Design and experiment of a flexible end effector for seedling picking with adjustable clamping diameter

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Abstract: To improve the adaptability of the stem-clamping end effector to variations in pepper plug seedling stem diameter, a flexible seedling-picking end effector with an adjustable gripping diameter was developed. The closing clearance between the two gripper plates was preset by replacing the miniature cam-follower bearing with bearings of different outer diameters, while rubber-covered gripping surfaces provided passive compliance and reduced the risk of stem damage and slippage. Based on the geometric relationship among the claw, connecting rod, push rod, and cam, the maximum claw opening and push-rod stroke were determined to be 32 and 4.7 mm, respectively, and the cam profile was designed to coordinate the opening, closing, holding, and releasing actions of the gripper. Mechanical tests showed that the average maximum pull-out resistance at picking angles of 0°, 20°, and 40° were 1.20, 1.18, and 1.29 N, respectively, which were substantially lower than the maximum tensile load of the seedling stems. Compared with rigid aluminum gripping surfaces, the rubber-covered gripper plates reduced the stem breakage rate from 66.67%-80.00% to 3.33%-6.67% and increased the transfer success rate from 76.67%-86.67% to 83.33%-93.33%. A three-factor Box-Behnken experiment was conducted using the rotational speed of the seedling-picking mechanism, stem diameter, and miniature-bearing outer diameter as experimental factors. Response surface optimization identified an optimal parameter combination of 66.1785 r/min for the rotational speed of the seedling pick-up mechanism, 2.1991 mm for the seedling stem diameter, and 10.0811 mm for the micro-bearing outer diameter. Under these conditions, the predicted seedling pick-up success rate and seedling injury rate were 93.1296% and 2.2087%, respectively, with an overall desirability of 0.976. The results demonstrate that the proposed end effector can preset the gripping diameter and reduce stem damage and slippage risks under the tested conditions, providing a practical design for automatic seedling picking.

Keywords: adjustable clamping diameter, end effector for seedling picking, seedling picking mechanism, stem clamping, non-circular gear, automated transplanting, experimental design

DOI: 10.25165/j.ijabe.20261904.10235

Citation: Ren Z Y, Hu M J, Li K, Yan W, Ji Y, Yang Y F, et al. Design and experiment of a flexible end effector for seedling picking with adjustable clamping diameter. Int J Agric & Biol Eng, 2026; 19(4): 123–132.

1 Introduction

In China, most vegetables are cultivated through seedling transplanting methods, primarily relying on manual labor and semi-automatic transplanting machines. However, these approaches still face challenges, such as high labor intensity and low operational efficiency[1-3]. As times change, the transition from semi-automatic to fully automated transplanting machines has become an unavoidable trend[4-6]. Currently, the automated seedling picking devices have high requirements for seedlings, and the end effector for seedling picking exhibits poor adaptability to seedling trays, thereby limiting the development of fully automated transplanting machines[7-10]. The end effector of the seedling picking mechanism functions as a clamping device. During operation, when the picking mechanism rotates, the seedling claws must grasp, hold, and release seedlings from the trays, achieving periodic operations. The performance of these components directly influences the seedling picking success rate and seedling injury rate[11-14]. Therefore, it is particularly necessary to design an end effector for seedling picking that is highly adaptable and has a low damage rate. Seedling picking end effectors can be classified by their gripping methods into three categories: pot-clamping, top-clamping combined, and clamp-stem types[15]. The pot-clamping type involves using the end effector claws of the picking arm to grasp the substrate of potted seedlings for picking and placement[16]. This method is characterized by its reliability and strong adaptability to crops; however, it can lead to substrate damage. The principle of the top-clamping combined seedling picking method involves using a push rod to eject the seedling tray, followed by clamping the matrix or stem of the seedlings[17]. This method is characterized by strong adaptability and high efficiency; however, it is also prone to issues such as failed seedling picking, damage to the matrix, and limited efficiency in extracting seedlings at intervals. In contrast, the seedling picking mechanism of the clamp-stem type employs an end effector claw at the end of the picking arm to grasp the stem above the root of the

Received date: 2025-09-25 **Accepted date:** 2026-06-30

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seedlings, thereby facilitating the picking and placement of the seedlings[18,19]. This clamping method is well-suited for robust crops such as peppers, tomatoes, and eggplants; however, it may cause damage to more delicate seedlings, resulting in limited adaptability.

This study focuses on pepper (*Capsicum annuum* L.) seedlings as the research subject due to their sturdy stems, which are less prone to damage during clamping, and their robust root systems, making them suitable for the clamp-stem type picking method. To address the existing issues of the clamp-stem picking technique, a flexible end effector with an adjustable gripping diameter has been designed based on its principles. Consequently, this research aims to develop a reasonable, adaptable, and innovative modification of the existing pneumatic gripper model. The design simulates the manual seedling picking process, where the seedling transfer mechanism corresponds to the human wrist, the picking claw functions similarly to the thumb and index finger, and the gripper jaws serve the same purpose as the fingertips. The theoretical modification results in a purely mechanical gripper that relies on a cam to automatically control the opening and closing of the gripper jaws, facilitating periodic automatic seedling picking and placement. During operation, the device grips the stem of the pepper seedlings, while the adjustable gripping diameter enhances the overall adaptability of the equipment. The redesigned claw structure is simple and compact, capable of accommodating different stem diameters, reducing the risk of irreversible biological damage to the stems, and meeting specific operational requirements.

2 Materials and methods

2.1 Physical and mechanical properties testing of pepper plug seedlings

During the transplanting process, the contact and collision between pepper plug seedlings and various working components may result in varying degrees of mechanical damage, which in turn can affect the growth of seedlings after planting[20]. Therefore, exploring the physical and mechanical properties related to mechanical transplanting is beneficial for optimizing component design, reducing damage rates, and improving operational quality. The experiment was conducted in April 2024 in the laboratory of the Comprehensive Experimental Building at the Nanjing Institute of Agricultural Mechanization, Ministry of Agriculture and Rural Affairs. The samples under investigation consist of "Xiaoxin Zhizun" pepper plug seedlings cultivated by the Nanjing Vegetable and Flower Research Institute, with an age range of 45-60 d. The seedlings are cultivated in 72-cell plug trays (6×12 configuration), with dimensions of 530 mm in length, 270 mm in width, and a height of 40 mm. The cells were inverted square frustums with upper and lower side lengths of 40 and 15 mm, respectively. The growth medium is composed of peat, perlite, and vermiculite in a ratio of 7:2:1, with a moisture content of 60% to 70%.

