EXPERIMENTAL TEST AND FINITE ELEMENT ANALYSIS OF POTATO IMPACT ACCELERATION
/
马铃薯碰撞加速度试验测试与有限元分析

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ABSTRACT
To analyze the maximum acceleration (a_{max}) of a potato colliding with different objects, both experimental test and finite element analysis (FEA) methods were used. Results showed that when potatoes were collided with the single rod, the steel plate and the double rods, the average discrepancies of FEA and experimental test values were 5.3%, 3.95% and 5.04%. The a_{max} increased with the increase of potato drop height, and decreased with the increase of potato mass. Under the same conditions, the a_{max} decreased in turn when the potatoes were collided with the steel plate, the single rod and the double rods. The FEA results showed that the a_{max} in collision with the steel plate was 60.78% to 96.29% higher than that with the double rods. The a_{max} in collision with the steel plate was 53.89% to 83.27% higher than that with the double rods. The a_{max} in collision with the single rod covered with soil was 37.65% and 31.54% lower than that without soil from different drop height or with different potato mass. The research methods and conclusions of this article provided a basis for the analysis of impact mechanics and damage mechanism of potatoes, and contributed to further researches related to solid-like agricultural and food products.

摘要
*为了分析马铃薯与不同对象碰撞的最大加速度，分别采用试验测试和有限元分析方法进行研究。结果表明：马铃薯分别与单杆条，钢板和双杆条碰撞时，有限元分析和试验结果的差别分别为*5.3%，3.95%和5.04%。*马铃薯最大碰撞加速度随碰撞高度增加而变大，随马铃薯质量增大而减小。碰撞条件相同时，马铃薯与钢板、单杆条和双杆条碰撞的最大加速度依次减小。马铃薯与钢板碰撞的最大加速度比与双杆条碰撞时高*60.78%到96.29%，比与单杆条碰撞时高53.89%到83.27%。马铃薯从不同高度或者以不同质量分别与单杆条碰撞时，有土壤条件下最大碰撞加速度比无土壤条件下分别减小37.65%和31.54%。本文的研究方法和结论为马铃薯碰撞分析和损伤机理研究提供了基础，为类似的固体农业物料和食品研究提供了参考。

INTRODUCTION
Mechanical collision in the harvesting and post-harvesting processes is among the major causes of the losses and damages of potatoes (*Celik, 2017; Nikara et al., 2020*). According to an American study, 70% of potato damage is caused by harvesting, 30% during transport and storage (*Peters, 1996*). The impact acceleration of potato not only has a positive correlation with its damage (T*homson and Lopresti, 2018; Xie, 2020a*), but also is the key parameter to the study of potato impact kinematics and dynamics. Researchers have adopted experimental studies[1] to analyze the potato mechanical impact and bruising based on various instruments including pendulum collision device, free drop collision device, electronic potato, instrumented sphere and acceleration measuring unit (*Canneyt et al., 2004; Dănilă, 2015; Deng et al., 2020*; *Geyer et al., 2009; Hyde et al., 1992; Mathew and Hyde, 1997; Nikara et al., 2018; Rady and Soliman, 2015; Strehmel et al., 2010; Xie et al., 2018; Xie et al., 2020a; Xie et al., 2020b*). But in the process of mechanized harvesting, sorting and transporting, potatoes usually collide with cylindrical steel rods with different tilt angles in different directions, which is a very complicated process. There are many difficulties to be solved in the process of collision analysis through experimental test. Finite element analysis (FEA) is a successful analysis tool for developing approximate solutions to complex engineering problems and is very popular (*Caglayan et al., 2018; Celik et al., 2019*).

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There have been many researches using FEA to study the collision damage of fruits and vegetables (*Ahmadi et al., 2016; Caglayan et al., 2018; Celik, 2017; Celik et al., 2019; Cerruto et al., 2015; Gao et al., 2018; Kabas and Vladut, 2015; Li et al., 2013; Nikara et al., 2020*).

Various influence factors on potato impact acceleration had been studied, which mainly consisted of drop height, impact material, soil type, potato mass, size, inside temperature and modulus of elasticity (*Bentini et al., 2006; Cerruto et al., 2015; Geyer et al., 2009; Mathew and Hyde, 1997; Thomson and Lopresti, 2018; Xie et al., 2020a; Xie et al., 2020b*). These studies were mainly based on experimental tests, and the way to obtain the impact acceleration was usually to implant an acceleration sensor into the real or instrumented potatoes. During the finite element analysis, potatoes were usually replaced by spheres, and the collision object was just steel plate (*Cerruto et al., 2015*).

