Simulation and experiment of a transplanting mechanism for sweet potato seedlings with 'boat-bottom' transplanting trajectory

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Abstract: Planting on mulched soil is the main cultivation mode for sweet potato slips in spring in northern China. The 'boat-bottom' planting method can bring high quantity and similar size for sweet potatoes. In this study, a mechanism for transplanting sweet potato seedlings on mulched was proposed, which could realize 'boat-bottom' transplanting trajectory and improve the planting efficiency. The virtual prototype model of the transplanting mechanism was constructed using ADAMS software, a soil particle model and a flexible body model of sweet potato seedling were established using EDEM software, and then a joint simulation was carried out to find out the interaction of mechanism, seedling and soil. By simulation, the trajectory of the clamping point, the sweet potato seedling posture, soil particles, pits, and relative force were all analyzed, which verified the rationality of the transplanting mechanism design. Finally, three kinds of sweet potato seedlings, watermelon red, Yan-25, and purple sweet potato seedlings were selected, and transplanting experiments were carried out on the mulch to verify that the theoretical trajectory, the simulated trajectory, and the actual trajectory were consistent. The transplanting success rates of the three kinds of sweet potato seedlings were all above 85%, indicating that different varieties of sweet potato seedlings had little effect on the transplanting effect of the mechanism, which reflected that the transplanting mechanism had good practicability and adaptability.

Keywords: sweet potato, transplanting device, 'boat-bottom' trajectory, Adams

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1 Introduction

Sweet potato (*Ipomoea batatas* L. Lam) is not only one of the main food crops but also a high-quality anti-cancer health food and a new energy source[1-3]. As the world's largest producer of sweet potatoes, China has the largest planting area with more than 3 million hectares of sweet potatoes throughout the year[4]. However, sweet potato planting mainly depends on manual, which is not only labor-intensive but also very inefficient. So it's urgent to develop mechanical transplanting for sweet potatoes.

Relying on variety improvement and new agronomic method is an effective mean to increase the high yield of food crops[5,6]. At present, the planting methods of sweet potato seedlings mainly include oblique planting, vertical planting, 'boat-bottom' planting, and horizontal planting. Among these, the 'boat-bottom' planting can make sweet potato seedlings have more nodes in the soil[7], so the percentage of large and medium sweet potatoes in each plant and the average yield are relatively high.

The transplanting technology is mainly suited to pot seedlings, blanket seedlings, and naked seedlings[8-11]. As a root crop of Convolvulaceae, sweet potato has the characteristics of drought resistance, barren tolerance, and strong adaptability. It is generally transplanted with naked seedlings[12]. Mechanical transplanting can not only reduce labor intensity but also improve work efficiency and ensure planting quality[13-15]. The planting device is the core working part of the transplanter. At present, planting mechanisms mainly include clamp type, chain clamp type, planetary gear type, and multi-link type[16-18]. The research on sweet potato seedling transplanters in Europe, America, Japan, and other countries is relatively early. For example, the semi-automatic chain clip transplanter produced by Marcinick, which is pulled by a high-horsepower tractor, adopts the vertical insertion method and is suitable for large farms. The ridges need to be raised before planting the seedlings. However, the damage to the ridge body is more serious when planting. The small self-propelled clip transplanter produced by ISEKI Co., Ltd. in Japan, is suitable for loose soil operations such as volcanic ash and has poor compaction, especially in areas where the soil is not easily crushed. Therefore, this type of transplanter is not suitable for planting sweet potato seedlings in China[7]. Domestic research on sweet potato seedling transplanting began in recent years and has been at a standstill due to problems such as complex structures, high production costs, and difficulty in coordinating machinery and planting agronomy[19,20]. For example, the various chain clip sweet potato transplanter produced by Nantong FLW Agricultural Equipment Co., Ltd. has reliable performance with vertical planting, it is not suited for mulched planting[21].