A total of 30 plants were randomly selected as experimental samples from the pepper plug seedlings. The following physical and morphological characteristics were measured: plant height, stem diameter in the 0–20 mm section, leaf area, seedling mass, distance from the lowest leaf to the surface of the growth medium, number of true leaves, and growth-medium moisture content. A representative pepper plug seedling used in the experiments is shown in Figure 1.

The results of the determination of physical property parameters indicate that stem diameter in the 0-20 mm section from the substrate ranges from 2.14 to 2.76 mm, with a mass ranging from 21.31 to 25.57 g. The plant height ranges from 155.28 to 165.32 mm, and the distance from the lowest leaf to the surface of the growth medium is between 50.12-53.64 mm, with the number of true leaves being between 6 and 7. The stems of the pepper plug seedlings exhibit a robust diameter, making them less prone to damage.

Figure 1 Photograph of a pepper plug seedling

Mechanical performance tests were conducted on the 0-20 mm section of the stem of the pepper plug seedlings using a universal testing machine to explore their mechanical properties. The testing equipment used was the SUNS-UTM6503 dual-column desktop electronic universal material testing machine (Figure 2), which had a load capacity of 0-5 kN and an adjustable loading-rate range of 0.01 to 500 mm/min. Tests were conducted according to standards for tension, compression, and plug picking. Foam padding was adhered to the gripping positions of the fixtures to prevent unnecessary damage to the stem[21].

a. Tensile grips b. Compression platens

Figure 2 SUNS-UTM6503 universal testing machine and fixtures used in the mechanical tests

In the tensile test, the two ends of a stem segment cut from the predetermined gripping position were secured by the upper and lower tensile grips of the universal testing machine. The upper grip moved upward at the preset loading speed until tensile failure occurred, while the tensile load–displacement data were recorded. The maximum tensile load of the pepper plug seedling stems ranged from 26.33 to 43.95 N, with an average value of 33.14 N. To reduce the risk of stem fracture during seedling picking, the plug removal resistance should remain below the minimum measured maximum tensile load of 26.33 N. The relationship between tensile load and displacement was described by the following fitting equation:

$$y = 38.513x - 1.1582, \quad R^2 = 0.9571 \tag{1}$$

The stem compression test was conducted to simulate the transverse loading exerted by the gripper plates and determine the biological yield load of the stem, thereby providing a basis for preventing slippage and compression damage during seedling picking. In the compression test, a stem segment cut from the predetermined gripping position was placed horizontally between the upper and lower compression platens, and the upper platen moved downward to apply transverse compression. At loading speeds of 30, 40, 50, and 60 mm/min, the average maximum compressive loads corresponding to the biological yield point were 172.45, 169.32, 153.86, and 144.26 N, respectively. These results indicate that the transverse compression response of the pepper plug seedling stems varied with the loading speed. To reduce the risk of stem bruising during clamping, the compressive load applied by the gripper plates should remain below the min/max compressive load measured within the tested range. At a loading speed of 50 mm/min, the relationship between compressive load and displacement was described by the following fitting equation:

$$y = -23.514x^2 + 154.41x + 0.2919, \quad R^2 = 0.9978 \tag{2}$$

During the seedling-picking process, the gripping mechanism must overcome the plug removal resistance to pull the pepper plug seedling smoothly out of the tray hole. This resistance includes not only the friction between the root components and the tray body, but also the adhesion between the plug and the inner wall of the tray hole, the resistance caused by contact deformation, and the weight of the pepper plug seedling. The corresponding force analysis and mechanical relationships were reported in our previous study[6]. Because the interaction between the plug and the tray body is complex, the individual force components were not calculated separately in this study. Instead, the overall plug removal resistance was measured directly using a universal testing machine.

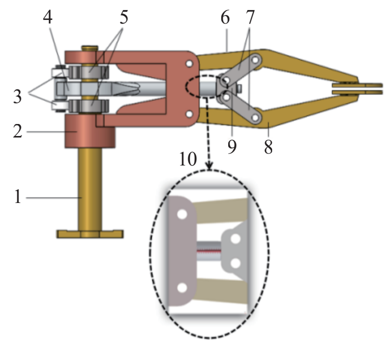
During actual mechanical seedling picking, the stem may deviate from the center of the tray hole or exhibit natural inclination. Moreover, the picking claws move along a predetermined curved trajectory; therefore, the actual pulling direction may not coincide with the vertical axis of the tray hole. To investigate the effect of the pulling direction on the plug removal resistance, picking angles of 0°, 20°, and 40° were selected. The picking angle was defined as the angle between the pulling direction and the vertical axis of the tray hole. The corresponding average maximum pull-out resistances were 1.20, 1.18, and 1.29 N, respectively.

The variation in pull-out resistance was mainly caused by changes in the contact condition between the plug and the inner wall of the tray hole. At 0°, the plug was pulled approximately along the axis of the tray hole, and the resistance was mainly generated by friction and adhesion at the contact interface. At 20°, one side of the plug may have separated from the inner wall of the tray hole earlier, producing a local peeling effect and reducing the effective contact area; consequently, the pull-out resistance decreased slightly. At 40°, the inclined pulling direction intensified the asymmetric deformation and lateral contact of the plug, thereby increasing the local normal force and frictional resistance and resulting in the highest pull-out resistance. The small difference between 0° and 20° may also have been influenced by the natural variability among the root-plug systems.

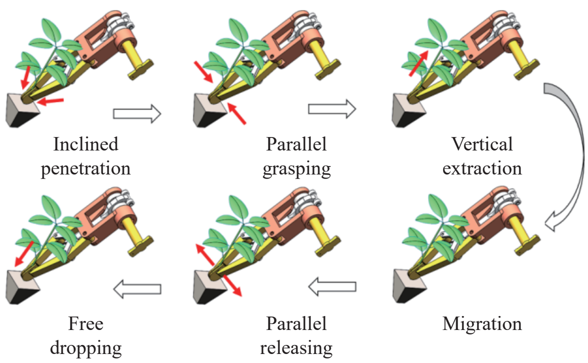
The tensile tests showed that the maximum tensile loads of the pepper plug seedling stems ranged from 26.33 to 43.95 N, with an average value of 33.14 N. The hightest average maximum pull-out resistance of 1.29 N was only approximately 4.90% of the minimum measured maximum tensile load of 26.33 N, whereas the latter was approximately 20.4 times the former. Therefore, under the experimental conditions of this study, the plug removal resistance was substantially lower than the load-bearing capacity of the stem. Stem fracture caused by excessive plug removal resistance was therefore unlikely during the seedling-picking process, further supporting the feasibility of the stem-clamping picking method.