Based on the above mentioned, there are few studies on the impact acceleration of potatoes using both the experimental test and finite element method. And the study on the comparisons of the potato impact acceleration with colliders of the steel plate, the single rod and the double rods has not been found yet. In the study of potato collision, there are few studies considering the effect of soil. In this article, both the FEA and experimental testing methods were adopted to analyze the impact acceleration of potatoes colliding with different objects in the process of harvesting, sorting and transportation. This article revealed the influence of potato mass, drop height, soil and colliders with different structures on the maximum acceleration (a_{max}) of potatoes, and provided references for potato breeding, structural design, and adjustment of working parameters of potato harvesting and post harvesting equipment.

MATERIAL AND METHODS

- **Raw materials for test**

Potatoes were dug out manually one day before the test from the potato planting base in Wuchuan County, Hohhot City. Ellipsoidal potatoes with undamaged surfaces were selected as the experimental materials. The potatoes were sealed with the soil in black plastic bags to avoid light and stored at a room temperature of about 15°C. The variety of potato was FuRuiTe, which was widely planted in Inner Mongolia Autonomous Region. Before the test, potatoes were washed clear with cold water, and then the excess was cutted off with a knife to make the tuber mass reach the specified value.

- **Potato collision test process**

The potato collision tests were carried out via the potato impact test rig and acceleration acquisition system (*Xie et al., 2018*), shown in Fig.1.

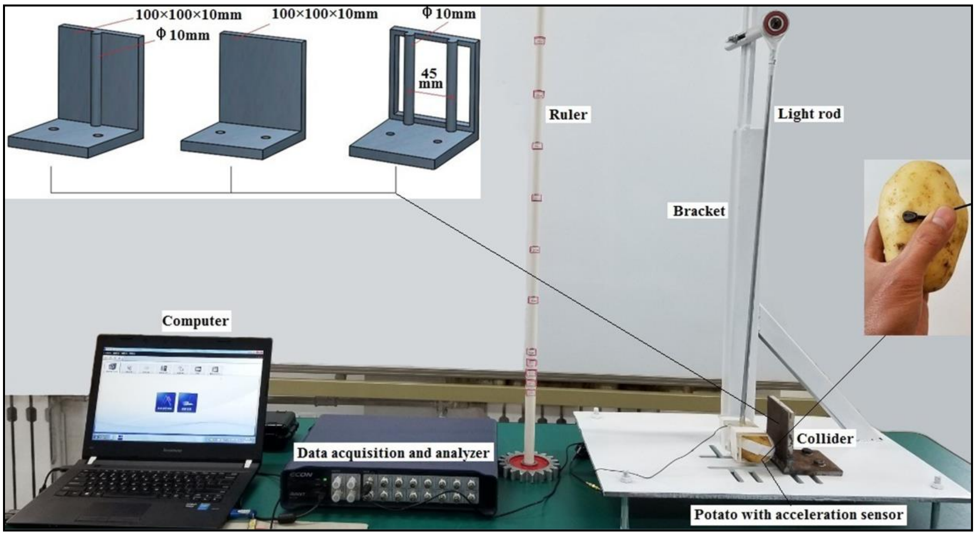

Fig. 1 - Test equipment

Both potatoes and colliders can be quickly replaced, so that the impact accelerations of potatoes under different conditions can be obtained. The acceleration acquisition system included a data acquisition and analyzer (AVANT-MI7016, Hangzhou Yiheng Technology Co., Hangzhou, China.), a 1.2 g-mass acceleration sensor with the accuracy of ±1.048 mv/m/s^2 and dimensions of 13×7.2×5.3 mm (1A803E, Jiangsu Donghua Testing Technology Co. Jiangsu, China.) and a computer.

In order to simulate the collision of potatoes during the harvesting and post-harvesting processes, three types of colliders (the single rod, the steel plate and the double rods) were analyzed. All the materials of the colliders were 65Mn steel. During the test, the acceleration sensor was fixed on the surface of the potato near the collision point with soft tape. The potato was lifted to a certain height and then released to collide with the collider. The test program was shown in Table 1. To obtain the reliable results, ten replicates were performed for each collision test.

