Dynamic analysis and experiment of the seedling pick-up mechanism for pepper hole tray seedlings

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Abstract: To improve the quality of seedling picking and throwing in the mechanical transplanting process of pepper hole tray seedlings, this study establishes a dynamic model of pepper hole tray seedlings during the picking and throwing stages. Through analyses of the instantaneous force on stem during clamping, substrate force during pulling, and kinematic analysis during throwing, the relationships between stem deviation from cotyledon center and clamping height, picking mechanism rotation speed and clamp opening speed, as well as throwing speed, throwing height, and horizontal throwing displacement are obtained. The main influencing factors affecting throwing success rate and their critical values are determined, with the optimal clamping position found to be 15 mm from the surface of the substrate to the stem. Bench experiments explore the effects of picking mechanism rotation speed, throwing height, and planting mouth diameter on throwing success rate, with the critical ranges of each factor aligning closely with theoretical analysis results, validating the accuracy and feasibility of the model. To investigate the optimal combination of picking and planting mechanisms under conditions of high throwing rate, a response surface experiment analysis is conducted to establish regression mathematical models between major influencing factors and assessment indicators. Experimental results demonstrate that with mechanism rotation speed at 67 r/min, throwing height at 93 mm, and planting mouth diameter at 137 mm, the optimized throwing success rate reaches 94.58%. This study provides valuable insights for improving the throwing quality of pepper hole tray seedlings during transplanting.

Keywords: seedling pick-up mechanism, plug seedlings, kinematic analysis, experimental design, critical conditions
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1 Introduction

Vegetables play a vital role in enhancing people's daily lives and driving national economic development. Plug seedling transplanting technology offers advantages such as increased land utilization and suitability for agricultural machinery operations[1-3]. Currently, most vegetable transplanting machines in China rely on semi-automatic manual feeding transplanters, where the seedling operation depends on agricultural machinery while the seedling picking still requires manual labor, leading to issues of low transplanting efficiency and high labor intensity[4-6]. Therefore, developing automatic seedling picking and transplanting devices for transplanters is of significant importance.

In recent years, scholars have conducted a series of studies on the mechanical characteristics of transplanting pots and the relevant mechanisms in the throwing process, achieving certain theoretical results[7]. Jiang et al.[8] established a dynamic model of the throwing process of rapeseed blanket seedlings, studied the critical conditions under which seedlings detach, and identified the key factors affecting seedling detachment. Jin et al.[9] investigated the root causes of the increase in potting and throwing rates by conducting a dynamic analysis of pot seedlings in stages, optimizing parameters, and ultimately confirming the rationality of parameter optimization. Wang et al.[10] analyzed the mechanical characteristics of plug seedlings to assess the breakage rate and success rate during mechanized throwing operations, established a contact mechanics model for the collision process between broccoli pot and planting mouth wall, and conducted dynamic analysis during throwing. Miao et al.[11] experimented with the pulling force and compression resistance of cucumber plug seedlings to explore the influence of their mechanical properties on the seedling picking success rate. They also established a dynamic model for the two-needle pot-clamping seedling retrieval mechanism. Zhang et al.[12] conducted statics and kinematics analyses of pot seedlings during the seed retrieval and throwing stages to ensure the effectiveness of seed retrieval and throwing. Wang et al.[13] established a kinematic model of a multi-level scissor type seedling splitting mechanism and clamping device, analyzed the force situation of pot seedlings during the seed retrieval process, and designed and analyzed the model of pot seedling falling motion and pneumatic system. However, there is limited research on the integration of performance parameters of the pepper hole tray seedlings retrieval mechanism and throwing mechanism.

The problem of seedling throwing is the key issue in achieving high-quality planting. During the operation of the seedling retrieval mechanism, the mechanism parameters and the mechanical

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characteristics of pepper hole tray seedlings, as well as the interaction between the gripper blade and the stem of the pepper hole tray seedlings, all affect the quality of throwing. In order to improve transplanting quality while ensuring transplanting efficiency, this study focuses on pepper hole tray seedlings, aiming to increase the seedling throwing success rate. Through the construction of a dynamic model, a combined approach of theoretical derivation and experimental verification is used to study the mechanical characteristics of pepper hole tray seedlings, identify key influencing parameters, and determine the optimal parameter combinations for mechanical seedling retrieval and throwing through throwing experiments. The goal is to provide a theoretical basis for the design of seedling retrieval mechanisms and the selection of throwing mechanisms.

2 Materials and methods

2.1 Structure and working principle of the seedling pick-up mechanism

The sun gear, middle gear ①, middle gear ②, and planet gear are all non-circular gears, as shown in Figure 1. In the mechanism, the gears in meshing satisfy the condition that for each complete rotation of the driving gear, the driven gear also completes one rotation. During operation, power is transmitted to the planet frame, causing it to rotate and in turn driving the internal non-circular gears to rotate correspondingly. The middle gear ① rotates around the sun gear, while the middle gear ② rotates along with the first, transferring power to the planet gear. The counterclockwise rotation of the planet frame drives the planet gear to rotate non-uniformly, achieving the periodic swinging of the seedling arm, thereby controlling the posture of the clamping. The opening and closing of the clamping are controlled by a cam mechanism. At this point, the absolute motion of the tip of the seedling arm consists of the uniform rotation of the planet frame and an uneven rotation around the center of the planet gear. Under the engagement transmission of non-circular gears, a specific motion trajectory is formed at the endpoint of picking-up seedling arm[14-17].