2.2 Overall structural design and working principle of the seedling picking end effector

The seedling picking end effector primarily consists of a T-shaped shaft, a gripper bracket, microbearings, a push rod, a cam, left and right grippers, a crank connecting rod, and connecting components, as illustrated in Figure 3. The T-shaped shaft is fixedly connected to the rotating mechanism via a T-shaped groove, while the cam 5 is connected to the T-shaped shaft 1 through a keyway. The gripper bracket 2 is also connected to the T-shaped shaft 1 via a keyway. The push rod 4 is connected to the T-shaped shaft 1, the gripper bracket 2, and the connecting component 9 through axial holes and threaded connections. The bearing 3 on the push rod is press-fitted onto the push rod 4. The left and right grippers (6, 8) are respectively connected to the gripper bracket 2 by pins. The crank connecting rod 7 connects at both ends to the grippers (6, 8) and the connecting component 9 through pins. The gripper bracket 2 is connected to the connecting component 9 via a spring, ensuring that the cam and the bearing on the push rod mesh properly. During operation, power from the transplanter ground wheel is transmitted through the chain-and-sprocket transmission system to the seedling-picking mechanism and then to the T-shaped shaft 1 and cam 5. As the cam rotates with the T-shaped shaft 1, the microbearing 3 on the push rod follows the cam profile. Together with the restoring action of the spring 10, this produces the periodic reciprocating motion of the push rod and drives the grippers to open, close, hold, and release according to the required timing.



a. End-effector for seedling picking



b. Schematic diagram of working principle

1. T-shaped shaft 2. Gripper bracket 3. Microbearing 4. Push rod 5. Cam 6. Right claw 7. Crank connecting rod 8. Left claw 9. Connector component 10. Spring

Figure 3 Structure and working principle of the flexible gripping mechanism with an adjustable gripping diameter

The specific operation process is as follows: during picking, the gripper plates are in an open state and are inserted at an angle on either side of the stem. After being inserted to the appropriate depth, the two gripper plates close and grip the stem. Under the transmission of seedling picking mechanism, the seedling is pulled out of the plug tray hole along the direction of the stem. During planting, the gripper plates open to release the held plug seedlings, which fall due to their own weight.

Previous studies have shown that applying elastic materials, such as silicone or rubber, to the gripper plates can reduce irreversible biological damage to seedling stems[22]. Accordingly, a flexible rubber layer was attached to the gripper plates, and a preset gap was retained between the plates in the closed state.

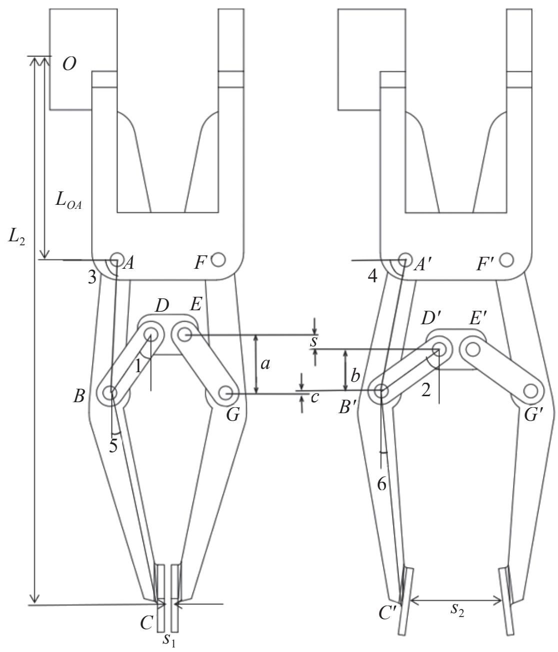
The microbearings used in this study were miniature rolling bearings installed on the push rod. The bearing in contact with the cam profile acted as a roller follower. By replacing this bearing with bearings of different outer diameters (10.0-10.3 mm), the position of the push rod and the closing clearance between the two gripper plates could be adjusted, thereby changing the effective gripping diameter. When the gripper closure was insufficient, a larger-diameter bearing was used to compensate for the clearance between the cam and the roller follower and increase the degree of closure. Conversely, when excessive closure caused interference between the cam and the push rod, a smaller-diameter bearing was used to reduce the interference and increase the closing clearance. In addition, a bearing with an outer diameter of 15 mm was installed between the T-shaped shaft and the push-rod slot to guide the reciprocating motion of the push rod and reduce friction.

2.3 Geometric parameter model of the seedling picking end effector

2.3.1 Geometric parameter model of the gripping claw

The seedling picking mechanism employs a two-finger gripper equipped with a flat clamping plate designed for seedling gripping. The gripping surfaces of the grippers should be embedded with flexible materials such as silicone to enhance friction, ensuring stability during the gripping process while minimizing the risk of damaging the pepper plug seedlings. The measured stem diameters of the pepper plug seedlings aged 45-60 d ranged from 2.14 to 2.76 mm. Accordingly, a nominal closing gap of 2 mm was retained between the two gripper plates as the design reference[4]. This value represents the preset closing clearance of the gripper rather than a uniform stem diameter, and the corresponding nominal diametral compression was designed not to exceed 1 mm. If the nominal closing gap proves insufficient or excessive during subsequent experiments, it can be adjusted by replacing the miniature cam-follower bearing with bearings of different outer diameters. During the seedling picking operation, the opened position of the grippers is aligned with the stem of the pepper plug seedlings. To ensure that only one seedling is grasped at a time, the opening of the grippers should not be excessively wide. However, during the planting process, the grippers need to open adequately; an opening that is too narrow may increase the likelihood of snagging seedlings. Furthermore, it must be considered that the growth position of the seedlings may not be at the center of the cell holes, potentially resulting in picking failure. Therefore, the gripper opening should be at least equal to the width of the cell holes[23-26]. In the experiments, two types of plug trays were utilized: a 72-cell tray with a 6*12 arrangement and a center-to-center distance of 32 mm between adjacent cells, and a 128-cell tray with an 8*16 arrangement and a distance of 30 mm between adjacent cells. To enhance the adaptability of the machinery to different specifications of trays, the maximum design opening for the grippers is set at 32 mm.