Planting on mulched soil is the main cultivation mode for sweet potato slips in spring in northern China. The advantages include heat preservation, moisture preservation, high seedling survival rate, root quality improvement, and crop yield increase[22,23]. The

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transplanting machine on mulched soil needs to avoid too large holes during the planting process, otherwise, it will easily cause great damage to the mulch, and even tear the film, which will cause the mulch to lose its function[24]. The transplanting machines on the market that can meet the requirements of planting on mulch are mainly pot seedlings transplanting vegetables, tobacco, and other crops. The pot seedlings are required to have a high verticality after transplanting, which cannot meet the agronomic requirements for transplanting sweet potato seedlings[25]. Therefore, it is very necessary to design a sweet potato seedling transplanting mechanism on mulch that meets ‘boat-bottom’ planting agronomic standards of China.

This study focused on developing a transplanting mechanism to realize sweet potato planting on mulched soil with ‘boat-bottom’ transplanting trajectory by EDEM-ADAMS joint simulation and planting experiment. This transplanting mechanism was developed not only to meet the agronomic standards for planting sweet potato seedlings in China but also to realize the sweet potato seedlings transplanting on the mulch.

2 Design requirements and working principle

2.1 Design requirements

According to the agronomic requirements of ‘boat-bottom’ method for planting sweet potato seedlings, the planting trajectory should be in line with the ‘boat-bottom’ trajectory, in detail, the planting depth is required to be 50-70 mm, and the plant spacing is required to be 300-400 mm, as shown in Figure 1.

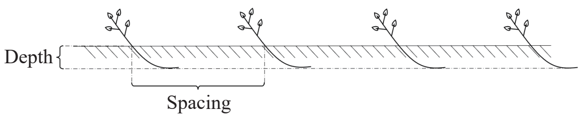
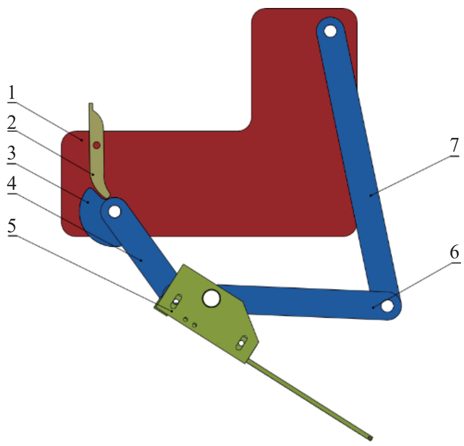


Figure 1 ‘Boat bottom’ planting method of sweet potato seedlings

2.2 Working principle

Relying on the mathematical modeling and the parametric optimization design function of Adams software, a transplanting mechanism was designed, and the three-dimensional model was shown in Figure 2. The mechanism mainly includes a frame, a crank, a connecting rod, a rocker bar, a cam, a swing push rod, and a seedling clamping device.



1. Frame 2. Swing push rod 3. Cam 4. Crank 5. Seedling clamping 6. Connecting rod 7. Rocker bar

Figure 2 Transplanting device structure diagram

A swing push rod (2), a cam (3), a crank (4), and a rocker bar (7) are installed on the frame (1). A seedling clamp is installed on the connecting rod, and the angle between the two is 30°. The swing push rod and the seedling clamp are connected by a pulling line.

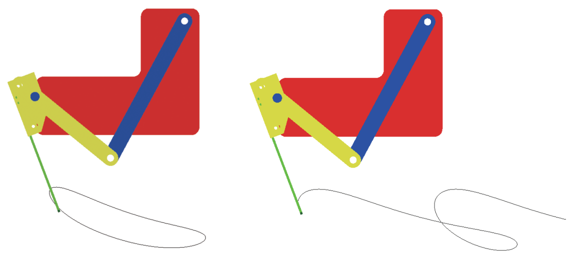
When the transplanting mechanism is working, the crank rotates and then drives the connecting rod and the rocker bar. The seedling clamp moves with the connecting rod to realize the planting, the cam fixedly connected with the crank rotates accordingly, drives the swinging push rod to swing, and then drives the tension and relaxation of the pulling line, so as to control the closure and opening of the finger clip of the seedling clamp, which together constitute the mechanical control system of the seedling clamp. In one planting cycle, first, the seedlings are placed in the specified position, and the clamp opens and reaches the root of the sweet potato seedlings, then the clamp closes to clamp the sweet potato seedlings. The clamp continues to move with the connecting rod and the sweet potato seedlings are planted into the soil. The clamp then goes back to the initial position with the connecting rod to prepare for the next transplanting.