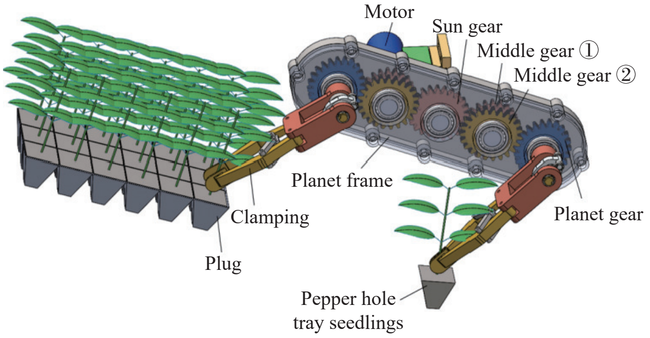


Figure 1 Working principle of seedling pick-up mechanism

2.2 Kinematic model of a non-circular gear planetary gear train

2.2.1 Displacement of the picking-up seedling arm endpoint

The motion trajectory of the seedling picking and seedling dropping process of pepper hole tray seedlings includes four parts: the seed picking stage, seed holding stage, seed throwing stage, and return stage. After the gripper clamps the stem and removes the seedling from the plug, it moves the seedling for throwing along the trajectory, with the seedling remaining approximately upright as it is transported to the throwing point. Upon reaching the throwing point, the gripper opens, releasing the seedling into the planting mouth, which then plants the seedling in the field as it moves. During the return stage, the gripper remains open, quickly returning to the seed intake point for the next cycle of seed picking.

To ensure the smooth operation of the seedling pick-up mechanism, it is essential to maintain relative stability between the gripper and the plug seedlings during the operation. To analyze the force situation of the plug seedlings during the seedling pick-up mechanism, a motion model of the seedling pick-up mechanism is established. The seedling trajectory curve is obtained based on the displacement equation of the tip of the seedling arm, while the smoothness of the mechanism operation is evaluated based on the velocity and acceleration of the tip of the seedling arm[18-22].

Transformation of the non-circular gear planetary gear system into an open-chain two-bar mechanism with an active rod length L_1 and a driven rod lengthL_2, as shown in Figure 2 and 3, in a rectangular coordinate system established with O as the origin, can be achieved based on the relationship between the bar lengths and the extreme points on the trajectory.

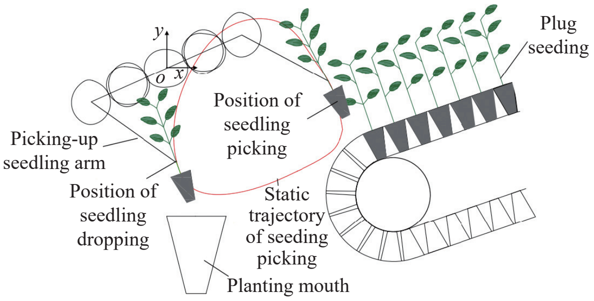


Figure 2 Seedling picking and dropping process of pepper plug seedling

$$\begin{cases} L_2+L_1 = \max\sqrt{x_Q^2+y_Q^2} \\ L_2-L_1 = \min\sqrt{x_Q^2+y_Q^2} \end{cases} \tag{1}$$

By re-arranging Equation (1), the lengths of the two bars can be determined as follows:

$$\begin{cases} L_1 = \dfrac{\max\sqrt{x_Q^2+y_Q^2}-\min\sqrt{x_Q^2+y_Q^2}}{2} \\ L_2 = \dfrac{\max\sqrt{x_Q^2+y_Q^2}+\min\sqrt{x_Q^2+y_Q^2}}{2} \end{cases} \tag{2}$$

where, L_1 is the length of O_1O_3, mm; L_2 is the length of O_3Q, mm; x_Q and y_Q are the respective horizontal and vertical coordinates of any point on the trajectory, mm.

Based on the geometric relationships in Figure 3, the position coordinate equation of point O_3 can be derived as follows:

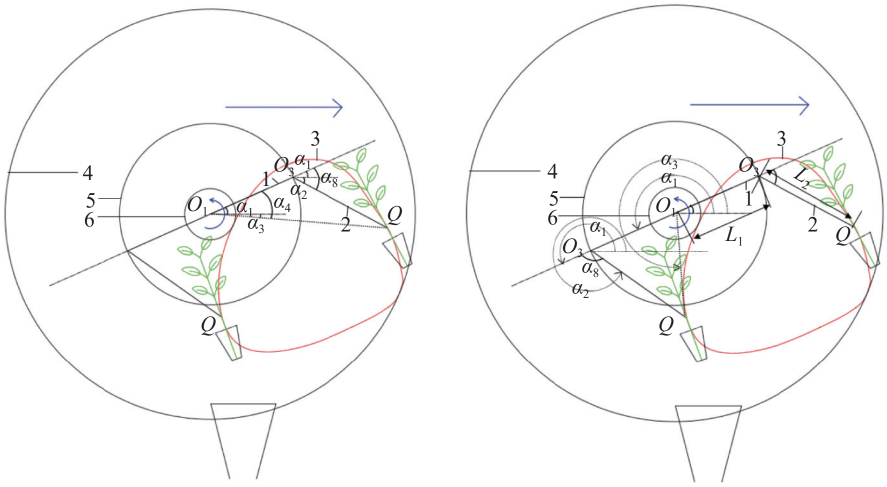
$$\begin{cases} x_{o_3} = L_1\cos\alpha_1 \\ y_{o_3} = L_1\sin\alpha_1 \end{cases} \tag{3}$$

where, α_1 is the angle between the planet frame and the x-axis positive direction in degrees, (°); x_{O_3} and y_{O_3} are the respective horizontal and vertical coordinates of the center of the planet gear, mm.