According to the parameter optimization results, the length of the picking arm L_2 is 160 mm, meaning that when the grippers are closed, the distance from the rotating center of the gripper bracket to the center of the gripper plates is 160 mm. To reduce the likelihood of snagging seedlings, the grippers should be designed to be as narrow and long as possible within a limited range, ensuring that the distance L_{OA} from the rotating center of the gripper bracket to the rotating center of the gripper is minimized at 50 mm. This results in an effective gripper height of 110 mm. To avoid interference, the length of the connecting component DE should be kept as short as possible while ensuring it can effectively limit the push rod movement, leading to a design of L_{DE}=10 mm. Considering the need to allow some vertical movement space for the connecting component, the front half of the gripper L_{AB} is designed to be 40 mm long. Additionally, to avoid interference during seedling planting when the grippers are open, the angle $\angle ABC$ should be as shallow as possible. To maintain a slender gripper profile while providing sufficient installation and swing space for connecting rod BD and avoiding near-collinear transmission and mechanical interference, L_{BC} was made as long as practicable, and L_{BD} as short as practicable. Accordingly, $\angle ABC$, L_{BC}, and L_{BD} were set to 165°, 72 mm, and 22 mm, respectively. The thickness of the gripper plates L_{jp} is designed to be 2 mm. The diagrams illustrating the closed and opened configurations of the grippers are shown in Figure 4.



a. Gripper closure model b. Gripper opening model

Figure 4 Schematic diagrams of gripper closure and opening models

The parameter variations from the closed state to the open state can be represented by the following equations:

When the gripper is closed, the length of segment BG is denoted as:

$$2L_{jp}+s_1+2L_{BC}\sin(\angle 5)=2L_{BD}\sin(\angle 1)+L_{DE} \tag{3}$$

At the initiation of gripper opening, the length of segment $B'G'$ is denoted as:

$$L_{A'F'}+2L_{A'B'}\cos(\angle 4)=2L_{jp}+s_2+2L_{B'C'}\sin(\angle 6) \tag{4}$$

The length of segment $B'G'$ can also be expressed as:

$$2L_{jp}+s_2+2L_{B'C'}\sin(\angle 6)=2L_{B'D'}\sin(\angle 2)+L_{DE} \tag{5}$$

When the gripper is closed, the angle between rod AB and the horizontal direction is represented as $\angle 3$, and the angle between rod BC and the vertical direction is represented as $\angle 5$; the relationship between the two is denoted as:

$$\angle 5 = 180^\circ - \angle ABC - (90^\circ - \angle 3) \tag{6}$$

When the gripper is opened, the angle between rod $A'B'$ and the horizontal direction is denoted as $\angle 4$, and the angle between rod $B'C'$ and the vertical direction is denoted as $\angle 6$; the relationship between the two is expressed as:

$$\angle 6 = 180^\circ - \angle ABC - (90^\circ - \angle 4) \tag{7}$$

When the gripper is in the closed configuration, the BD effective length of the gripper can be represented as:

$$L_{AB}\sin(\angle 3) + L_{BC}\cos(\angle 5) = 110\text{mm} \tag{8}$$

Therefore, the angle between rod BD and the vertical direction can be denoted as:

$$\angle 1 = \sin^{-1}\frac{\left(2L_{jp} + s_1 + 2L_{BC}\sin(\angle 5) - L_{DE}\right)}{2L_{BD}} \tag{9}$$

Combining Equations (6) and (8), rounding the data yields the result: $\angle 3 = 87^\circ, \angle 5 = 12^\circ$. From Equation (10), $\angle 1 = 35^\circ$. When the gripper is opened, the angle between rod $B'D'$ and the vertical direction can be represented as:

$$\angle 2 = \sin^{-1}\frac{\left(2L_{jp} + s_2 + 2L_{BC}\sin(\angle 6) - L_{DE}\right)}{2L_{BD}} \tag{10}$$

Combining Equations (5) and (8) and rounding the data yields $\angle 4 = 79^\circ, \angle 6 = 4^\circ$. From Equation (11), we obtain: $\angle 2 = 55^\circ$. In the gripper closed state, the vertical length of rod BD is denoted as:

$$a = L_{BD}\cos(\angle 1) \tag{11}$$

In the gripper open state, the vertical length of rod $B'D'$ is denoted as:

$$b = L_{BD}\cos(\angle 2) \tag{12}$$

The height gained by the gripper during the transition from the closed state at point B to the open state at point B' is denoted as:

$$c = L_{AB}(\sin(\angle 3) - \sin(\angle 4)) \tag{13}$$

Thus, the stroke of the push rod is represented as:

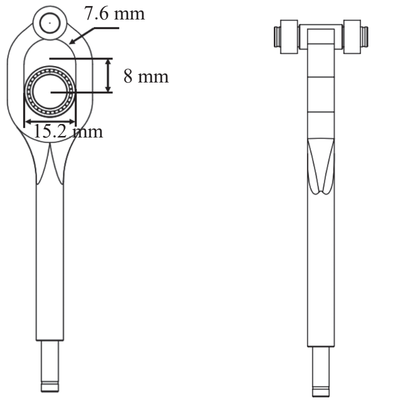
$$s = a - b - c \tag{14}$$

After calculation and rounding, the stroke of the push rod is determined to be: s=4.7 mm.

2.3.2 Geometric parameter model of the push rod

To reduce wear between the push rod and cam, as well as between the push rod and T-shaped shaft, microbearings are installed on both sides of the push rod above the area of contact with the cam, and additional bearings are added at the interface between the T-shaped shaft and the push rod hole. Moreover, while the push rod hole must provide sufficient vertical movement space for the bearings, it should also provide some limit on the fore and aft movement.

The travel of the push rod indicates that the bearings on the T-shaped shaft will move vertically within the push rod hole by at least the stroke of the push rod, meaning that the height of the push rod hole should be at least equal to the stroke of the push rod. Based on a required stroke of 4.7 mm, the center-to-center distance between the two slots on the push rod is designed to be 8 mm, with the total length of the push rod hole set at 23.2 mm. The width of the push rod hole is determined based on the outer diameter of the bearing at the push rod and T-shaped shaft interface. To maintain its limiting function, the width of the push rod hole should be slightly larger than the outer diameter of the bearing. Selecting an outer diameter of 15 mm for the bearing, the width of the push rod hole is set at 15.2 mm. A schematic diagram of the push rod model is illustrated in Figure 5.



a. Frontal view of push rod b. Side view of push rod

Figure 5 Schematic of push rod model

2.3.3 Structural design of the cam profile curve

The cam functions as a rotating or sliding component in the mechanical linkage system and is typically used in conjunction with the push rod to convert the rotary motion of the cam into linear motion of the push rod[27]. This study leverages the motion characteristics of the cam to control the periodic opening and closing of the seedling picking gripper. Taking into account both the avoidance of motion interference between the two seedling picking arms and the structural integrity of the cam, the minimum nominal diameter (base circle radius) of the cam profile is designed to be 20 mm. As noted in Section 2.3.1, the stroke of the push rod is 4.7 mm, which leads to a maximum cam profile radius of 24.7 mm. Considering the positions of both the picking and planting points, the profile of the cam can be established. The two distinct states of the push rod corresponding to the cam's profile represent the forward and return strokes. To minimize damage to the stem of the pepper plug seedlings during the picking process and reduce snagging rates during planting, it is necessary for the gripper plates to close slowly during picking, corresponding to the forward stroke of the push rod, while they should open rapidly during planting, which aligns with the return stroke of the push rod. The specific motion dynamics required for the picking process are as follows:

When the picking gripper reaches the picking point, the gripper plates move to either side of the stem of the pepper plug seedlings, executing a gripping motion to hold the stem. The gripper plates transition from an open state to a closed state, applying a gripping angle of 35°. During this phase, the push rod is in a forward stroke state, moving from 0 to 4.7 mm, while the cam progresses through an angular travel from 0.00° to 37.72°.