Table 1

Program of collision tests

Test number	Drop height (mm)	Potato mass (g)	Colliders	Analysis methods
1	100	250	single rod / steel plate / double rods	experimental test / FEA
2	200			
3	300			
4	400			
5	500			
6	600			
7	300	150		
8		250		
9		350		
10		450		

- **Three dimensional solid modeling of potato**

The procedure of the three dimensional modeling of potato was shown in Fig.2.

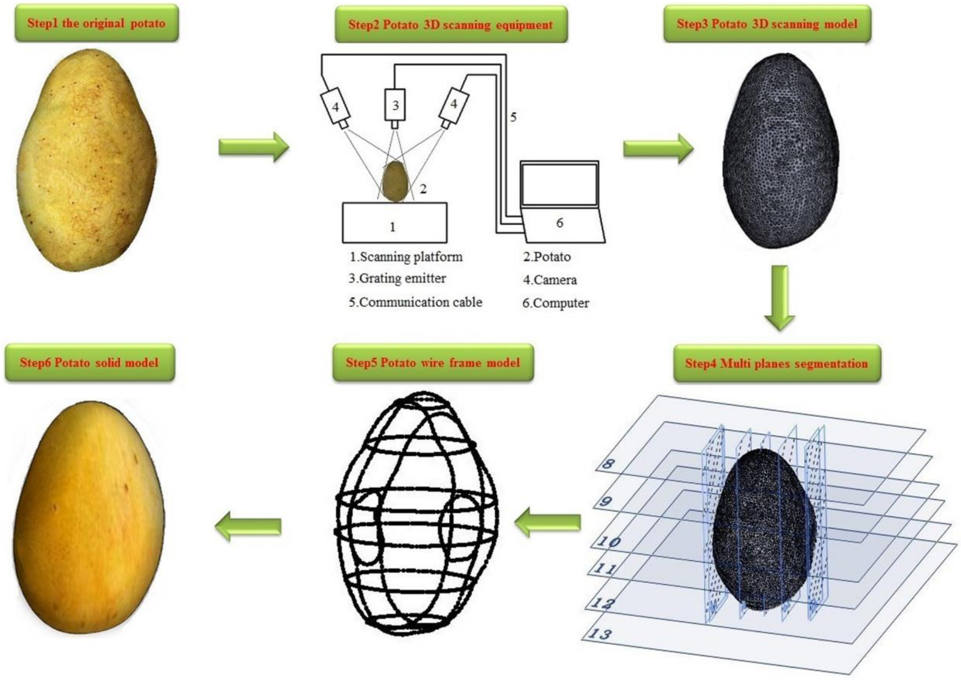

Fig. 2 - Modeling procedure of the potato three dimensional model

To obtain the irregular solid model of potato, a real ellipsoid potato with a mass of 250 g and a volume of 256 cm^3 was used (Fig.2-step1). The 3D scanning method and non-contact raster photography scanning technology were applied to obtain the 3D scanning model of the real potato (*Meng et al., 2015*) (Fig.2-step2). The 3D scanning model was a polygonal mesh model established on the basis of point cloud data (*Giammanco et al., 2017*), and the size of the polygon was related to the curvature of the model surface. To facilitate the meshing and control of the model during the FEA process, the potato 3D scanning model was imported into SolidWorks in STL format to obtain the three dimensional solid model (Fig.2-step3). The multiple parallel planes along the long axis and short axis of the ellipsoid potato were established (Fig.2-step 4). A cross curve was generated at the intersection of each plane and the model, and the potato wire frame model was constructed (Fig.2-step 5). The potato solid model was generated from the wire frame model based on the surface modeling method in SolidWorks (Fig.2-step6). The models of the three types of colliders were directly built in SolidWorks and each of the collider was formed an assembly with the potato solid model.