Further analysis of the geometric relationships in Figure 3 yields the following expressions of α_3, α_4, α_2:

$$\alpha_3 = \tan^{-1}\frac{y_Q}{x_Q} \tag{4}$$

satisfying the conditions in the triangle O_1O_3Q



a. From the farthest point to the nearest point on the trajectory

b. From the nearest point to the farthest point on the trajectory

1. Active bar (planet frame) 2. Driven bar (seedling arm) 3. Expected trajectory 4. Trajectory maximum boundary circle from the origin 5. Active bar return region circle 6. Trajectory minimum boundary circle from the origin

Note: L_1 is the length of O_1O_3, mm; L_2 is the length of O_3Q, mm; α_1 is angle between planet frame and x-axis, (°); α_3 is angle between O_1Q and x-axis, (°); α_4 is angle between O_1Q and O_1O_3 , (°); α_2 is angle between O_3Q and x-axis, (°); α_8 is angle between O_3Q and O_1O_3, (°). Same as below.

Figure 3 Mathematical model of an open-chain two-bar mechanism

$$\alpha_4 = \cos^{-1}\frac{L_1^2+\left(\sqrt{x_Q^2+y_Q^2}\right)^2-L_2^2}{2L_1\sqrt{x_Q^2+y_Q^2}} \tag{5}$$

$$\alpha_2 = \tan^{-1}\frac{y_Q-L_1\sin\alpha_1}{x_Q-L_1\cos\alpha_1} \tag{6}$$

where, α_3 is the angle between O_1Q and the x-axis positive direction, (°); α_4 is the angle between O_1Q and O_1O_3, (°); α_2 is the angle between O_3Q and the x-axis positive direction, (°); $\alpha_3\in\left[-\frac{\pi}{2},\ \frac{\pi}{2}\right]$; $\alpha_4\in[0,\ \pi]$; $\alpha_2\in\left[-\frac{\pi}{2},\ \frac{\pi}{2}\right]$

When the endpoint of the seedling arm is taken from the farthest point on the trajectory to the nearest point on the trajectory, the conditions hold true.

$$\alpha_8=\alpha_1+\alpha_2 \tag{7}$$

$$\alpha_4=\alpha_1+\alpha_3 \tag{8}$$

where, α_8 represents the angle between O_3Q and O_1O_3, (°).

At this point, the position coordinates of the endpoint of the seedling arm are taken.

$$\begin{cases} x_Q=L_1\cos\alpha_1+L_2\cos\alpha_2 \\ y_Q=L_1\sin\alpha_1-L_2\sin\alpha_2 \end{cases} \tag{9}$$

When taking the endpoint of the seedling arm from the closest point to the farthest point on the trajectory, the condition is met.

$$\alpha_8=\alpha_2-\alpha_1 \tag{10}$$

$$\alpha_4=\alpha_3-\alpha_1 \tag{11}$$

The position coordinates of the endpoint of the seedling arm are determined.

$$\begin{cases} x_Q=L_1\cos\alpha_1+L_2\cos\alpha_2 \\ y_Q=L_1\sin\alpha_1+L_2\sin\alpha_2 \end{cases} \tag{12}$$

2.2.2 Velocity and acceleration of the seed picking arm endpoint

During operation, the planetary frame rotates counterclockwise at a constant angular velocity. Due to the different phases at the ends of the active rod but completion of the same motion within one period, only one end of the active rod is studied. By taking the first and second derivatives of Equation (9) with respect to the position coordinates of the endpoint of the seedling arm, the velocity equation and acceleration equation of the endpoint of the seedling arm are derived.

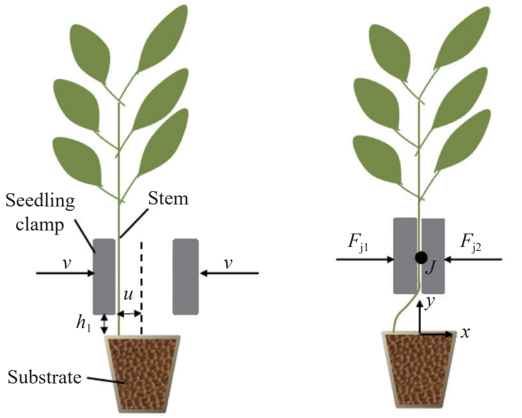
$$\begin{cases} \dot{x}_Q=-L_1\dot{\alpha}_1\sin\alpha_1-L_2\dot{\alpha}_2\sin\alpha_2 \\ \dot{y}_Q=L_1\dot{\alpha}_1\cos\alpha_1-L_2\dot{\alpha}_2\cos\alpha_2 \end{cases} \tag{13}$$

$$\begin{cases} \ddot{x}_Q=-L_1\dot{\alpha}_1^2\cos\alpha_1-L_2\dot{\alpha}_2^2\cos\alpha_2-L_2\ddot{\alpha}_2\sin\alpha_2 \\ \ddot{y}_Q=-L_1\dot{\alpha}_1^2\sin\alpha_1+L_2\dot{\alpha}_2^2\sin\alpha_2-L_2\ddot{\alpha}_2\cos\alpha_2 \end{cases} \tag{14}$$