3 Virtual prototype model and simulation

ADAMS software and EDEM software have their own advantages, but they also have their own shortcomings. ADAMS software is suitable for dynamic simulation, but not suitable for discrete element simulation[26,27]. EDEM software is suitable for establishing a discrete element model, and cannot set up complex motion for imported a geometric model[28,29]. EDEM-ADAMS co-simulation combines the advantages of the two software complementary and enables more complex simulation experiments[30].

3.1 Dynamic model setting and simulation

The virtual prototype model of the transplanting mechanism was set in ADAMS software. According to the plant spacing requirements, the planting frequency of the virtual prototype was set to 60 r/min, and the forward speed was set to 0.35 m/s. Then the transplanting trajectory could be obtained by simulation, which is shown in Figure 3. From Figure 3, it can be seen that the simulation trajectory conforms to the ‘boat-shape’ trajectory.



a. Static trajectory b. Moving trajectory

Figure 3 Trajectory simulation in Adams

In the co-simulation of EDEM and ADAMS, EDEM transmits the force of soil particles to ADAMS, so it is necessary to modify the general force vector parameters. The definition is changed to a subroutine. The user parameter is set to 0.0, and the program function is ACSI _Adams. The solution ID is set to 1, 2, 3, 4, 5, and 6 in the order of addition (Figure 4).

3.2 Discrete element model setting and joint simulation

EDEM software was used to establish the soil particle model and the flexible body model of sweet potato seedlings. The simulation parameters of the discrete element model are set as listed in Table 1.

A soil groove with a size of 500 mm, a width of 100 mm, and a height of 150 mm is established. In order to reduce the simulation time, the soil particle model is set to be spherical with a radius of

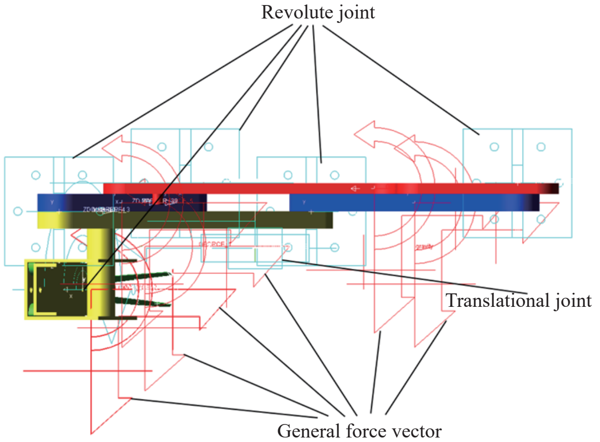


Figure 4 Connection relation of various parts of transplanting mechanism

Table 1 Main parameters of discrete element simulation

Parameter	Value
Soil particle density/kg·m^{-3}	2610
Soil particle shear modulus/Pa	1.09e+06
Poisson 's ratio of soil particles	0.4
Soil particle radius/mm	3
Geometric density/kg·m^{-3}	7801
Geometric Young′s modulus/Pa	2.07e+11
Geometric Poisson′s ratio	0.29
Sweet potato seedling density/kg·m^{-3}	1152
Shear modulus of sweet potato seedlings/Pa	1.81e+05
Sweet potato seedlings Poisson 's ratio	0.3
Soil-soil restitution coefficient	0.2
Soil-soil Static friction coefficient	0.4
Soil-soil dynamic friction coefficient	0.3
Surface energy between soil and soil/J·m^{-2}	1.25
Soil-geometric interbody recovery coefficient	0.5
Soil-geometry Static friction coefficient	0.5
Soil-geometry dynamic friction coefficient	0.3
Soil-sweet potato seedlings Recovery coefficient	0.5
Soil-sweet potato seedlings Static friction coefficient	0.83
Soil-sweet potato seedlings dynamic friction coefficient	0.7
Geometry-sweet potato seedlings Recovery coefficient	0.4
Geometry-sweet potato seedlings Static friction coefficient	0.5
Geometry-sweet potato seedlings dynamic friction coefficient	0.4
Normal stiffness of sweet potato seedling particles/N·m^{-3}	5e+08
Shear stiffness of sweet potato seedling particles/N·m^{-3}	5e+08
Critical normal stress of sweet potato seedling particles/Pa	1e+10
Critical shear stress of sweet potato seedling particles/Pa	1e+10
Contact radius of sweet potato seedling particles/mm	1.2
Gravity acceleration/m·s^{-2}	9.81