- **FEA procedure**

The FEA program was shown in Table 1. During the FEA process, potatoes were collided with different colliders at different velocities. The instantaneous impact contact velocity can be calculated according to Eq. (1).

$$v_0 = \sqrt{2gH} \qquad (1)$$

where v_0 is the impact contact velocity. *H* is the potato drop height and g is the standard earth gravity (9.806 m/s^2). The FEA process was carried out in ANSYS Workbench 19.2, and LS-DYNA was used as the analysis module due to its good capability of nonlinear analysis. Potato was regarded as a nonlinear body, and the material model was bilinear isotropic elastic-plastic. The modulus of elasticity of potato was 3.35MPa, the yield strength was 0.8776MPa and tangent modulus was 0 MPa (*Deng et al., 2021*). The potato Poisson's ratio was 0.49 (*Caglayan et al., 2018; Celik et al., 2019*). The materials of the colliders were 65Mn, the modulus of elasticity was 206 GPa and Poisson's ratio was 0.3. The rod diameters of the colliders were 10mm. The contact types between the potato and colliders were frictionless. During the collision process, the potato was regarded as a flexible body, and the colliders were rigid with fixed constraints. The impact contact velocity was set as the initial conditions. The FEA calculation time was 15ms, and the output was set to 60 equal interval results. After pre-processing, the K file was generated and solved by LS-DYNA solver and post processed by LS-Prepost 4.5. A Lenovo desktop computer (Intel Core i5-4460 CPU @ 3.20 GHz, NVIDIA GeForce GT 750, and RAM: 4 GB) was utilized as the solving platform. The FEA collision models and mesh parameters were shown in Fig.3.

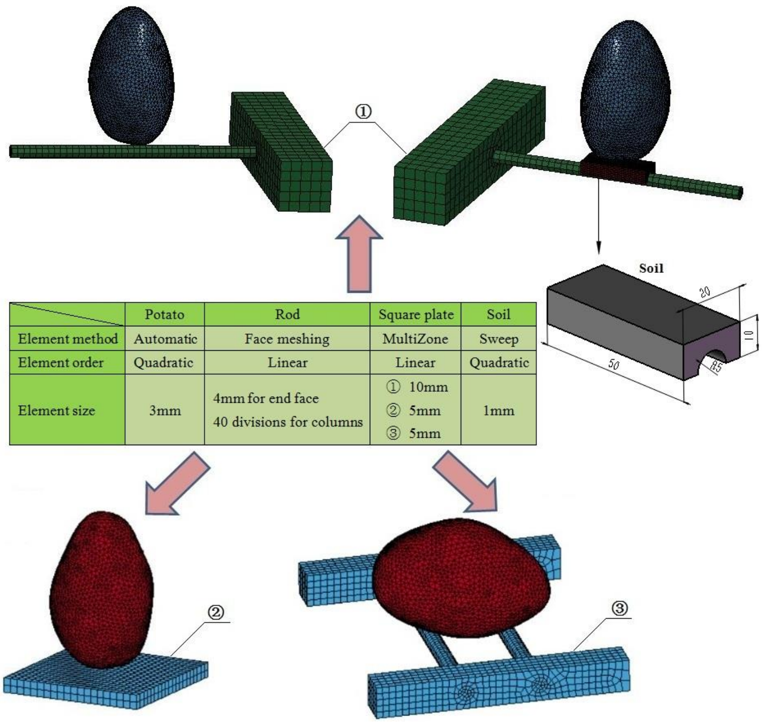

Fig. 3 - FEA collision models and mesh parameters

To analyze the effect of soil on potato impact acceleration, a rectangular soil block with a thickness of 5mm was covered on the collider of the single rod. According to the potato mass and drop heights in Table 1, the finite element analysis was carried out to compare with the collider of the single rod without the cover of soil. Due to the large deformation of soil in the collision process, the Explicit Dynamics was used as the analysis module to make the calculation process easier to converge. The soil was considered as a flexible and nonlinear body with a density of 1500 kg/m^3, modulus of elastic 1.2 MPa, Poisson's ratio of 0.3 and yield stress of 0.4 MPa (*Gao et al., 2014; Jia et al., 2011; Zhang et al., 2019*). The volume of the potato solid model was 252cm³, and the corresponding potato mass can be obtained by setting different densities. The different drop heights were simulated by setting the corresponding impact contact velocity according to the Eq.(1).

- **Potato collision kinematics analysis**

The potato collision process included a compression and a recovery stage (*Deng et al., 2020*). In the compression stage, the potato velocity gradually decreased from the initial impact contact velocity, and the acceleration gradually increased from zero. When the compressive displacement reached the maximum, the potato velocity decreased to zero and the acceleration increased to the maximum. The curves of the collision velocity and acceleration of potato were shown in Fig.4. v_0 was the initial impact contact velocity. t_m was the time of the maximum compressive displacement (Fig.4(a)), and at this time the potato impact acceleration was the maximum value a_m (Fig.4(b)).