2.3 Dynamic analysis of pepper hole tray seedlings

2.3.1 Mechanical analysis of the stem during seed picking

Research by Hu et al.[23] has shown that the mechanical properties of the stem section from 0-20 mm are better, so this range is chosen as the gripping interval. However, due to the phenomenon of stems deviating from the center of the bowl in the actual growth state of pepper hole tray seedlings, the stems bend during actual gripping, as shown in Figure 4, thereby affecting the gripping position. It is necessary to analyze the impact of stem deviation from the bowl on the gripping position.



a. Diagram of plug seeding clamping movement

b. Stem mechanics modelling of plug seeding

Figure 4 Dynamic analysis of seedling clamping process

Mechanical analysis of the stem when gripped by the gripper plate at the moment of gripping is carried out. The stem is studied to analyze its mechanical state when gripped by the gripper plate. By analyzing the stress and deformation of the stem under gripping, the optimal gripping position is determined to reduce the impact of stress and deformation on the stem, thereby improving the efficiency and quality of seedling removal.

The stem is in an unstable state at the moment of gripping, and its deflection curve equation is approximately given by Equation (15):[24,25]

$$w = u\left(1 - \cos\frac{\pi x}{2h_1}\right) \tag{15}$$

where, x is the selected position of the section; w is the deflection; y is the deflection representing the horizontal displacement at the section, mm; u is the distance the stem deviates from the center of the bowl, mm; and h_1 is the distance from the stem clamping position to the surface of the substrate, mm.

By taking the derivatives of Equation (15), the first and second derivatives are obtained.

$$\frac{dw}{dx} = \frac{\pi u}{2h_1}\sin\frac{\pi x}{2h_1} \tag{16}$$

$$\frac{d^2w}{dx^2} = \frac{\pi^2 u}{4h_1^2}\sin\frac{\pi x}{2h_1} \tag{17}$$

The bending strain energy of the stem under gripping force is given by the equation.

$$U = \frac{EI}{2}\int_0^{h_1}\left(\frac{d^2w}{dx^2}\right)^2 dx \tag{18}$$

$$I = \frac{\pi D^2}{64} \tag{19}$$

where, U is the bending strain energy of the stem, J; I is the moment of inertia of x section, mm^2; E is the elastic modulus of the stem, Pa; and D is the diameter of the stem, mm.

The work done on gripping the stem is given by the equation:

$$W = F_j u \tag{20}$$

where, F_j is the gripping force, N.

The total potential energy of the stem is calculated as shown:

$$E_p = U - W \tag{21}$$

Substituting Equation (18) into Equation (19) yields:

$$U = \frac{\pi^5 u^2 E D^4}{4096 h_1^2} \tag{22}$$

According to the potential energy standing value theorem[26]:

$$\frac{\partial E_p}{\partial u} = \frac{2\pi^5 E D^4}{4096 h_1^2}u - F_j = 0 \tag{23}$$

From this, we can conclude that:

$$F_j = \frac{2\pi^5 E D^4}{4096 h_1^2}u \tag{24}$$

The bending stress in the cross-section of the stalk at point A is:

$$\sigma_1 = \frac{F_j}{\dfrac{\pi D^3}{32 h_1}} \tag{25}$$

By combining the two equations, the relationship between the seedling throwing height h_1 and the distance u the stem deviates from the center of the bowl at point A on the cross-section of the stem is established.

$$h_1 = \sqrt{\frac{\pi^4 u E D}{64\sigma_1}} \tag{26}$$

It is noted that, when the seedling throwing height h_1 is constant, the distance u the stem deviates from the center of the bowl is positively correlated with the bending stress σ_1 on the stem at point J. Conversely, when the bending stress σ_1 on the stem at point J is constant, the distance u the stem deviates from the center of the bowl is positively correlated with the seedling throwing height h_1. By substituting the experimentally measured values u, E, D, σ_1 into the equation, the corresponding distance h_1 is determined as 15 mm after rounding the data, providing a theoretical basis for the design of the gripping position for the stem.

2.3.2 Mechanical analysis of pepper hole tray seedlings during seedling picking

When pulling out the pepper hole tray seedlings, the bowl body is subjected to its own gravity, soil adhesion force, frictional force of the plug sidewall, and support force of the plug sidewall; while the stem is subjected to the clamping force of the gripper, and static friction force between the gripper and the stem. In the analysis, the plug seedling stem direction is taken as the y-axis, and a plane rectangular coordinate system is established with the direction perpendicular to the stem as the x-axis. The soil adhesion force, frictional force of the plug sidewall, and support force of the plug sidewall are simplified to four side forces of the plug acting on the bowl body. In the ideal conditions, the magnitudes of the four side forces acting on the bowl body are equal. The bowl body experiences a vertical resultant force, equivalent to the force required to pull the plug seedlings out of the plug, known as the detachment force. The simplified mechanical model is shown in Figure 5.