3 mm. The total particle mass of the factory is set to be 19.575 kg, the generated particle is 5 kg/s, and the starting time is 1e-12 s. Switch to the simulator interface, and set the Rayleigh time step is 10%, the simulation time is set to 5 s and after the setting is completed, the simulation is carried out. The flexible body model of sweet potato seedlings is added in the co-simulation to simulate the whole transplanting process, visually showing the posture change of sweet potato seedlings after they are planted, and improving the accuracy of the transplanting device simulation. In the process of transplanting sweet potato seedlings, the leaves of sweet potato seedlings will not affect the pose of sweet potato seedlings under the soil. Therefore, without affecting the simulation effect, the sweet potato seedlings are established into a slender cylindrical model with a diameter of 4 mm and a length of 300 mm. The model consists of a number of particles with a physical radius of 1 mm bonded together. The simulation model is set up as shown in Figure 5.

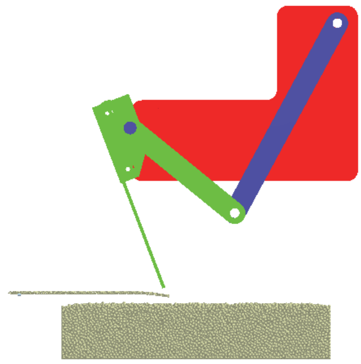


Figure 5 Discrete element model setting

4 Analysis of simulation results

4.1 Analysis of simulation results of dynamic model

The virtual prototype model was simulated by ADAMS software, and the trajectory of the clamping seedling point was generated as shown in Figure 6. It can be seen that the simulated planting depth is 57 mm, which meets the agronomic standards of planting sweet potato seedlings by the ‘boat bottom’ method.

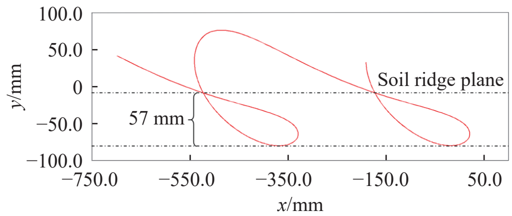


Figure 6 Movement trajectory of the transplanting mechanism

4.2 Analysis of co-simulation results

After the co-simulation, the posture changes of sweet potato seedlings, the velocity changes of soil particles, the influence of clamper on soil pit, and the force of finger clip of seedling clamp device at different times (0 s, 0.2 s, 0.4 s, 0.6 s, 0.8 s, and 1.0 s) were analyzed.

4.2.1 Posture changes of sweet potato seedlings

Select six time points of 0 s, 0.2 s, 0.4 s, 0.6 s, 0.8 s, and 1.0 s to observe sweet potato seedling posture changes in one planting cycle, as shown in Figure 7.

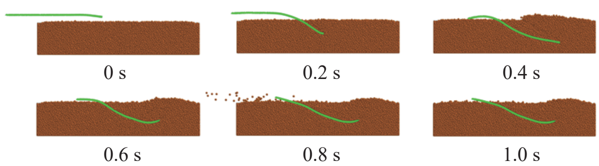


Figure 7 Sweet potato seedling pose changes

At 0s, the sweet potato seedling is clamped and ready to be transplanted. At 0.2 s, the sweet potato seedlings begin to enter the soil with the clamper. At 0.4 s, sweet potato seedlings have been obliquely inserted into the soil, and the root reaches the lowest point in the transplanting process. When the time is 0.6 s, the sweet potato seedling posture has basically presented the ‘boat bottom’ shape. During the period of 0.6-0.8 s, the transplanting clamper leaves the soil, and the soil disturbed by the clamper begins to return, covering the sweet potato seedlings. At 1.0 s, the transplanting device moves to the initial position to prepare for the next transplanting.

