Design and experiment of flexible clamping device for pepper plug seedlings

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Abstract
At present, there are leakage and injury of pepper seedlings in the process of seedling transplantation. Based on the mechanical properties of pepper stem, a clamping mechanism with the function of crab pincers is designed using bionics principle. The clamping mechanism uses the CAM device to drive the gear and rack meshing. The control clamping gripper’s opening and closing stroke is 2–30 mm. The stroke of CAM gear is 1.94 mm, obviously save the clamping time. In order to achieve flexible clamping and reduce seedling injury, elastic silicone, rubber, and nylon materials were used as clamping materials. The finite element analysis was carried out to simulate the force in the clamping process, and the stress of the silicone gripper was found to be the minimum, and the stress range was $1.53 \times 10^{-3} - 1.42$ MPa. The results of clamping damage test and seedling picking migration test showed that the clamping damage rate of the silicone gripper was 3.28%. The clamping damage degree was the lowest, which is consistent with the theoretical analysis. The seedling leakage rate was 5.86%. The success rate of seedling picking was 94.14%, and the success rate of migration was 83.20%. It proved that flexible clamping device designed in this study had reliable working performance and good transplanting effect.

Keywords
Mechanical property, flexible clamping mechanism, finite element analysis, clamping damage test, transplanting quality test

Introduction
China has 28 provinces planting pepper, with a planting scale of more than 2 million hectares. The manual transplanting has a large amount of labor and high labor cost which accounts for 50% of the total production cost. The semi-automatic transplanting can complete the planting stage, which requires manual assistance to complete the seedling picking and holding stages, resulting in low efficiency. Due to the need manual work to complete the seedling picking stage in the transplanting process, it is not possible to completely liberate the labor from the pepper transplanting work. To sum up, the development of automatic pepper plug seedling transplanter is conducive to improving the efficiency of transplanting, reducing labor costs and alleviating the shortage of labor in rural China. The seedling picking device is one of the key components of the automatic pepper plug seedling transplanter, and the realization of automatic seedling picking and planting is the main difference between the automatic transplanter and the semi-automatic transplanter. Scholars have carried out
research and innovation on picking seedling machinery.\textsuperscript{2–4} According to the methods of picking seedling machinery, they can be roughly divided into three forms: clip type, top out type and pneumatic type, among which clip type can be divided into clip bowl type and clip stem type.\textsuperscript{5–10} In order to achieve accurate seedling selection and reduce the occurrence of seedling leakage, Bouldin et al.\textsuperscript{11} in the United States designed the clamping device, which consisted of an upright support and a pair of gripper fingers with pivot connections and separated intervals to facilitate the clamping of seedlings. Han et al.\textsuperscript{12} designed an automatic feeding system driven by air pressure based on PLC. The gripper reversed the position of the grippers to take the seedling. The total reliability rate of the system reached 98.92%. Zhang et al.\textsuperscript{13} designed an automatic seedling extraction device for tomato plug seedlings based on push-rod type. The device adopted the top rod from the bottom of the plug seedlings. It was suitable for large-area transplanting of Xinjiang pepper, tomato, cotton and other cash crops. In order to reduce the seedling injury in the process of seedling extraction, Yang and other cash crops. In order to reduce the seedling injury in the process of seedling extraction, Yang et al.\textsuperscript{14} developed the slippage pointer with vision and force sensors as the end-effector based on the industrial robot ADEPT-SCARA. It could be accurately positioned and controlled the gripper force to reduce the injured seedlings. Gao et al.\textsuperscript{15} designed a kind of inclined plug seedling transplanting into type gripper. By using the linkage mechanism to oblique into single drive type seedling movement and inserted matrix pointer according to certain Angle, it could effectively reduce the scratch cave seedlings.