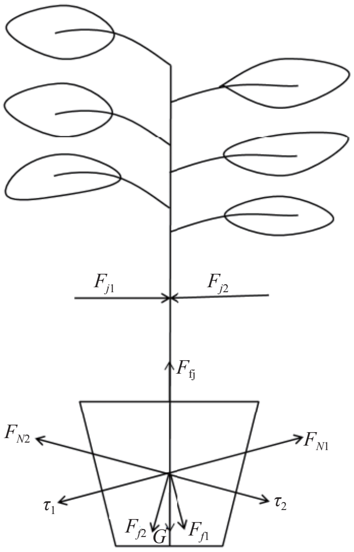


Figure 5 Diagram of force analysis on seedling block

The detachment force can be derived from Equation (27):

$$F_T = 4\left(F_{fi}\cos\theta + \tau_i\sin\theta - F_{Ni}\sin\theta\right) + G \tag{27}$$

As seen in Figure 5, the actual clamping force F_l of the clamping mechanism satisfies:

$$F_l = \mu_1\left(F_{j1} + F_{j2}\right) \tag{28}$$

In ideal conditions:

$$F_{j1} = F_{j2} \tag{29}$$

$$F_l = F_{fj} = 2\mu_1 F_{j1} \tag{30}$$

To ensure successful detachment, it should be greater than the detachment force:

$$F_l = F_T + \mathrm{ma} \tag{31}$$

$$a = \frac{v^2}{2s} \tag{32}$$

$$F_{j1} = \frac{4\left(F_{fi}\cos\theta + \tau_i \sin\theta - F_{Ni}\sin\theta\right) + G}{2\mu_1} + \frac{mv^2}{\mu_1 s} \tag{33}$$

where, F_T is the detachment resistance of the plug seedlings, N; F_{fi} is the frictional force of the plug sidewall against the bowl, N; θ is the cone angle of the plug, (°); τ_i is the adhesive force of the plug to the bowl, N; F_{Ni} is the support force of the plug sidewall to the bowl, N; G is the weight of a single pepper hole tray seedling, N; F_l is the actual picking force, N; F_{j1}, F_{j2} are the frictional forces of the clamping mechanism on the plug seedlings, N; F_{fj} is the maximum static friction force between the gripper and the stem, N; μ is the maximum static friction coefficient between the gripper and the stem, taken as 0.4[23]; a is the instantaneous acceleration of the bowl at the moment of detachment from the plug, mm/s^2; s is the length of the picked seedling; v is the instantaneous velocity during picking, mm/s.

From the clamping force equation, it is evident that the higher the picking rotation speed, the greater the clamping force exerted on the stem. To avoid excessive clamping force that may damage the stem, the operating rotation speed should be controlled reasonably. Mechanical tests on pepper hole tray seedlings show that the picking force is mainly used to overcome the adhesive effect between the bowl and the plug, with minimal influence from the gravitational force of the plug seedlings; under quasi-static loading, the detachment resistance is much smaller than the tensile strength, ensuring the normal withdrawal of pepper hole tray seedlings from the plug.

2.3.3 Kinematic analysis of pepper hole tray seedlings during seedling throwing

To ensure the successful throwing of the plug seedlings, a kinematic analysis of the state of the plug seedlings during the throwing process is conducted. The motion process during throwing mainly involves the gripper holding the plug seedlings and moving them to the throwing point, where the cam stroke undergoes a sudden change, causing the gripper to open rapidly and release the plug seedlings. Instantly after throwing, the plug seedlings move along a trajectory tangent direction with a certain velocity, planting mouth picks up the plug seedlings, the plug seedlings collide with the inner wall of the planting mouth and then slide through friction inside the planting mouth until reaching the beak tip, and are planted as the beak opens in the field[27-29]. To improve the seedling throwing success rate, it is vital to ensure that the plug seedlings fall precisely into the center of the planting mouth.

For ease of calculation, the motion model of pepper hole tray seedlings has been simplified. The simplified mechanical model is depicted in Figure 6, where the plug seedling is subjected to its own gravity and air resistance in the vertical direction, with air resistance proportional to the falling speed of the plug seedlings[30,31], and undergoes accelerated motion with an initial velocity of 0; while in the horizontal direction, it experiences no force and moves uniformly with an initial velocity of v_0.

The air resistance acting on the plug seedlings is

$$F_v = k_1 v_l \tag{34}$$

When the plug seedlings undergo accelerated motion with an initial velocity of 0 in the vertical direction, the resultant force in the vertical direction is:

$$G - k_1 v_l = ma_l \tag{35}$$

where, F_v is the air resistance, N; k_1 is the air resistance coefficient; v_l is the velocity of the plug seedlings in the vertical direction at time l, mm/s; G is the weight of the plug seedlings, N; m is the weight of a single plug seedling in grams, g; a_l is the acceleration of the plug seedlings in the vertical direction at time l, mm/s^2.

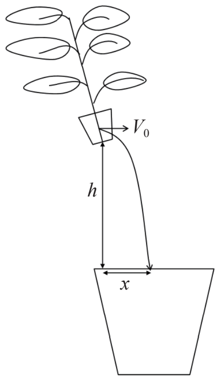


Figure 6 Kinematic analysis of seedling dropping process

By performing a double integration on both sides of Equation (35), the displacement of the plug seedlings in the vertical direction can be obtained as:

$$h = \frac{gm^2}{k_1^2}\left(e^{\frac{k_1 t}{m}} - 1\right) \tag{36}$$

Rearranging Equation (36) yields the expression for the time corresponding to the plug seedlings' descent process.