After the gripping action is completed, the picking gripper continues to maintain the closed position while pulling the seedlings upward, entering a rest state where the push rod remains at 4.7 mm. At this stage, the cam angle transitions from 37.72° to 263.37°.

Upon completion of the holding phase, it is necessary to release the seedlings into the planting nozzle, which requires the gripping plates to quickly transition from the closed gripping state to the rapid opening planting state. The push rod then enters the return stroke state, from 4.7 mm back to 0 mm, while the cam's return angle shifts from 263.37° to 265.00°.

After the planting action is completed, the gripper plates should remain open in preparation for the subsequent picking cycle, with the push rod entering a near-rest state at 0 mm, during which the cam transitions from 265.00° to 360.00°, thus completing the operational cycle.

Taking the picking point as the starting point of the cam, the planting point is located at a clockwise angle of 108.15° from the picking point. The picking and planting points represent the boundaries for controlling the opening and closing of the gripper in the cam-push rod mechanism. When the gripper arrives at the picking point, it transitions from an open to a closed state, at which the planetary frame remains at its initial position, meaning the angle rotated is 0°, and the angle between the planetary frame and the gripping mechanism is 180°. When the gripper reaches the planting point, it transitions from a closed to an open state, at which the planetary frame has rotated 251.85°, creating an angle of 95.9° with the gripping mechanism. The relationship between the picking process and the cam-push rod mechanism is summarized in Table 1.

Table 1 Correspondence between the seedling picking process and the cam-push-rod mechanism

Motion stages of seedling picking task	Motion process of push rod	Stroke of push rod/mm	Cam motion process	Cam motion angle δ/(°)
Segment of seedling clipping preparation	Push-travel	0.00-4.7	Push-travel motion angle δ_t	0.00-37.72
Segment of seedling clipping and holding	Farthest dwell	4.7-4.7	Farthest dwell angle δ_s	37.72-263.37
Segment of seedling dropping	Return-travel	4.7-0.00	Return-travel motion angle δ_h	263.37-265.00
Segment of returning	Nearest dwell	0.00-0.00	Nearest dwell angle δ_s'	265.00-360.00

Based on the operational stages and angular variations during the picking process, a displacement diagram of the push rod is designed, as shown in Figure 6; using this displacement diagram, the profile curve of the cam is also designed, as shown in Figure 7.

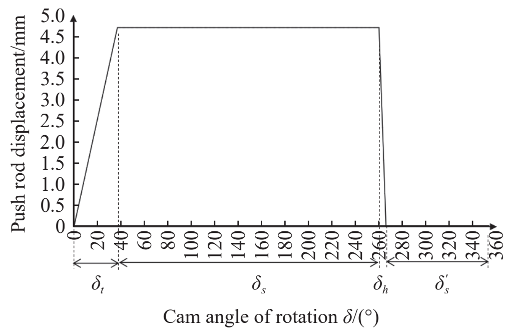
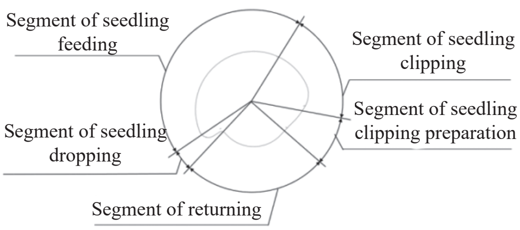
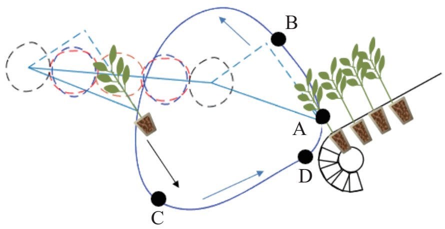


Figure 6 Displacement diagram of the follower push rod



a. The cam profile movement phase of the active part



b. Trajectory of seedling picking

Figure 7 Matching relationship of cam working section and trajectory of seedling picking

3 Results

3.1 Performance evaluation and experimental validation of the flexible seedling-picking end effector

The complete stem-clamping non-circular-gear planetary seedling-picking mechanism was manufactured and evaluated in our previous study[19]. The whole-machine tests verified its ability to complete stem gripping, plug removal, seedling transfer, and seedling release. To avoid duplication, the present study focuses on the flexible gripper with an adjustable gripping diameter and evaluates its damage-reduction performance, transfer stability, adaptability to operating and seedling parameters, and performance under the optimized parameter combination. To validate the gripping effect of the flexible clamping mechanism with an adjustable gripping diameter, this study installed the seedling picking mechanism on an automated transplanting machine at the Haoye Machinery Factory in Qingzhou, Shandong, to conduct transplanting operation experiments, as shown in Figure 8.

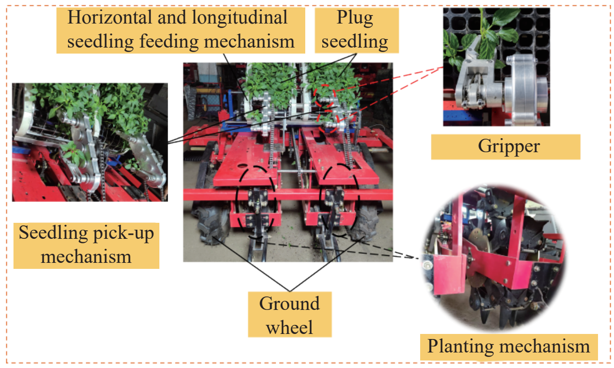


Figure 8 Installation position and operating state of the gripper on the automated transplanting machine

During operation, the ground wheels drive the chain sprocket, synchronizing the operations of the longitudinal and transverse seedling conveying mechanisms, the seedling picking mechanism, and the planting mechanism. The experimental subjects consisted of pepper plug seedlings cultivated extensively in greenhouses in Qingzhou, with an age controlled within the suitable transplanting period of 45-60 d. The seedlings were grown in 72-cell plug trays (6×12 configuration), with overall dimensions of 530 mm×270 mm and a height of 40 mm. The cell holes are square pyramids with upper and lower diameters of 40 mm and 15 mm, respectively. The growth medium consists of a uniform mixture of peat, perlite, and vermiculite in a ratio of 7:2:1, with a moisture content of 60% to 70%. The equipment used in the experiment included the seedling picking mechanism, a camera, Vernier calipers, and rulers.