In order to further solve the problems of leakage and injury of pepper plug seedlings in the process of automatic seedling extraction and transplanting,\textsuperscript{16} We began to use flexible materials to achieve flexible clamping. Compared with rigid clamping, flexible clamping can effectively reduce the damage to stem and ensure the survival rate of hole disk seedling after transplantation. Flexible clamping devices at home and abroad can be roughly divided into pneumatic adsorption type,\textsuperscript{17,18} multi-finger clamping gripper type,\textsuperscript{19–22} flexible material clamping type.\textsuperscript{23–25} Deng et al.\textsuperscript{26} designed an air-suction end-effector by simulating the action of hand and sucker adsorption, adjusted the position of end-effector to be consistent with the direction of apple growth by universal joint, and sucked the apple down by negative pressure airflow. Pi et al.\textsuperscript{27} designed an adaptive three finger clamping gripper based on the structural characteristics of octopus in bionics. It controlled the opening and closing of the claw to complete fruit picking by pneumatic device. Zhang et al.\textsuperscript{28} designed a flexible clamping conveying device. The synchronous belt of the clamping wheel adopted “H” belt, so that the conveyor belt and the clamping wheel could jointly clamp vegetable stalks without causing mechanical damage to plants.

In this study, based on the bionics principle, the clamping action of crab claws was simulated,\textsuperscript{29} and a flexible clamping device was proposed for pepper picking seedling machinery which could realize the function of seedling and transplanting. We used ANSYS to carry on statics analysis to grippers of three kinds of flexible materials and selected the best material to design clamping grippers. We used flexible clamping device for transplanting to reduce the damage to the stem of hole tray seedling.

**Study on the mechanism of flexible clamping**

**Radial compression mechanical characteristics of stem of pepper**

According to the preliminary material characteristics test, the stem of 0–20 mm from the upper surface of the plug seedling was relatively thick, which was most suitable for the clamping part of the stem seedling. The experimental method was to place the stem horizontally between two clamps, adjusted the position of the upper clamps to just touch the surface of the stem, set the compression displacement as the diameter of the stem, and got the change rule of mechanical parameters in the whole compression process, which was convenient for mechanical analysis in each stage. Single factor compression tests were carried out at 5, 10, 15, 20, and 25 mm/min loading speeds respectively to obtain the variation law of compressive load and compressive stress.

The experimental results of stem compression characteristics of pepper plug seedling are shown in Table 1. The experimental results show that the compression force ranges from 5.07 to 18.14 N and the compressive strength ranges from 0.63 to 2.27 MPa at the loading speed of 5, 10, 15, 20, and 25 mm/min. At the loading speed of 5 mm/min, the minimum value of each parameter was obtained. While at the loading speed of 25 mm/min, the maximum value of each parameter was obtained.

The load-compression displacement curve in Figure 1 shows that there are two points A and B in the curve. Point A is the biological yield point of stem, and point B is the fracture point of stem. OA section is the initial stage of loading load, and the relationship between load and compression displacement is approximately linear.

The fitting formula of linear growth of OA segment is:

\[
y = 13.392x - 1.9264
\]  

(1)
The compression characteristics of the stem are related to the design of the clamping device. According to the compression deformation curve of the stem, the compression displacement can only be designed before the biological yield point of the stem, so as to ensure only elastic deformation of the stem of pepper plug seedling and reduce the damage to the stem epidermis cells.

The test of pepper plug seedling disengagement dish force

The pepper stem is the connecting part of the leaves and the roots. The taking stem transplanting mechanism removes the complete hole seedling is one of the key to ensure the successful transplanting. The determination of the pepper plug seedling disengagement dish force can both provide the basis for the design of the stem picking mechanism, and analyze the factors affecting the disengagement dish force.

The experiments in Figure 2 were carried out to determine the pepper plug seedling disengagement dish force. The hole plate of the seedling pot was fixed at the bottom, neither moving up with the action of tension, nor causing transverse extrusion and deformation of the hole plate. Keeping the stem perpendicular to the horizontal plane and using the method of static loading, the plug seedlings were completely removed from the hole plate and recorded as the end of the test. The quality, clamping force and elastic modulus of plug seedlings were recorded. The tests needed to be repeated for 20 times. The test results were shown in Table 2.

Pepper plug seedling disengagement dish force is 0.44–1.95 N, and the quality of the hole disk seedling is 4.22–6.39 g, which proves that the main factor affecting the clamping force is not the gravity of pot seedling, the friction force between pot and pot seedling. It is mainly related to the degree of rooting and water content of substrate.