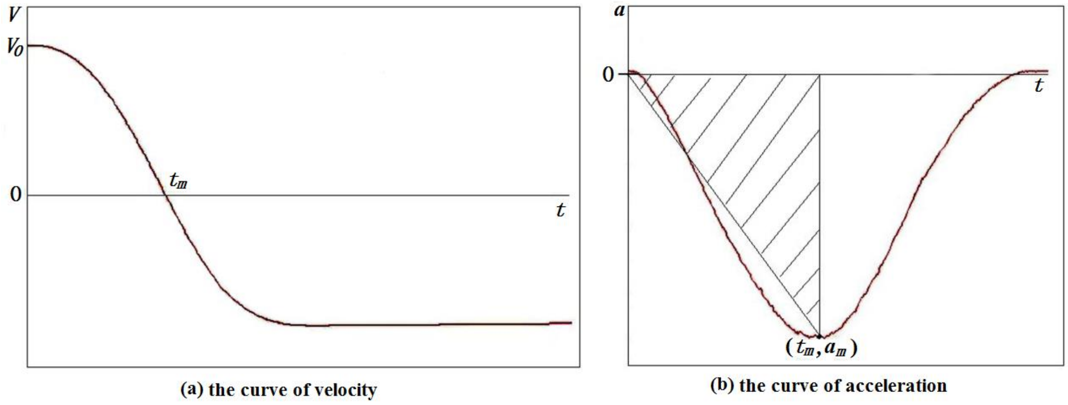

Fig. 4 - Curves of potato collision velocity and acceleration

During the compression stage, the impact velocity and acceleration of the potato satisfied the following equation.

$$\int_0^t a dt = v_0 - v_t \tag{2}$$

where: t is the impact contact time; a is the potato impact acceleration. v_0 is the initial impact contact velocity. v_t is the potato velocity at the time of t. When v_t was zero, the potato compressive displacement reached the maximum value, and the corresponding time was t_m. According to Eq. (1), Eq. (2) can be transformed into the Eq. (3).

$$\int_0^{t_m} a dt = \sqrt{2gH} \tag{3}$$

where t_m is the time of the maximum compressive displacement. H is the potato drop height and g is the standard earth gravity (9.806 m/s²). The integral value on the left side of the Eq. (3) can be approximated by the shaded area in Fig.4(b). Therefore, Eq. (4) can be obtained.

$$\frac{1}{2} a_m t_m = \sqrt{2gH} \tag{4}$$

Where a_m is the maximum collision acceleration of potato and the following equation can be obtained.

$$a_m = \frac{2\sqrt{2gH}}{t_m} \tag{5}$$

It was shown in Eq.(5) that when the potato drop height was a constant, the maximum collision acceleration was inversely proportional to the corresponding impact contact time.

RESULTS AND DISCUSSION

- **Comparison of test and FEA results**

According to the program in Table 1, both the experimental test and FEA methods were used to obtain the a_{max} of the potato colliding with the three types of colliders. Under the same condition, the discrepancy of a_{max} obtained by the two methods was calculated according to Eq. (6).

$$e = \frac{|a_{max}(FEA) - a_{max}(Test)|}{a_{max}(Test)} \times 100\% \quad (6)$$

where e is the discrepancy; $a_{max}(FEA)$ is the a_{max} obtained by the FEA method; $a_{max}(Test)$ is the a_{max} obtained by the experimental test. The values and discrepancies of a_{max} were shown in Table 2.

Table 2

Values and discrepancies of a_{max} obtained by the experimental test and FEA method