$$t = \frac{m}{k_1}\ln\left(1 + \frac{hk_1^2}{gm^2}\right) \tag{37}$$

If the time required for the gripper to open from closure to the point of seedling release at the throwing spot is denoted as t_k, and the distance the gripper opens is s, then the opening speed of the gripper is given by:

$$v_k = \frac{\frac{s}{2}}{t_k} \tag{38}$$

Substituting Equation (37) into Equation (38) and rearranging gives:

$$s = \frac{2mv_k}{k_1}\ln\left(1 + \frac{hk_1^2}{gm^2}\right) \tag{39}$$

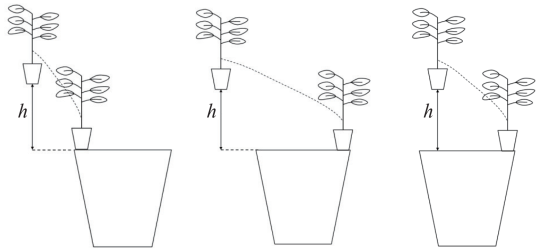
From Equation (39), it is evident that the distance s the gripper opens is directly proportional to the speed v_k at which the gripper opens. Put simply, the faster the gripper opens, the greater the extent of gripper opening, leading to a higher seedling throwing success rate. The speed v_k at which the gripper opens is linked to the rotation speed of the seedling pickup mechanism, thus the rotation speed of the seedling pickup mechanism impacts the quality of seedling throwing.

When the plug seedlings undergo uniform motion with an initial velocity of v_0 in the horizontal direction, the displacement of the plug seedlings in the horizontal direction is:

$$x = v_0 t = \frac{mv_0}{k_1}\ln\left(1 + \frac{hk_1^2}{gm^2}\right) \tag{40}$$

Equation (40) indicates that the horizontal displacement of the plug seedlings is positively correlated with the throwing speed v_0 and throwing height h. Greater throwing speed and throwing height result in a larger horizontal displacement of the plug seedlings. The horizontal displacement of the plug seedlings influences the position of the planting mouth, consequently affecting the seedling throwing success rate. Therefore, establishing the throwing speed v_0 and seedling throwing height h as factors influencing the seedling throwing success rate is crucial.

To enhance the adaptability of the planting mouth position to the throwing speed, the critical conditions for the plug seedlings to precisely fall into the planting mouth at different throwing speeds are explored, as depicted in Figure 7.



a. Critical position at minimum velocity 1 b. Critical position at minimum velocity 2 c. Critical position at minimum velocity 3

Figure 7 Critical position analysis of seedling dropping process

Setting the precise falling of the plug seedlings into the planting mouth as the critical condition value for analysis, the critical range for seedling throwing success rate is:

$$\begin{cases} x-\dfrac{d_1-d_2}{2}\le b\le x+\dfrac{d_1+d_2}{2},\ b\ge \dfrac{d_1}{2} \\ x-\dfrac{d_1-d_2}{2}\le b\le \dfrac{d_1}{2},\ b\le \dfrac{d_1}{2} \end{cases} \tag{41}$$

where, d_1 is the width of the upper mouth of the planting mouth, mm; d_2 is the lower length of the bowl body, mm; b is the distance between the throwing point and the centerline of the planting mouth, mm.

Calculations based on Equations (40) and (41) are conducted to determine the reasonable range of parameters corresponding to the horizontal displacement during throwing, ensuring that the plug seedlings fall as close to the center of the planting mouth as possible and providing a theoretical basis for seedling throwing experiments.

3 Bench testing of the seed picking mechanism

The above parameter analysis reveals that the seedling pick-up mechanism speed influences the opening speed of the clamps during seedling throwing and the horizontal displacement during seedling throwing, and the seedling throwing height affects the throwing displacement during seedling throwing. The planting mouth diameter impacts the adaptability of plug seedlings ejected at different speeds. Therefore, the seedling pick-up mechanism rotation speed, seedling throwing height, and planting mouth diameter are identified as the major influencing factors on the seedling throwing success rate. Considering the agronomic requirements, the seed picking rotation speed is set at 60-80 r/min. Through theoretical calculations and data rounding, a seed picking rotation speed of 60-80 r/min, a seedling throwing height of 50-150 mm, and a planting mouth diameter ranging from 106-150 mm are determined.

The experiment was conducted in April 2024 at the Nanjing Institute of Agricultural Mechanization, Ministry of Agriculture and Rural Affairs. As shown in Figure 8, the experiment focused on the use of "Xiaoxin Zhizun" pepper seedlings developed by the Nanjing Vegetable and Flower Research Institute. The seedling age was controlled within the suitable throwing period of 45-60 d. The seedling tray used was a 72 (6×12) cell plug, with overall dimensions of 540 mm×280 mm and a height of 40 mm. The holes were square pyramids with upper and lower diameter side lengths of 40 mm and 15 mm, respectively. The seedling substrate comprised peat, perlite, and vermiculite mixed in a 7:2:1 ratio with a moisture content of 60% to 70%. The equipment included a seedling pick-up mechanism, a homemade stand, a camera, and others. Figure 8a illustrates the seedling pulling processes of the seedling pick-up mechanism, during which the gripper transitions from an open state to a closed position around the stems on both sides of the pepper hole tray seedlings, facilitating the seedling pulling operation. Figure 8b depicts the seedling throwing phase, where the gripper moves from a closed state to an open position at the throwing location, thereby accomplishing the seedling throwing operation.

a. Seedling pulling processes b. Seedling throwing processes

Figure 8 Seedling picking and throwing test

3.1 Single-factor experiment for seedling picking operations

To investigate the effect of the picking mechanism rotational speed on the seedling picking success rate and injury rate of pepper seedlings, experiments were conducted at different rotational speeds set at 60, 70, and 80 r/min. A total of 54 pepper seedlings from the seedling trays were picked at each rotational speed condition, and the experimental data were recorded. The results of the experiments are presented in Table 1.