Design of flexible clamping mechanism

Composition and working principle of the device

Based on the previous research on the flexible clamping mechanism of plant stems, a flexible clamping device suitable for stem clamping seedling picking was designed, as shown in Figure 3. It mainly included

| Load speed (mm/min) | The range of maximum compression force (N) | Mean ± standard deviation (N) | The range of compressive strength (MPa) | Mean ± standard deviation (MPa) |
|--------------------|------------------------------------------|-------------------------------|----------------------------------------|-----------------------------|
| 5                  | 5.07–14.25                               | 11.22 ± 2.47                 | 0.63–1.78                              | 1.40 ± 0.31                 |
| 10                 | 6.33–15.48                               | 11.26 ± 1.77                 | 0.79–1.94                              | 1.51 ± 0.22                 |
| 15                 | 7.05–16.91                               | 12.83 ± 1.97                 | 0.88–2.11                              | 1.60 ± 0.25                 |
| 20                 | 7.07–17.03                               | 12.96 ± 2.23                 | 0.88–2.21                              | 1.61 ± 0.28                 |
| 25                 | 7.83–18.14                               | 13.09 ± 2.78                 | 0.98–2.27                              | 1.61 ± 0.35                 |

Figure 1. Load-compression displacement curve.

Figure 2. The test of disengagement dish force.
grippers, opening and closing mechanism consisting of rack and gear, CAM, guide rod, sleeve shaft, push rod. The clamping device adopted double-sided clamping method. One end of the clamping gripper was designed to be connected with the gear, which meshed with the rack. Under the action of the CAM, the guide rod made the fixed axis reciprocating movement and drove the sleeve shaft push rod to reciprocate in the axial direction. The push rod was connected with the rack. The rack was engaged with the gear. In order to achieve clamping and releasing of pepper plug seedlings, the gear was connected with the clamping claw which drove the clamping claw to complete the closing and opening of two actions.

Table 2. Results of the test on disengagement force.

| Interval value (0–20 mm) | Quality of the hole disk seedling (g) | disengagement force (N) | Modulus of elasticity (MPa) |
|-------------------------|--------------------------------------|-------------------------|-----------------------------|
| Maximal value           | 6.39                                 | 1.95                    | 21.53                       |
| Minimum value           | 4.22                                 | 0.44                    | 2.07                        |
| Average value           | 5.405                                | 1.16                    | 10.33                       |
| Standard deviation      | 0.614                                | 0.40                    | 4.91                        |

The design of flexible grippers

The gripper is the key part of flexible gripper, as shown in Figure 4. When a crab picks up its food, the claws hold it in place in a double lock. Based on the bionics principle, the clamping and releasing motion was designed like the crab’s clamping motion. The flexible gripper was double-sided gripper. The part of the inner surface in direct contact with the stem of the plug seedling was designed to have a wavy pattern similar to the crab clamp. The stable clamping of the stem of the plug seedling was realized by increasing the friction coefficient.

According to the morphological characteristics of the stem, the clamping part of the stem could be simplified into a cylinder with a diameter of 2 mm and a length of 20 mm. When the grippers was closed, the compression amount of the stem of the plug seedling was 1 mm and the gap between the two grippers was 1 mm. When the grippers was opened, to avoid interference between the grippers and the seedling of the adjacent hole plate in the hole plate, the opening volume of the grippers was designed to be 30 mm less than 32 mm (the length of the upper mouth of hole plate). According to the rod length requirements of the double crank connecting rod mechanism, the length of the part was determined to be 80 mm. According to the size of the best clamping part of the stem, a rectangular gripper piece with a shape of $20 \times 20$ mm was designed.

Figure 3. Flexible clamping mechanism for clipping stems: (a) overall assembly drawing and (b) internal structure drawing. 1. The hole tray seedling, 2. gripper, 3. rack mounting plate, 4. the lower shell, 5. the upper shell, 6. wheel gear, 7. push rod, 8. sleeve shaft, 9. guide rod, and 10. CAM.
The inside side of the piece was designed with wavy pattern. Better grip stability could be achieved by applying a smaller force.