Test number	a_{max} for single rod collision			a_{max} for steel plate collision			a_{max} for double rods collision		
	Test (m/s²)	FEA (m/s²)	e (%)	Test (m/s²)	FEA (m/s²)	e (%)	Test (m/s²)	FEA (m/s²)	e (%)
1	675.1	664.05	1.64	718.74	753.89	4.89	447.04	427.96	4.27
2	979.1	1004.9	2.64	1176.52	1132.9	3.71	628.24	648.85	3.28
3	1329.99	1273.1	4.28	1462.7	1429.9	2.24	798.1	817.85	2.47
4	1610.06	1508.7	6.30	1731.62	1676.9	3.16	919.2	966.25	5.12
5	1807.99	1721.9	4.76	1951.8	1916.1	1.83	1015.38	1099.55	8.29
6	1972.5	1909	3.22	2257.16	2135.7	5.38	1149.94	1222.3	6.29
7	1469.29	1568.9	6.78	1667.5	1766.7	5.95	1083.6	1014.1	6.41
8	1329.99	1273.1	4.28	1462.7	1429.9	2.24	798.1	817.85	2.47
9	1180.5	1112.3	5.78	1340.84	1235.5	7.86	771.13	713.4	7.49
10	1152.26	999.35	13.27	1143.34	1117.3	2.28	672.82	643.75	4.32
	Average of e		5.3	Average of e		3.95	Average of e		5.04

According to the results in Table 2, the discrepancies of a_{max} between the FEA and test results were almost within 10%. When potatoes were collided with the single rod, the steel plate and the double rods, the average discrepancies of a_{max} were 5.3%, 3.95% and 5.04%, respectively. The results in Table 2 showed that it was accurate and reliable to use the FEA method to analyze the potato impact acceleration, and it also provided a verification basis for the use of FEA to study the collision issues of potatoes during the harvesting and post-harvesting processes.

The test results of the presented research for potatoes colliding with the single rod were based on the earlier research conducted by *Xie et al. (2020a, 2020b)*, which were in good agreement with the presented FEA results. When the potato was collided with the steel plate, *Cerruto et al. (2015)* reported that the a_{max} were 935 m/s² and 1437 m/s² for the drop heights of 100 mm and 200 mm with the potato mass of 250 g and modulus of elasticity of 3.5 MPa. The a_{max} showed in the presented simulation were 753.89 m/s² and 1176.52 m/s² in the same conditions of drop height, potato mass and collider. The differences could be due to the different potato shape and modulus of elasticity.

- **Effect of drop height and potato mass on impact acceleration**

According to the results in Table 2, the curves of the a_{max} of test with different drop heights were shown in Fig.5 when the potato mass was 250 g.

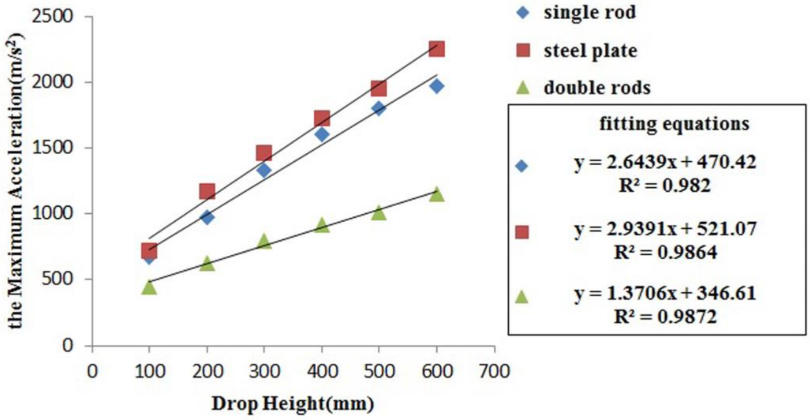

Fig. 5 - Curves of the a_{max} with the drop height

As the drop height increased, the a_{max} gradually increased. Within the range of the potato drop height in Table 1, the fluctuation amplitudes of the test a_{max} for the single rod, the steel plate and the double rods were 1297.4 m/s^2, 1538.42 m/s^2, and 702.9 m/s^2, respectively. The fitting equations showed that there were linear relationships between the drop height and the a_{max} for all the three types of colliders, and the minimum R^2 value was 0.982. When the potato mass was a constant, the higher the drop height was, the larger the collision velocity and momentum would be. The impact contact time decreased slightly with the increase of drop height (*Gao et al., 2018*). According to the impulse theorem, the collision contact force would increase due to the larger momentum and shorter impact contact time, so that the a_{max} increased with the increase of the drop height.

The curves of the a_{max} of test with different potato masses were shown in Fig.6 when the potato drop height was 300 mm. The larger the potato mass was, the smaller the a_{max} would be. Within the range of the potato mass in Table 1, the fluctuation amplitudes of the test a_{max} for the single rod, the steel plate and the double rods were 317.03 m/s^2, 524.16 m/s^2, and 410.78 m/s^2, respectively. The fitting equations showed that there were linear relationships between the potato mass and the a_{max} for all the three types of colliders, and the minimum R^2 value was 0.8481.