Table 1 Seedling picking operation test

Seedling pick-up mechanism rotation speed/r·min^{-1}	Seedling pick-up efficiency/ plant·min^{-1}	Success rate of seedling pick-up/%	Rate of injured seedlings/%
60	120	96.30	0
70	140	96.30	0
80	160	94.44	0

3.2 Optimization experiment for transplantation parameters

Following the industry standard JB-T10291-2013 (Transplanter of dry land plant)[32] and considering the requirements of the stem picking mechanism, the experiment evaluated the seedling throwing success rate Y_1 as the key performance indicator. Factors explored during the experiment included seedling pick-up mechanism rotation speed, seedling throwing height, and planting mouth diameter. The rotation speeds were set at 60 r/min, 70 r/min, and 80 r/min, corresponding to seedling picking efficiency of 120 plants/min, 140 plants/min, and 160 plants/min, respectively. The seedling throwing heights were set at 50 mm, 100 mm, and 150 mm, and the planting mouth diameters were set at 110 mm, 130 mm, and 150 mm. Each rotation speed condition involved testing with 36 pepper hole tray seedlings and recording the experimental data.

The seedling throwing success rate Y_1 was used as the performance metric and calculated using the following formula:

$$Y_1 = \frac{N_1}{N} \times 100\% \tag{42}$$

where, Y_1 is the seedling throwing success rate, %; N is the total number of successful seedling picks in each experimental group (Pieces); N_1 is the number of seedlings successfully transplanted in each experimental group (Pieces).

Box-Behnken response surface methodology was employed for optimization experiments, with seedling pick-up mechanism rotation speed r (r/min) as factor A, seedling throwing height (mm) as factor B, and planting mouth diameter (mm) as factor C, while the seedling throwing success rate Y_1 served as the evaluation metric. A three-factor three-level experiment was conducted, and the levels of factors are listed in Table 2.

Table 2 Factors and levels of experiments

Factors	Levels		
	−1	0	1
(A) Seedling pick-up mechanism rotation speed/r·min^{-1}	60	70	80
(B) Seedling throwing height/mm	50	100	150
(C) Planting mouth diameter/mm	110	130	150

Based on the aforementioned experimental data, utilizing Design-Expert 10 for data analysis, each experiment was replicated 36 times to obtain the seedling throwing success rate Y_1 under each condition. The experimental results of each test plan and the evaluation criterion of the seedling throwing success rate in the model are listed in Table 3.

The regression equation analysis in Table 4 indicates that the regression model for the seedling throwing success rate has a significance level of $p<0.001$, showing strong statistical significance and demonstrating the model's meaningfulness. The lack-of-fit term with $p>0.05$ suggests high model adequacy. The adjusted R^2 value of 0.9808>0.8000 indicates that the experimental values can be explained by this model. The regression coefficients in the regression equation were subjected to F-test and p-test at a 95% confidence level.

The regression equation is as follows:

$$Y_1 = 93.89 - 2.76A - 1.04B - 1.03C + 1.39AB + 0.03AC - 0.70BC - 5.61A^2 - 4.95B^2 - 3.53C^2 \tag{43}$$

The regression equation analysis revealed that the linear term A, and quadratic terms A^2, B^2, and C^2 had a highly significant impact on the seedling throwing success rate. The linear terms B, C, and the interaction term AB had a significant effect.

The interaction effects between factors are illustrated in Figure 9.

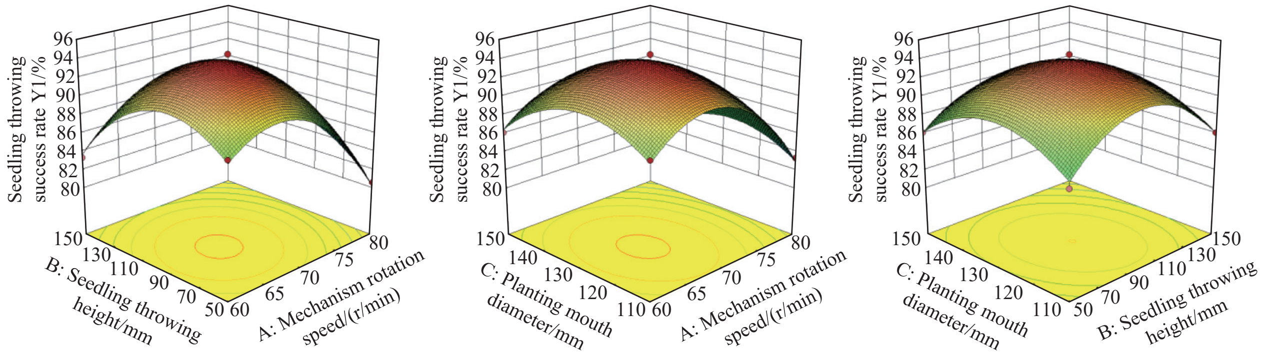
Table 3 Response surface analysis scheme and test results