In the simulation experiment, the posture of the sweet potato seedling below the soil ridge plane is 'boat bottom' shape. As shown in Figure 8, through the comparative analysis of the simulation trajectory of the transplanting device in ADAMS, it is found that the general contours of the two are basically consistent. It can be seen that the designed transplanting device has theoretically met the transplanting standard of 'boat-bottom'.

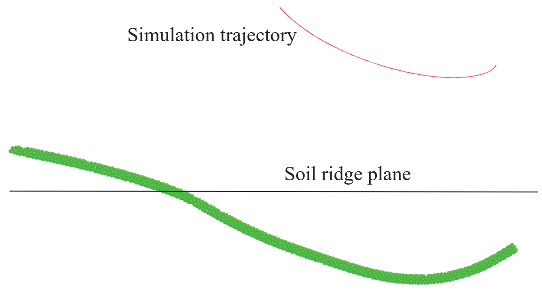


Figure 8 Comparison of potato seedling simulation pose and simulation trajectory

4.2.2 Variation of soil particle velocity

The cloud picture of soil particle motion velocity at the six time points is shown in Figure 9. In the figure, the darker the color of particle flow is, the faster the soil particle moves.

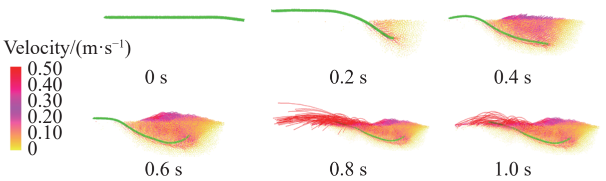


Figure 9 Cloud map of soil particle velocity

Through observation, it is found that the disturbance of clamper on soil particles is obvious after entering soil. In the initial stage of transplanting, that is, 0 s, sweet potato seedlings do not move, and there is no soil particle movement. When the time is about 0.2 s, the soil particles are affected by the finger clip disturbance, and the velocity of some soil particles changes. In the period of 0.4-0.6 s, the disturbance of soil particles is most obvious, and the particle velocity has changed in a large area. In the period of 0.8-1.0 s, the clamper leaves the soil, and some soil particles are brought out. From the color, it can be seen that the velocity of the soil particles in this period is the largest, and the soil particles begin to return under the action of gravity.

In order to further study the velocity change of soil particle movement, the average and maximum values of combined velocity and velocity in X-axis, Y-axis, and Z-axis were analyzed. It can be seen from Figure 10 that the average combined velocity of soil particles has two peaks at about 0.40 s and 0.60 s respectively. Combined with the movement of the above transplanting device, at 0.40 s, the finger clip of the transplanting device is inserted most into the soil, and at this time, the clip seedling point is at the lowest point in the whole transplanting process. Therefore, the soil particles are disturbed most obviously and the velocity is the largest, with a velocity of about 0.016 m/s. At 0.60 s, the finger clip of the transplanting device is about to be completely removed from the soil. At this time, the soil particles carried by the transplanting device begin to flow back, and a peak value of the velocity of the soil particles is found again, about 0.013 m/s. Among the average velocity in each direction, the average velocity in X-axis direction changes obviously, and the changing trend is basically consistent with the average combined velocity. Before 0.50 s, the changing trend of the average velocity and the average combined velocity of the Y-axis is basically the same. After 0.50 s, the average velocity peak of the Y-axis is about 0.009 m/s at 0.52 s. The average velocity in the Z-axis direction changes little and has no obvious peak.

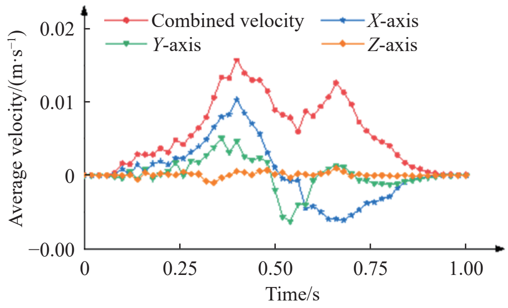


Figure 10 Average velocity curve of soil particles

4.2.3 Influence of clamper on soil subsidence pit

Six time points of 0 s, 0.2 s, 0.4 s, 0.6 s, 0.8 s, and 1.0 s are selected for analysis, and the formation of soil hole after clamper disturbance is shown in Figure 11.