**The design of gear and rack**

As can be seen from Figure 5, the gears at the upper end of the two grippers rotated around the gear shaft. Two gears engaged with the middle rack and the rack moved in a straight line. As far as possible to shorten the width of the gripper $l_{AA}$, the distance between the rack axis and the gear shaft $l_{OA}$ was designed to be 22.5 mm. $l_{BC}$ was designed to be 10 mm due to the limitation of the opening width of the hole tray.

The crown of the seedling in the hole disk is in the shape of umbrella. The maximum leaf span is about 120 mm$^2$ to prevent the phenomenon of hanging seedlings between the crown and the clamping mechanism. The $l_{OC}$ was designed to be 90 mm. The radius of gear indexing circle $R_1$ was designed as 15 mm, and the included Angle between AB and OA during clamping and releasing process was calculated respectively.

The Angle $\theta$ between AB and OA during clamping:

$$\theta = \arctan \frac{l_{OC}}{l_{OA} - l_{BC} - 0.5}$$  \hspace{1cm} (2)

The Angle $\beta$ between AB and BC during clamping:

$$\beta = \pi - \theta$$  \hspace{1cm} (3)

The Angle $\theta'$ between AB and OA during opening:

$$l_{A'C'} = \sqrt{\frac{l_{A'B'}^2 + l_{A'C'}^2}{-2l_{A'B'}l_{A'C'} \cos \beta}}$$  \hspace{1cm} (4)

$$\theta' = \arccos \left( \frac{l_{A'B'} - 15 + l_{A'C'}}{2l_{A'B'}l_{A'C'}} \right)$$

$$\theta' = \arccos \left( \frac{l_{A'B'}^2 + l_{A'C'}^2 - l_{B'C'}^2}{2l_{A'B'}l_{A'C'}} \right)$$  \hspace{1cm} (5)

The length of rack travel $l_{A'O}$:

$$l_{A'O} = \frac{(\theta' - \theta) \times \pi \times R_1}{180}$$  \hspace{1cm} (6)

$$l_{A'O} = 1.94 \text{ mm}$$

**The design of CAM-guide rod**

Figure 6 showed that the right end of the guide rod was in contact with the CAM and moved up and down under the driving action of the CAM. The left side of the guide rod was connected with the sleeve shaft to push the seedling rod to move, and the screw passing through the middle of the guide rod served as the lever fulcrum. In Figure 5, $\triangle A'N'M'$ and $\triangle ANM$ were similar triangles. Assuming the CAM stroke was $l_l$, the
CAM stroke could be calculated. The length of $l_1$ was 1.94 mm.

$$\frac{l_A}{l_{AO}} = \frac{l_{OC}}{l_1}$$  \hspace{1cm} (7)

When the clamp mechanism was driven by the double crank linkage mechanism, the end point formed the seedling movement track as shown in Figure 7(a). The CAM working stage was divided into seedling clipping stage, seedling pulling stage, seedling feeding stage, seedling dropping, and reduction stage. The corresponding relationship between the CAM working stage and seedling movement track was shown in Figure 7(b). CAM design parameters were shown in Table 3.

According to the formula of base circle radius in CAM design criterion, the radius of the base circle of the CAM, $r_0$:

$$r_0 \geq \rho - \left( s + \frac{d^2 s}{dd^2} \right)$$  \hspace{1cm} (8)

Where, $\rho$ is the radius of curvature of theoretical contour (mm); $s$ is the distance of the follower relative to the base circle (mm); $\varphi$ is the Angle of rotation of the follower relative to the initial position (rad).

### Finite element analysis of clamping mechanism

With the development of agricultural machinery, the end actuator of flexible material production has played its own advantages in picking and planting. The flexible end gripper of fruit and vegetable picking made of silicone and rubber materials can avoid excessive damage to the fruit.33–35 Flexible splints made of nylon materials have good flexibility and can adapt to different shapes through deformation.36 According to the characteristics of the operation object, it is particularly important to reasonably choose the flexible material as the holding material. Silicone, rubber and nylon are the most commonly used flexible materials.
The finite element analysis of the clamping mechanism is mainly aimed at the clamping part of the gripper which is in contact with the stem of plug seedling. In this study, the gripper materials were silicone, rubber and nylon. The deformation process were geometrically nonlinear and materially nonlinear. In this study, finite element analysis was used to directly reflect the degree of deformation. By comparing the state and properties of the three materials, the best material for the gripper was selected.