3.1.1 Effect of flexible rubber gripping surfaces on stem breakage and transfer performance

The stem breakage rate and transfer success rate were selected to evaluate the stem-protection performance and transfer stability of the gripper, respectively. The stem breakage rate was defined as the percentage of seedlings exhibiting visible stem breakage or irreversible stem damage after gripping. The transfer success rate was defined as the percentage of seedlings that remained securely held and were successfully transferred to the release position without slipping from the gripper plates. To investigate the impact of flexible materials on the stem breakage and transfer success rates, a test group used rubber material (Youdong 001) with a hardness value of 70 applied to the gripper plates, while the control group used no flexible materials (maintaining the original aluminum contact surface of the gripper plates). The rotational speed of the seedling picking mechanism was kept constant at 60 r/min, with other irrelevant variables controlled under the same conditions. Thirty pepper plug seedlings were selected for each group, with each experiment repeated three times, and the experimental results are presented in Table 2.

Table 2 Comparison of the performance of rigid and rubber-covered gripper plates

Treatment	Replicate	Number of seedlings/plants	Stem breakage rate/%	Transfer success rate/%
Control group	1	30	73.33	86.67
	2	30	66.67	76.67
	3	30	80.00	86.67
Experimental group	1	30	3.33	83.33
	2	30	6.67	90.00
	3	30	3.33	93.33

The results indicate that the breakage rate of the pepper plug seedlings in the control group can reach as high as 80%, while the maximum damage rate in the test group with rubber-covered gripper plates was only 6.67%, demonstrating that the flexible rubber material significantly reduces stem damage. Additionally, the lowest success rate in the control group was recorded at 76.67%, whereas the test group achieved a minimum success rate of 83.33%. This improvement in transfer success rates in the presence of rubber is attributed to the higher coefficient of friction of rubber (0.6), compared to that of aluminum (0.2), which is more conducive to successful transfer of the seedlings[28].

3.1.2 Multi-factor response surface experiment

To further evaluate the adaptability and operating performance of the gripper, a Box-Behnken response surface method involving three factors at three levels was employed for optimization trials[6]. The rotational speed of the seedling picking mechanism was designated as factor A, the stem diameter as factor B, and the outer diameter of the microbearing as factor C. The evaluation metrics selected for this study were the seedling picking success rate Y_1 and the seedling injury rate Y_2. The experimental factors and levels are summarized in Table 3.

According to the JB/T10291-2013 industry standard "Dryland Planting Machinery"[29], and in accordance with the operational requirements of the stem clipping seedling picking mechanism, the seedling picking success rate Y_1 and the injury rate Y_2 were identified as the evaluation indicators. Using the pepper plug seedlings as the test subjects, experimental trials were conducted focusing on the parameters of picking mechanism rotational speed, stem diameter, and microbearing outer diameter. The rotational speeds were set at 60, 70, and 80 r/min; the stem diameters were chosen as 1.75 mm (45 d), 2.25 mm (50 d), and 2.75 mm (55 d); the outer diameters of the microbearings were set at 10.0, 10.1, and 10.2 mm.

The seedling-picking success rate Y_1 and injury rate Y_2 were selected to evaluate the operational reliability and low-damage performance of the gripper, respectively. The seedling-picking success rate represents the percentage of seedlings for which the gripper successfully completed stem gripping, plug removal, transfer, and release. The injury rate represents the percentage of seedlings that sustained stem injury or leaf breakage during the seedling-picking process. The two indices were recorded independently and were not complementary.

$$Y_1 = \frac{N_1}{N} \times 100\% \tag{15}$$

$$Y_2 = \frac{N_2}{N} \times 100\% \tag{16}$$

where, Y_1 is the seedling picking success rate, %; Y_2 is the injury rate, %; N_1 is the number of successfully picked seedlings; N_2 is the number of injured seedlings; and N is the total number of seedlings in each experimental group. A seedling that is successfully picked but sustained mechanical damage was counted in both N_1 and N_2; therefore, $Y_1 + Y_2$ is not necessarily equal to 100%.

Based on the experimental data, Design-Expert 10 software was utilized for processing and analysis. A total of 36 seedlings were sampled for each experimental group, with three repetitions to derive the picking success rate Y_1 and injury rate Y_2 under various conditions, as detailed in Table 4.

Table 3 Factors and levels of experiments

Factors	Levels		
	–1	0	1
(A) Seedling pick-up mechanism rotation speed/r·min^{-1}	60	70	80
(B) Stem diameter/mm	1.75	2.25	2.75
(C) Outer diameter of microbearing/mm	10.0	10.1	10.2

Table 4 Response surface analysis scheme and test results

Serial No.	Factors			Seedling picking success rate/%	Seedling injury rate/%
	A	B	C		
1	60	1.75	10.1	83.33	2.78
2	80	1.75	10.1	72.22	11.11
3	60	2.75	10.1	80.56	5.56
4	80	2.75	10.1	66.67	13.89
5	60	2.25	10.0	86.11	5.56
6	80	2.25	10.0	75.00	11.11
7	60	2.25	10.2	80.56	5.56
8	80	2.25	10.2	69.44	13.89
9	70	1.75	10.0	80.56	8.33
10	70	2.75	10.0	77.78	8.33
11	70	1.75	10.2	77.78	8.33
12	70	2.75	10.2	72.22	11.11
13	70	2.25	10.1	91.67	2.78
14	70	2.25	10.1	94.44	2.78
15	70	2.25	10.1	88.89	5.56
16	70	2.25	10.1	91.67	2.78
17	70	2.25	10.1	91.67	2.78