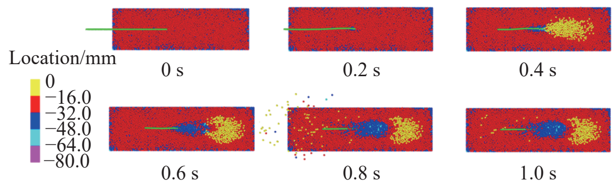


Figure 11 Effect of transplanting device on soil

In the initial stage of transplanting, i.e. 0 s, sweet potato seedlings do not move, and there is no change in soil. At 0.2 s, the sweet potato seedlings begin to be planted into the soil, and smaller holes appear. In the period of 0.2-0.4 s, the hole gradually increases, and the soil above the hole is slightly stirred upward by the seedling clamping device, which is higher than the initial soil ridge plane. After 0.6 s, the seedling clamper leaves from the soil gradually. At this time, the soil particles begin to fall back to fill the hole, and some other particles are adhered or scattered by the seedling clamper, which could not return to the position of the hole. Therefore, an elliptical hole is formed at the upper part of the sweet potato seedling, and the depth is slightly lower than the initial plane of the soil ridge.

4.2.4 Force analysis of soil on seedling clamper

In the process of transplanting, the clamper contact with the soil and the acting force was analyzed (Figure 12). It can be seen from Figure 12a that the force of the right finger clamp of the clamping device in the X-axis direction is obvious, followed by the Z-axis direction, and the force in the Y-axis direction is small, and the maximum force is about 0.015 N. It can be seen from Figure 12b that the force of the left finger clip of the seedling clamping device is more obvious in the X-axis direction of the axis, the force in the Y-axis and Z-axis directions is similar, and the maximum force is about 0.02 N.

Comparing the two figures, it is found that the resultant force on the left and right sides of the seedling clamping device is slightly different, but the changing trend is generally consistent. Because the movement direction of the finger clips on both sides of the clamping device is opposite in the Z-axis direction, the force change trend of the two finger clips in the Z-axis direction is opposite.

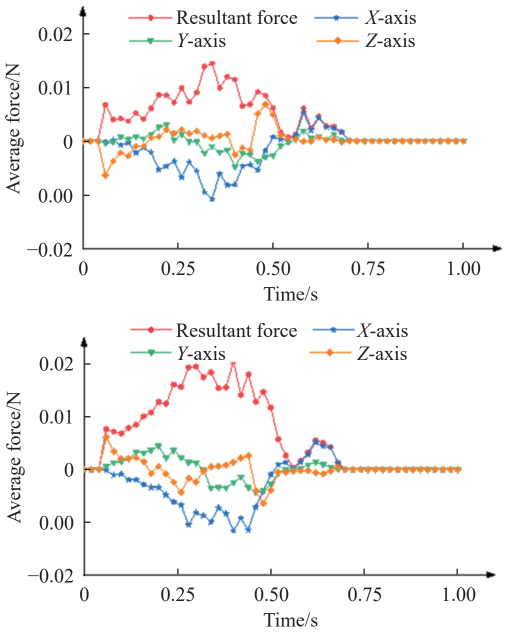
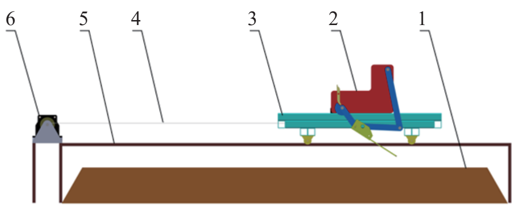


Figure 12 Force of finger clamp of seedling clamping device

5 Physical prototype experiment

The experimental bench system of the transplanting device was built, and the trajectory verification test of the clamping point of the transplanting device was completed on the bench. The three-dimensional model of the designed experimental bench system is shown in Figure 13.