**Gripper modeling**

Establishing the gripper model as shown in Figure 8 in the Geometry module of ANSYS. The rubber and silicone materials are hyper elastic materials with complex deformation process. Ogden 1st model was selected in Engineering Data module. Nylon material belongs to linear elastic material. Linear Elastic model was selected. The gripper Model was obtained by adding the material attributes in Table 4.

![Figure 8. Modeling and meshing diagram.](image)

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**Finite element analysis results**

In the set up module, a remote displacement and fixed support along the radial direction of the stem were applied to simulate actual clamping movement. The remote displacement of the left and right clamps was designed to be 0.5 mm respectively. We could obtain the deformation degree and stress and strain of different material grippers with the change of clamping displacement.

Figure 9 reflected the stress and strain and total deformation results of the three clamps under the same amount of compression displacement in the clamping process. The grippers of the three materials all had self-deformation to a certain extent during compression. The main stress and strain were concentrated in the contact part of stem and grippers, radiating from the contact center line to the surroundings. The stress value of silicone and rubber gripper was much less than that of nylon gripper, which indicated that silicone and rubber can adapt to the loading load through their own deformation. The stress range of silicone gripper was $1.53 \times 10^{-4} - 1.42$ MPa, which was within the compressive strength range of stem of pepper plug seedling. It met the working requirements of hole disk seedling clamping. It couldn’t cause irreversible biological damage to stem. The best gripper material was determined to be Silicone.

**Verification test of clamping effect**

**The test of clamping damage**

In the process of seedling extraction and planting, material damage degree was selected as the evaluation...
index of clamping damage. The test objects were 60 pepper plug seedlings with good growth and suitable seedling age. The average stem diameter of seedlings was 2.08 mm and the depth of the pots was about 45 mm. By the way, each seedling had six leaves and the spacing between the consecutive pots was 32 mm. The rotation speed of seedling taking mechanism was set at 60 r/min, and the experiment was repeated for 60 times, as shown in Figure 10. We calculated and recorded the material damage degree of stem of each plug seedling.

Calculating the damage degree of materials $\sigma$:

$$\sigma = \frac{S}{A} \times 100\%$$ (9)

Where $S$ is area of material damage, $(\text{mm}^2)$; $A$ is maximum contact area between stem and gripper $(\text{mm}^2)$.

According to the test results in Table 5, the maximum damage degree, minimum damage degree and average damage degree caused by silicone grippers to stem were 4.54%, 2.69%, and 3.28%. In the process of seedling extraction and planting, the flexible clamping device could significantly improve the injured seedlings in the process of pepper plug seedling transplantation.

During the transplanting process, the maximum matrix damage rate caused by rigid clamping device was 13.55%, the minimum matrix damage rate was 2.41%, and the average matrix damage rate was 9.26%. The flexible clamping device designed in this study would not cause matrix damage by adopting the stem-clamping method. It was beneficial to the growth of pepper plug seedling after transplanting. Compared with rigid clamping devices, flexible clamping devices also had certain disadvantages, such as stability and wear resistance.

### Migration test of seedling by flexible clamping device

In order to verify the seedling migration effect of the flexible clamping device, the seedling migration test of
the flexible clamping device was carried out as shown in Figure 11. The experiment was conducted in the laboratory of Nanjing Agricultural Mechanization Research Institute. In this experiment, 128 holes seedlings of Xiaoxin No.19 pepper with seedling age of 45 days and seedling height of about 150 mm were selected. The flexible clamping device was assembled on the clamping stem seedling taking mechanism, and the seedling taking mechanism was installed on the multi-functional test table of the plug seedling transplanting. Based on our expectation to achieve the expected transplanting frequency, the rotation speed were set as 60, 70, and 80 r/min, and the speed was adjusted by using a governor for the experiment. A total of 180 pepper plug seedlings were selected for the experiment, and were divided into three groups, corresponding to the rotation speed of 60, 70, and 80 r/min, respectively. The laboratory temperature was 15°C, relative humidity was 60%, and soil moisture content was 56.75%. The evaluation indexes were the success rate of seedling picking and migration. The flexible clamping device successfully took out the seedlings from the hole tray which was recorded as the success rate of seedling extraction. The flexible clamping device carried the seedlings taken out from the hole tray and successfully planted them into the soil trough according to the ideal movement trajectory. In this process, we needed to ensure the planting uprightness which was recorded as the success rate of migration. The number of seedlings successfully picked and migrated in the process of seedling migration was recorded in the experiment.