As shown in Tables 5 and 6, the quadratic regression models for the seedling pick-up success rate (Y_1) and seedling injury rate (Y_2) were both highly significant. The p-values of the Y_1 and Y_2 models were $P<0.0001$ and $P=0.0002$, respectively, indicating that both regression models were statistically significant. The P-values for the lack-of-fit terms of the two models were 0.9140 and 0.7510, respectively, both greater than 0.05, indicating that the lack of fit was not significant and that the quadratic regression models adequately described the relationships between the experimental factors and response variables. For the seedling pick-up success rate model, the coefficient of determination (R^2) was 0.9851. The corresponding values for the seedling injury rate model was 0.9672. These results demonstrate that both models had high goodness of fit and could be used to analyze response trends and optimize the operating parameters.At a confidence level of 95%, the significance of each regression term was evaluated using F-tests and p-tests. The regression equations in terms of the coded factors were obtained as follows:

$$Y_1 = 91.67 - 5.90A - 2.08B - 2.43C - 0.70AB - 0.0025AC - 0.70BC - 7.64A^2 - 8.33B^2 - 6.25C^2 \quad (17)$$

$$Y_2 = 3.34 + 3.82A + 1.04B + 0.70C + 0.00AB + 0.70AC + 0.70BC + 2.50A^2 + 2.50B^2 + 3.19C^2 \quad (18)$$

Table 5 Variance analysis of regression equation (Y_1)

Source	Seedling picking success rate/%				
	Sum of squares	*df*	Mean square	*F*-value	*p*-value
Models	1148.38	9	127.6	51.57	< 0.0001
A	278.83	1	278.83	112.7	< 0.0001
B	34.69	1	34.69	14.02	0.0072
C	47.29	1	47.29	19.11	0.0033
AB	1.93	1	1.93	0.78	0.4062
AC	2.50E-05	1	2.50E-05	1.01E-05	0.9976
BC	1.93	1	1.93	0.78	0.4062
A^2	245.78	1	245.78	99.34	< 0.0001
B^2	292.36	1	292.36	118.16	< 0.0001
C^2	164.49	1	164.49	66.48	< 0.0001
Lack of fit	1.92	3	0.64	0.17	0.914
Pure error	15.4	4	3.85		
Total	1165.7	16			

Note: $p<0.001$ indicates a highly significant effect; $p<0.05$ indicates a significant effect

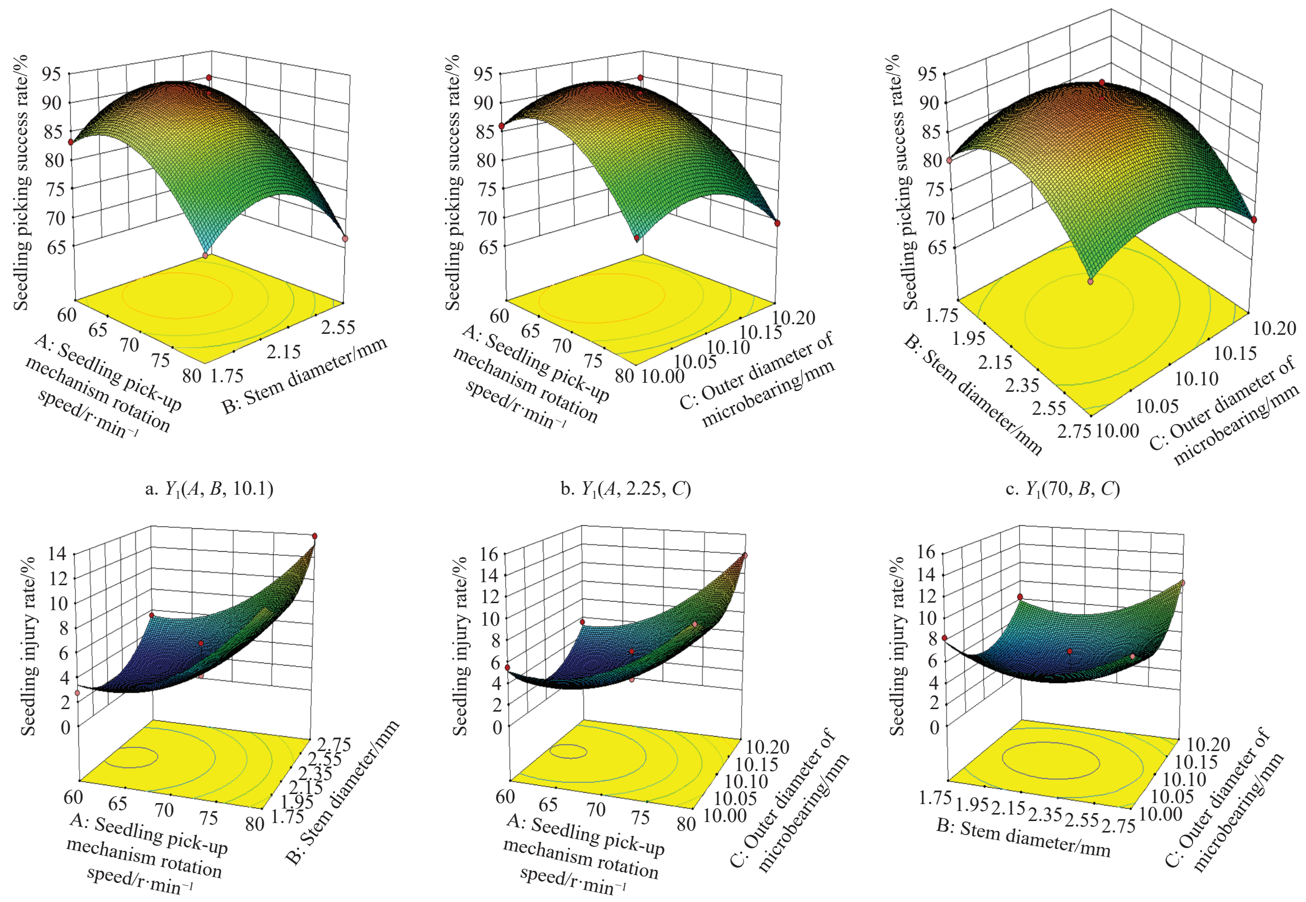
As shown in Table 5, the linear terms *A*, *B*, and *C*, together with the quadratic terms A^2, B^2, and C^2, had significant effects on the seedling pick-up success rate, whereas the interaction terms *AB*, *AC*, and *BC* were not significant. According to Table 6, the linear terms *A* and *B*, as well as the quadratic terms A^2, B^2, and C^2, significantly affected the seedling injury rate, with the rotational speed of the seedling pick-up mechanism (*A*) exerting the most pronounced effect. The linear term *C* and all interaction terms were not statistically significant. The nonsignificant linear effect but significant quadratic effect of the micro-bearing outer diameter (*C*) indicates that its influence on the seedling injury rate was predominantly nonlinear.