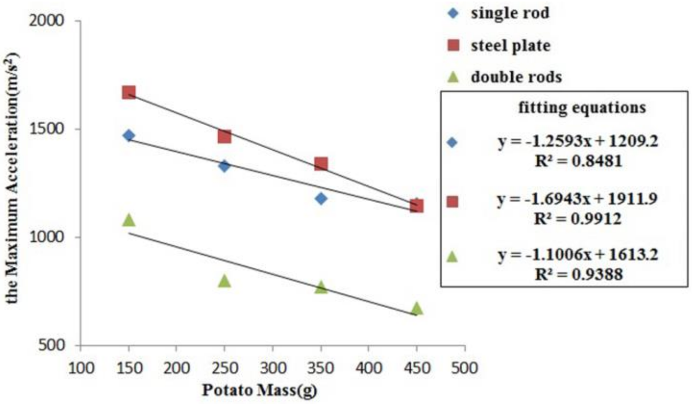

Fig. 6 - Curves of the a_{max} with the potato mass

The trends of the acceleration curves both in Fig.5 and Fig.6 were similar with the test results conducted by *Xie et al. (2020a, 2020b)* and *Geyer et al. (2009)*, and consistent with the FEA results conducted by *Cerruto et al. (2015).*

According to the FEA results, the relationship between the impact contact time corresponding to the a_{max} and the potato mass can be obtained, as shown in Fig.7. The larger the potato mass was, the longer the impact contact time for the a_{max} would be. According to the Eq.(5), when the drop height was a constant, the a_{max} was nagative to the impact contact time. Therefore, the a_{max} decreased with the increase of the potato mass in Fig.6.

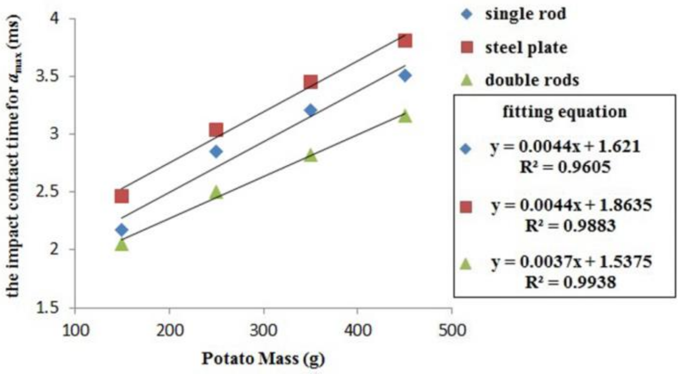

Fig. 7 - Curves of impact contact time with potato mass

Another explanation for the decreased a_{max} with the increased potato mass was that the thickness of potato tissue between the acceleration sensor and collider cushioned the increase of acceleration when the sensor was implanted into the potato (*Geyer et al., 2009; Xie et al., 2020a*).

According to the effects of potato mass and drop height on the impact acceleration of potato, selecting potato with moderate mass for breeding can reduce the impact acceleration in the process of potato harvesting. Adjusting the working parameters of the potato harvester and controlling of the relative height between the potato conveying arm and transport vehicle reasonably to reduce the drop height between the potato and the colliders can effectively reduce the potato impact acceleration, thus reducing the potato damage rate.

- **Effect of colliders on potato impact acceleration**

Based on the curves in Fig.5 and Fig.6, it can be found that the a_{max} had the same trends when potatoes were collided with the single rod, the steel plate and the double rods. Under the same conditions, the a_{max} for the potato colliding with the steel plate was the largest, and that was the smallest for the double rods. It was because of that when the potato was collided with the double rods, the contact area increased, and the collision contact force became smaller, so that the a_{max} became smaller. When the potato was collided with the single rod, the normal collision direction of the potato changed during the collision process because of the cylindrical curved surface of the rod and the irregular curved surface of the potato. Therefore, the acceleration component in the normal collision direction was reduced. When the potato was collided with the steel plate, the acceleration was mainly on the normal direction of the steel plate surface. So, the a_{max} would be greater than that of the single rod collision. Based on the test results in Table 2, when the potato mass was 250 g and the drop height was from 100 to 600mm, the a_{max} in collision with the steel plate was 60.78% to 96.29% higher than that with the double rods, and 6.46% to 20.16% higher than that with the single rod. When the drop height was 300mm and the potato mass was from 150 to 450 g, the a_{max} in collision with the steel plate was 53.89% to 83.27% higher than that with the double rods, and -0.77% to 13.58% higher than that with the single rod.

