70 HA)         | 120      | -1.4045    | 2.7594 |
|                     |          | 0.3623     | -6.6940|
|                     |          | -8.0093    | 3.1163 |
| TPU (90 HA)         | 120      | 4.7963     | 3.3423 |
|                     |          | 10.0632    | -5.2268|

| Density [kg/m$^3$] | Elasticity modulus E [MPa] | Poisson's ratio $\mu$ |
|---------------------|-----------------------------|------------------------|
| Aluminum alloy [13] | 2750                         | 69000                  | 0.35                  |
| Cortex [6]          | 840                          | 3                      | 0.35                  |
| Skin [6]            | 840                          | 12                     | 0.35                  |
| Core [6]            | 950                          | 7                      | 0.35                  |

3.2. Analysis of simulation test results

A total of 17 testing groups were performed in the simulation experiment. The experiment schemes and results are reported in Table 3. Tables 4 reports the Analysis of Variance (ANOVA) results used to evaluate the quadratic model. It can be seen that $X_1$, $X_2$, $X_3$, $X_1X_2$, and $X_1^2$ exhibited a significant effect ($p < 0.05$) on the tension. The $R^2$ value for tension is observed as 0.9783, representing a strong agreement between the model and the experimental results. Furthermore, the Pred. $R^2$ value (0.7071) is in good agreement with the Adj. $R^2$ values (0.9503) for tension. The adequate precision (Adeq. Precision) measures the signal to noise ratio. The ratios of 19.69, which are greater than 4, indicates an adequate signal to noise ratio. Therefore this response can be optimized using the regression model as follows:

$$Y = 9.59 + 6.47X_1 - 1.91X_2 + 1.83X_3 - 1.78X_1X_2 + 0.96X_1X_3 - 0.39X_2X_3$$
$$+ 4.2X_1^2 + 1.11X_2^2 - 0.22X_3^2$$

(2)

Table 3. Experiment schemes and results.

| $X_1$ | $X_2$ | $X_3$ | $N$ |
|-------|-------|-------|-----|
| 1     | 0     | 0     | 10.13|
| 2     | 0     | 0     | 9.29 |
| 3     | 1     | 1     | 17.201|
| 4     | -1    | -1    | 9.04 |
| 5     | 1     | 0     | 23.02|
| 6     | -1    | 1     | 6.72 |
| 7     | 0     | -1    | 9.35 |
| 8     | 0     | 0     | 10.42|
| 9     | -1    | 0     | 6.05 |
| 10    | 1     | 0     | 17.04|
| 11    | 0     | 0     | 8.62 |
| 12    | 0     | -1    | 13.38|
| 13    | 1     | -1    | 26.65|
| 14    | 0     | 1     | 10.85|
Table 4. ANOVA of the tension

| Items      | SoS  | DOF | MS      | F-value | p-value |
|------------|------|-----|---------|---------|---------|
| Model      | 517.97 | 9   | 57.55   | 34.98   | <0.0001*** |
| $X_1$      | 363.48 | 1   | 363.48  | 220.95  | <0.0001*** |
| $X_2$      | 29.12  | 1   | 29.12   | 17.7    | 0.004**   |
| $X_3$      | 26.75  | 1   | 26.75   | 16.26   | 0.005**   |
| $X_1X_2$   | 12.67  | 1   | 12.67   | 7       | 0.0275*   |
| $X_1X_3$   | 3.67   | 1   | 3.67    | 2.23    | 0.1787    |
| $X_2X_3$   | 0.6    | 1   | 0.6     | 0.36    | 0.5649    |
| $X_1^2$    | 74.14  | 1   | 74.14   | 45.07   | 0.0003*** |
| $X_2^2$    | 5.21   | 1   | 5.21    | 3.17    | 0.1183    |
| $X_3^2$    | 0.2    | 1   | 0.2     | 0.12    | 0.7376    |
| Residual   | 11.52  | 7   | 1.65    |         |          |
| Lack of Fit| 9.5    | 3   | 3.17    | 6.27    | 0.0541    |
| Pure Error | 2.02   | 4   | 0.5     |         |          |
| Cor Total  | 529.48 | 16  |         |         |          |

Model Summary Statistics

| Std. Dev. | 1.28 | R-Squared | 0.9783 |
| Mean      | 11.99| Adj R-Squared | 0.9503 |
| C.V. %    | 10.7 | Pred R-Squared | 0.7071 |
| PRESS     | 155.11 | Adeq Precision | 19.69 |

The response surface results of the regression equation are shown in Figure 5. TPU stiffness and fruit size have positive effects on the tension. On the contrary, as the distance from fruit’s center of mass to the palm increases, the tension tends to decrease. TPU stiffness has the largest effect on the tension, followed by the distance from fruit’s center of mass to the palm, and fruit size. The optimized parameters are determined to be a TPU stiffness of 90HA, a distance of 65mm, and an apple with 84.3mm diameter. Table 5 reports the predicted optimal conditions and compares the simulation and model optimization results.
Figure 5. The response surface of effects of TPU stiffness and the distance from fruit’s center of mass to the palm on the tension (a), the response surface of effects of TPU stiffness and fruit size on the tension (b), and the response surface of effects of the distance from fruit’s center of mass to the palm and fruit size on the tension (c).