Serial number	Factors			Seedling throwing success rate Y_1/%
	A	B	C	
1	60	50	130	88.89
2	80	50	130	80.55
3	60	150	130	83.33
4	80	150	130	80.55
5	60	100	110	88.89
6	80	100	110	83.33
7	60	100	150	86.11
8	80	100	150	80.67
9	70	50	110	86.11
10	70	150	110	86.11
11	70	50	150	86.11
12	70	150	150	83.33
13	70	100	130	94.44
14	70	100	130	94.44
15	70	100	130	94.44
16	70	100	130	91.67
17	70	100	130	94.44

Table 4 Regression equation analysis

Source	Seedling throwing success rate				
	Sum of squares	df	Mean square	F-value	p-value
Models	408.08	9	45.34	39.72	<0.0001
A	61.16	1	61.16	53.58	0.0002
B	8.69	1	8.69	7.62	0.0281
C	8.45	1	8.45	7.4	0.0298
AB	7.73	1	7.73	6.77	0.0353
AC	0.0036	1	0.0036	0.003 15	0.9568
BC	1.93	1	1.93	1.69	0.2344
A^2	132.54	1	132.54	116.11	<0.0001
B^2	102.98	1	102.98	90.21	<0.0001
C^2	52.33	1	52.33	45.85	0.0003
Lack of fit	1.85	3	0.62	0.4	0.7598
Pure error	6.14	4	1.53		
Total	416.07	16			

Note: $p<0.001$ shows extreme significance; $p<0.05$ shows significance.



a. $Y(A, B, 130)$ b. $Y(A, 100, C)$ c. $Y(70, B, C)$

Figure 9 Influence of two-factor interaction on seedling throwing success rate

4 Discussion

According to Table 1, it is observed that as the mechanism rotational speed increases, the seedling picking success rate slightly decreases. This can be attributed to the fact that at higher rotational speeds, the occurrence of seedling carryover becomes more prevalent, thus reducing the picking success rate. At rotational speeds of 60, 70, and 80 r/min, there are no instances of damage caused by the gripping mechanism's clamping action on the stem. This is primarily due to the fact that the gripper is made from flexible materials, and the seedlings in the pepper seedling hole trays possess strong compressive resistance.

In Figure 9, the response surface showed that at a planting mouth diameter of 130 mm, the seedling throwing success rate varied with seedling throwing height and mechanism rotation speed. The seedling throwing success rate increased as the mechanism rotation speed increased until a certain point, indicating the importance of maintaining a balance to ensure optimal seedling quality.

When the seedling throwing height reached 100 mm, the seedling throwing success rate varied with the planting mouth diameter at different levels across mechanism rotation speeds. It was observed that as the mechanism rotation speed increased, leading to greater horizontal displacement of the seedlings, a larger planting mouth diameter resulted in better seedling picking performance. However, beyond a certain range, the seedling quality decreased due to poor adjustment of the seedlings' pre-throwing posture.

When the seedling pick-up mechanism rotation speed is 70 r/min, the seedling throwing success rate varies with the increase in seedling throwing height at different levels of planting mouth diameter; it initially increases and then decreases. As the seedling throwing height gradually increases, the horizontal displacement when the seedlings are thrown out of the cell plug increases. When the seedling throwing height reaches 100 mm, the cell tray seedlings land precisely at the center position of the planting mouth diameter, resulting in the highest seedling throwing success rate.

By utilizing the constrained optimization module in the Design-Expert software, the optimal parameter combination for maximum seedling throwing success rate was determined to be seedling pick-up mechanism rotation speed of 67.37 r/min, seedling throwing height of 93.37 mm, and planting mouth diameter of 137.33 mm, resulting in a maximum seedling throwing success rate of 94.44%. Based on this optimal parameter combination, experimental validation was conducted with seedling pick-up mechanism rotation speed of 67 r/min, seedling throwing height of 93 mm, and planting mouth diameter of 137 mm, achieving a seedling throwing success rate of 94.58%. The experimental results closely matched the predicted values, confirming the reliability of the model. This parameter combination serves as a reference for improving the quality of pepper hole tray seedling transplantation.

5 Conclusions

1) A dynamic analysis of the non-circular gear planetary gear system for seedling pick-up mechanism was conducted. Through the establishment of the kinematic model of this planetary gear system, equations for the displacement, velocity, and acceleration of the endpoint of the seedling picking arm were derived, providing crucial reference for mechanism design to ensure stable and efficient operation.

2) Dynamic analyses of pepper seedlings in the seedling picking and transplantation stages were carried out. This included mechanical analysis of stem bending during seedling picking, mechanical analysis of pepper hole tray seedlings during the picking stage, and kinematic analysis of pepper hole tray seedlings during the transplantation stage. These analyses determined the dynamic characteristics of pepper hole tray seedlings, quantitatively evaluated key factors affecting seedling throwing success rate, and provided important theoretical support for improving pepper hole tray seedling cultivation efficiency.

3) Through the single-factor test, the effect of the rotation speed of the seedling picking mechanism on the success rate of seedling picking and the rate of injury was obtained. Validation of the established model through a Box-Behnken response surface experiment with three factors at three levels confirmed the accuracy and feasibility of the model. With the optimal parameter combination, the seedling throwing success rate can reach 94.58%. The results of the seedling picking tests can provide a design basis for the non-circular gear planetary seedling picking mechanism. The transplantation tests can offer theoretical support for the parameter design of the planting mechanism and the coordinated operation between the seedling picking and planting mechanisms.

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