- **Effect of soil on potato impact acceleration**

The effect of soil on potato impact acceleration was shown in Fig.8. The a_{max} in collision with the single rod covered with soil increased linearly with the increase of drop height, and decreased linearly with the increase of potato mass, which had the same trend as that without the cover of soil. When 250g potato collided with the 65Mn single rod from 100 to 600 mm drop height, the a_{max} with soil was 37.65% lower than that without soil. When the drop height was 300mm and the potato mass was from 150 to 450 g, the a_{max} with soil was 31.54% lower than that without soil. The results indicated that soil can buffer the collision between potato and rod, effectively reduce the impact acceleration of potato, and thus reduce the occurrence of potato damage.

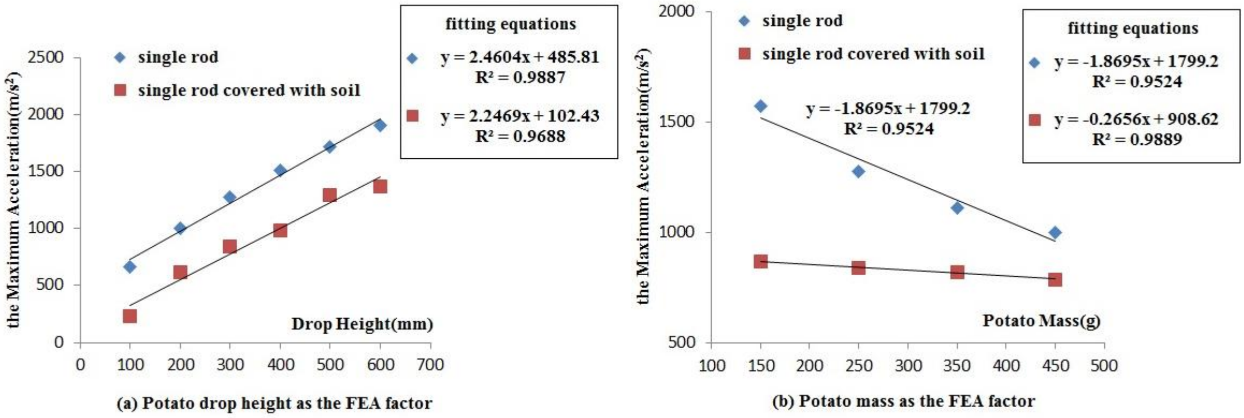

Fig. 8 - Curves of the a_{max} with or without soil

In the process of potato mechanized harvesting, the reasonable adjustment of the structural parameters of the potato-soil separation device can increase the normal acceleration of the upper separation screen appropriately, which is not only conducive to the crushing and separation of potato soil mixture, but also can reduce the occurrence of potato damage due to the buffering of soil. Because of the less soil on the lower separation screen, the normal acceleration should be reduced and the tangential acceleration should be increased. Therefore, it is beneficial to reduce the damage of potato and to make the potato move quickly to the back of the separation screen.

CONCLUSIONS

Analyzing the impact acceleration of potatoes under the impact loading is important for the research of potato impact kinematics and dynamics and can help to understand the occurrences of potato damage. In this article, both the experimental test and FEA method were used to analyze the impact acceleration of potatoes colliding with the single rod, the steel plate and the double rods. The results showed that when potatoes were collided with the single rod, the steel plate and the double rods, the average discrepancies of the a_{max} obtained by the FEA method and the experimental test were 5.3%, 3.95% and 5.04%, respectively. The trends of the a_{max} for the potato colliding with the three types of colliders were the same. And the a_{max} increased with the increase of the drop height, and decreased with the increase of the potato mass. Under the same conditions, the a_{max} decreased in turn for the potato colliding with the steel plate, the single rod and the double rods. In the range of drop height and potato mass level carried out by the FEA, the a_{max} of the collision between potato and single rod with soil condition was 37.65% and 31.54% lower than that without soil. This study had also highlighted that advanced reverse engineering, computer aided design, and simulation techniques were very useful and should be considered as important applications in the areas of agricultural and food research.

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