The interactive effects of any two factors on the success rate and injury rate metrics are illustrated in Figure 9.

Table 6 Variance analysis of regression equation (Y_2)

Source	Seedling injury rate/%				
	Sum of squares	*df*	Mean square	*F*-value	*p*-value
Models	239.53	9	26.61	22.96	0.0002
A	116.59	1	116.59	100.57	< 0.0001
B	8.69	1	8.69	7.50	0.029
C	3.86	1	3.86	3.33	0.1106
AB	0	1	0	0	1
AC	1.93	1	1.93	1.67	0.2377
BC	1.93	1	1.93	1.67	0.2377
A^2	26.36	1	26.36	22.74	0.002
B^2	26.25	1	26.25	22.65	0.0021
C^2	42.90	1	42.90	37.01	0.0005
Lack of fit	1.93	3	0.64	0.42	0.751
Pure error	6.18	4	1.55		
Total	247.65	16			

Note: p<0.001 indicates a highly significant effect; p<0.05 indicates a significant effect



a. $Y_1(A, B, 10.1)$ b. $Y_1(A, 2.25, C)$ c. $Y_1(70, B, C)$

d. $Y_2(A, B, 10.1)$ e. $Y_2(A, 2.25, C)$ f. $Y_2(70, B, C)$

Figure 9 Influence of two-factor interaction on seedling picking success rate and seedling injury rate

4 Discussion

As illustrated in Figure 9, although none of the interaction terms reached statistical significance, the response surfaces visually demonstrate the response trends under the simultaneous variation of two factors. When the micro-bearing outer diameter was fixed at 10.1 mm, the seedling pick-up success rate initially increased and then decreased as the rotational speed increased at different stem-diameter levels, whereas the seedling injury rate generally increased markedly. An appropriate increase in rotational speed facilitated the ability of the clamping mechanism to overcome the resistance generated by the adhesion between the seedling roots and the substrate, thereby promoting successful seedling extraction. However, an excessively high rotational speed increased the dynamic impact during clamping and seedling extraction, resulting in deviations in the seedling pick-up position and greater stem damage. Consequently, the seedling pick-up success rate decreased, while the seedling injury rate increased.

When the stem diameter was fixed at 2.25 mm, the seedling pick-up success rate initially increased and subsequently decreased with an increase in the micro-bearing outer diameter, whereas the seedling injury rate first decreased and then increased. When the micro-bearing outer diameter was relatively small, the clamping clearance was large, resulting in insufficient effective clamping force between the clamping plates and the stem and a greater likelihood of slippage during seedling extraction. As the micro-bearing outer diameter increased, the clamping clearance gradually became better matched to the stem diameter, thereby improving the seedling pick-up performance. However, an excessively large micro-bearing outer diameter produced an overly small clamping clearance and increased the local contact pressure applied to the stem, which could damage the epidermal or internal tissues of the stem.

When the rotational speed of the seedling pick-up mechanism was fixed at 70 r/min, the seedling pick-up success rate initially increased and then decreased with increasing stem diameter at different micro-bearing outer diameters, whereas the seedling injury rate first decreased and subsequently increased. For seedlings with relatively small stem diameters, the contact area between the clamping plates and the stem, as well as the transmissible frictional force, was limited, increasing the likelihood of stem slippage. When the stem diameter was excessively large, the contact pressure generated during clamping increased, thereby increasing the risk of compressive damage to the stem. Therefore, an appropriate matching relationship existed between the stem diameter and the clamping clearance.

With the objective of maximizing the seedling pick-up success rate and minimizing the seedling injury rate, numerical optimization was performed using Design-Expert software. The optimal parameter combination was determined to be a rotational speed of the seedling pick-up mechanism of 66.1785 r/min, a stem diameter of 2.1991 mm, and a micro-bearing outer diameter of 10.0811 mm. Under these conditions, the predicted seedling pick-up success rate and seedling injury rate were 93.1296% and 2.2087%, respectively, with an overall desirability of 0.976. Considering the adjustment accuracy of the mechanism and the available specifications of the micro-bearing, the verification experiment may be conducted using a rotational speed of 66 r/min, an average stem diameter of approximately 2.20 mm, and a micro-bearing outer diameter of 10.1 mm. Under these practical conditions, the predicted seedling pick-up success rate and seedling injury rate were approximately 92.90% and 2.13%, respectively. This parameter combination can provide a reference for improving the operational performance of stem-clamping pick-up mechanisms for pepper plug seedlings.

5 Conclusions

A flexible seedling-picking end effector with an adjustable gripping diameter was developed for pepper plug seedlings. By replacing the miniature cam-follower bearing with bearings of different outer diameters, the closing clearance between the two gripper plates could be preset. The rubber-covered gripping surfaces provided passive compliance and improved gripping stability.

The average maximum pull-out resistances at picking angles of 0°, 20°, and 40° were 1.20, 1.18, and 1.29 N, respectively, which were substantially lower than the maximum tensile load of the seedling stems, ranging from 26.33 to 43.95 N. Compared with the rigid aluminum gripping surfaces, the rubber-covered gripper plates reduced the stem breakage rate from 66.67%-80.00% to 3.33%-6.67% and increased the transfer success rate from 76.67%-86.67% to 83.33%-93.33%.

Response surface optimization identified an optimal parameter combination consisting of a rotational speed of 66.1785 r/min for the seedling pick-up mechanism, a seedling stem diameter of 2.1991 mm, and a micro-bearing outer diameter of 10.0811 mm. Under these conditions, the model predicted a seedling pick-up success rate of 93.1296% and a seedling injury rate of 2.2087%, with an overall desirability of 0.976. Considering the adjustment accuracy of the mechanism and the commercially available micro-bearing specifications, the subsequent validation test may be conducted at a rotational speed of 66 r/min, an average stem diameter of approximately 2.20 mm, and a micro-bearing outer diameter of 10.1 mm.

The proposed end effector reduced stem damage and slippage risks under the tested conditions. However, it relies on preset closing-clearance adjustment and passive compliance and does not provide real-time gripping-force measurement or closed-loop control. Remaining picking failures were mainly associated with seedling entanglement, installation and alignment errors, and interference between the picking arms. Future work will focus on improving mechanical alignment and developing force-sensing and adaptive gripping methods.

Acknowledgement

This work was supported in part by the National Major Science and Technology Project for Agriculture (Grant No. 202216030301) and in part by the Jiangsu Provincial Modern Agricultural Machinery Equipment and Technology Promotion Project, "Research, Development, and Application of Sowing and Transplanting Technologies and Equipment for *Euryale ferox*" (Grant No. NJ2025-01).

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