Table 5. The comparison between simulation and modelling optimization results.

|                | TPU stiffness (HA) | Distance (mm) | Fruit size (mm) | Tensile force (N) |
|----------------|--------------------|---------------|-----------------|------------------|
| Optimization   | 90                 | 65.26         | 84.49           | 26.98            |
| Simulation     |                    |               |                 | 26.01            |
| Error (%)      |                    |               |                 | 3.60             |

Figure 6 showed the changes of the total contact area and tension in the simulation test with 90HA TPU stiffness, 65mm grasp distance and an 85mm-diameter apple. It is can be seen that soft fingers began to contact with apple skin at 0.114s, and then the relative sliding occurs, leading to a drastic change in the total contact area until the fruit was pulled at 0.21s. After the separation of the fruit from the lower soft finger at 0.26s, the tensile force increased with the increase of the total contact area due to a significant bend caused by relative slide. The maximum total contact area and maximum tension were 107.42mm² and 26.01N, respectively. Then the fruit begins to slip out of the control of the end-effector. Moreover, by observing the grasping and pulling process of the fruit, we found that the smaller grasp distance and larger fruit size were beneficial to increase the contact area, making soft fingers provide greater tension.

Figure 6. Changes of contact area and tensile force with time.
3.3. Validation test

According to the optimization results of Section 3.2, the soft finger with TPU stiffness of 90HA was selected and the grasp distance was set as 65mm. Thus, Formula (2) can be written as a relationship between the tensile force \( T \) and the fruit size \( D \):

\[
T = -2.18 \times 10^{-3} D^2 + 0.64 D - 10.21 .
\]  

(3)

Twenty fresh Pinklady fruits were collected in November 2020 and experiments were conducted at the harvesting date. The diameter and maximum tension of the fruit were recorded. As shown in Figure 7, there was a good agreement between the simulation results and the experiment results with a \( R^2 \) value of 0.8821. Compared with the tensile force of over 30N reported in our previous work [14], the tensile force of about 27N indicates a possibility of picking failure using the vertical pull method. Thus, increasing the friction force on the soft finger surface and the driving torque will be the methods to improve the grasp ability of the end-effector in the further work.

Figure 7. Correlation between simulation and experiment results of fruit size effect on the tension.

4. Conclusion

In this article, a flexible three-finger end-effector based on fin ray effect (FRE) was performed to evaluate the ability to resist dynamic loads during apple picking. A finite element method (FEM) simulation was performed to predict fin ray effect (FRE) gripper’s tensile force using Abaqus software. The results of response surface analysis (RSM) showed the significant effects of TPU stiffness, grasp distance and fruit size on the vertical tension of the end-effector. Moreover, there is a good correlation between the test results and the regression model. Finally, increasing the friction force on the soft finger surface and the driving torque will be the methods to improve the grasp ability of the end-effector in the further work.

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References

[1] N. Zulkifli, N. Hashim, H.H. Harith, M.F. Mohamad Shukery, Finite element modelling for fruit
stress analysis - A review, Trends Food Sci Tech, 97 (2020) 29-37.
[2] H.K. Celik, A.E.W. Rennie, I. Akinci, Deformation behaviour simulation of an apple under drop case by finite element method, J Food Eng, 104 (2011) 293-298.
[3] R. Lewis, A. Yoxall, M.B. Marshall, L.A. Canty, Characterising pressure and bruising in apple fruit, Wear, 264 (2008) 37-46.
[4] E. Dintwa, M. Van Zeebroeck, H. Ramon, E. Tijskens, Finite element analysis of the dynamic collision of apple fruit, Postharvest Biol Tec, 49 (2008) 260-276.
[5] W. Ji, Z. Qian, B. Xu, G. Chen, D. Zhao, Apple viscoelastic complex model for bruise damage analysis in constant velocity grasping by gripper, Computers and Electronics in Agriculture, 162 (2019) 907-920.
[6] E. Ahmadi, H. Barikloo, M. Kashfi, Viscoelastic finite element analysis of the dynamic behavior of apple under impact loading with regard to its different layers, Computers and Electronics in Agriculture, 121 (2016) 1-11.
[7] W. Ji, Y. Ding, B. Xu, G. Chen, D. Zhao, Adaptive Variable Parameter Impedance Control for Apple Harvesting Robot Compliant Picking, Complexity, (2020) 4812657.
[8] Z. Wang, M.Z.Q. Chen, J. Yi, Soft robotics for engineers, HKIE Transactions, 22 (2015) 88-97.
[9] W. Crooks, S. Rozen-Levy, B. Trimmer, C. Rogers, W. Messner, Passive gripper inspired by Manduca sexta and the Fin Ray® Effect, International Journal of Advanced Robotic Systems, 14 (2017) 1729881417721155.
[10] L. Bu, C. Chen, G. Hu, J. Zhou, A. Sugirbay, J. Chen, Assessment of apple damage caused by a flexible end-effector, INMATEH Agricultural Engineering, 62 (2020) 309-317.
[11] X. Shan, L. Birglen, Modeling and analysis of soft robotic fingers using the fin ray effect, The International Journal of Robotics Research, 39 (2020) 1686-1705.
[12] R.W. Ogden, Large deformation isotropic elasticity—on the correlation of theory and experiment for incompressible rubberlike solids, Proceedings of the Royal Society of London. A. Mathematical and Physical Sciences, 326 (1972) 565-584.
[13] Y. Liu, H. Liu, Z. Chen, Post-fire mechanical properties of aluminum alloy 6082-T6, Constr Build Mater, 196 (2019) 256-266.
[14] L. Bu, G. Hu, C. Chen, A. Sugirbay, J. Chen, Experimental and simulation analysis of optimum picking patterns for robotic apple harvesting, Sci Hortic-amsterdam, 261 (2020) 108937.