According to the migration test results of seedlings in Table 6, the migration success rate of the flexible clamping mechanism was affected by the rotational speed of the mechanism. The higher the rotational speed of the mechanism kept, the lower the migration success rate would be. The main reason was that the increase of the rotation speed of the mechanism would cause the vibration of the seedling taking mechanism, leading to the decrease of the migration success rate.

### Table 5. Clamping damage degree of silicone gripper.

| The rotation speed (r/min) | Area of contact between gripper and stem (mm²) Mean ± standard deviation | Stem damage area (mm²) Mean ± standard deviation | Maximum degree of stem damage (%) | Minimum degree of stem damage (%) | Mean degree of stem damage (%) Mean ± standard deviation |
|---------------------------|-------------------------------------------------|-------------------------------------------------|----------------------------------|----------------------------------|----------------------------------------------------------|
| 60                        | 42.93 ± 1.25                                    | 1.41 ± 0.17                                     | 4.54                             | 2.69                             | 3.28 ± 0.34                                               |

### Figure 11. Seedling picking-migration test: (a) experiment process, (b) overall assembly, and (c) internal structure.

### Table 6. Parameters of seedling picking-migration test.

| Group number | The rotation speed (r/min) | Seedling number of leakage | Leakage rate (%) | Number of successful seedling picking | Success rate of seedling picking (%) | Number of successfully migrated seedling | Migration success rate (%) |
|--------------|---------------------------|---------------------------|-----------------|---------------------------------------|--------------------------------------|------------------------------------------|---------------------------|
| 1            | 60                        | 3                         | 5.00            | 57                                    | 95.00                                | 51                                       | 85.00                     |
| 2            | 70                        | 4                         | 6.67            | 56                                    | 93.33                                | 49                                       | 81.67                     |
| 3            | 80                        | 6                         | 10.00           | 54                                    | 90.00                                | 48                                       | 80.00                     |
causing part of substrate of the plug seedling to scatter, which would affect the planting effect of the seedling. Secondly, in the process of seedling picking and migration, the inertia was greatly affected by the rotation speed of the mechanism. The tilting phenomenon occurred when the mechanism releasing plug seedling.

Conclusion

(1) In this study, the mechanical properties of stem of plug seedlings related to flexible clamping are studied, and the maximum radial compression of stem is determined to be 50% of stem diameter, providing theoretical data support for the design of flexible clamping device.

(2) Using the bionics principle, the clamping mechanism was designed by imitating the action of crab claw. The clamping mechanism mainly achieved the opening and closing of the clamping grippers through the meshing of gears and rack. The stroke of the clamping mechanism was controlled by the CAM device. The stroke of the CAM was 1.94 mm, which could control clamping gripper’s opening and closing. The clamping mechanism could be realized in the range of 2.00–30.00 mm, which met the action requirements of clamping stem seedling.

(3) Because of the fast speed of the mechanism during transplanting, the original combination of rigid clip and push rod would cause seedling injury in the process of removing seedlings. Silicone, rubber and nylon were selected as clamping materials. ANSYS was used to simulate the clamping action of the three clamping pieces, and the stress and strain and total deformation results of the clamping pieces were obtained. The results showed that the stress range of silicone grippers was $1.53 \times 10^{-4}$–1.42 MPa, which was within the compressive strength range of pepper stem. Silicone was determined to be the gripper material.

(4) The clamping damage experimental results showed that the average damage rate of the flexible clamping device was 3.28%, which significantly improved the injured seedlings. In the seedling migration test, seedling leakage rate was 5.86%, the seedling picking success rate was 94.14% and the migration success rate was 83.20%. The flexible clamping device designed in this study was reasonable and feasible and the operation performance was good.

Declaration of conflicting interests

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