1. Soil ridge 2. Transplanting mechanism 3. Trolley 4. Wire rope 5. Track 6. Traction motor

Figure 13 Three-dimensional model of experimental bench system

The drive motor and traction motor are 6IK250RGM-CF AC gear velocity regulation/deceleration motor, the traction velocity can be adjusted in 0-0.88 m/s, and the rotation speed of the driving part can be adjusted in 0-67.5 r/min. According to the parameter settings in the simulation of the virtual prototype of the transplanting device, the plant spacing designed by the transplanting device is 350 mm. Therefore, when the forward velocity is 0.35 m/s, the transplanting period is 1 s, that is, the rotation velocity of the crank is 60 r/min. When the system works, the drive motor drives the crank to rotate, drives the mechanical control system to work, and then controls the clamping device. At the same time, the traction motor drives the trolley along the track through the wire rope to simulate the working state of the transplanting mechanism installed on the transplanting machine (Figure 14).

The three varieties of sweet potato seedlings of watermelon red, Yan-25, and purple sweet potato are used to carry out the transplanting experiment on the plastic film. In each experiment, 200 sweet potato seedlings of different varieties are tested. The transplanting device moves forward at 0.175 m/s, 0.350 m/s, and 0.525 m/s, respectively. The qualified rate of the planting depth of sweet potato seedlings, the qualified rate of the soil length of sweet potato seedlings, the rate of seedling missing, the rate of seedling injury, the coefficient of variation of plant spacing, the success rate of transplanting, and the length and width of the broken film hole are recorded and measured. The experiment results are listed in Tables 2-4. Through the analysis of the data, the length of the normal membrane rupture hole is 8.23-15.74 mm, and the width of the membrane rupture hole is 4.49-6.97 mm. The transplanting success rates of the three sweet potato seedlings are above 85%, and the difference is small, indicating that different varieties of sweet potato seedlings have little effect on the transplanting success rate, and the transplanting mechanism has good adaptability.

Figure 14 Effect of transplanting

Table 2 Transplanting performance results at 0.175 m/s moving speed

Project	Watermelon red	Yan-25	Purple sweet potato
Seedling number	200	200	200
Depth qualified rate/%	96	95	93
Qualified rate of soil entry length/%	93	94	90
Seedling deficiency rate/%	4	5	7
Injury seedling rate/%	9	12	6
Coefficient of variation of row spacing/%	11	9	13
Success rate of transplanting/%	91	93	90

Table 3 Transplanting performance results at 0.35 m/s moving speed

Project	Watermelon red	Yan-25	Purple sweet potato
Seedling number	200	200	200
Depth qualified rate/%	87	89	91
Qualified rate of soil entry length/%	85	86	90
Seedling deficiency rate/%	13	11	9
Injury seedling rate/%	11	9	8
Coefficient of variation of row spacing/%	8	12	11
Success rate of transplanting/%	85	86	88

Table 4 Transplanting performance results at 0.525 m/s moving speed

Project	Watermelon red	Yan-25	Purple sweet potato
Seedling number	200	200	200
Depth qualified rate/%	82	81	84
Qualified rate of soil entry length/%	81	79	84
Seedling deficiency rate/%	18	19	16
Injury seedling rate/%	7	10	9
Coefficient of variation of row spacing/%	9	11	8
Success rate of transplanting/%	79	77	81

6 Conclusions

The mechanism for transplanting sweet potato seedlings with 'boat bottom' method was realized, and the transplanting experiment was carried out on mulched soil.

1) The virtual prototype model was simulated. ADAMS was used to analyze the simulation trajectory of the clamping point of the clamping device, and EDEM-ADAMS was used to jointly simulate and analyze the changes in sweet potato seedling posture, soil particles, pits, and device force, so as to verify the correctness of the theoretical model and structural design of the transplanting device and the feasibility of transplanting on the mulch;

2) Through the transplanting experiment of the physical prototype, it was found that when the forward velocity of the transplanting device was less than or equal to 0.35 m/s, the transplanting success rates of watermelon red, Yan-25 and purple sweet potato were all above 85%, and the difference was small, indicating that sweet potato varieties had little influence on the transplanting effect, and the transplanting device had good adaptability.

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