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The relationship between physical properties of tubers measured during pendulum impact tests and tuber fracture damage

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Zusammenfassung, Résumé p. 219

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Summary

The relationship between physical factors measured electronically by using a pendulum (energy absorbed during impact, calculated from rebound of the pendulum arm, deformation, and time of contact of the indentor head with the tuber during impact) and fracture damage (external and internal damage) was investigated in potato genotypes showing a wide range of damage susceptibility. The physical factors were highly correlated one with another and all gave good correlations with fracture damage. However, the highest correlations with damage were generally found for energy absorbed and permanent deformation which, for example, respectively explained 91 % and 93 % of the variation in external damage. A slight improvement, particularly with tubers showing the maximum score for external damage, was found when the damage was expressed as a damage rating calculated from a multiple regression of external damage + depth of damage + width of damage.

Introduction

Many methods have been used to assess the susceptibility of tubers to impact damage ranging from complete harvesters to quasi-static physical tests (see Hughes et al., 1985, for more detailed discussion). Although harvesters provide a very practical test, such a method is difficult to standardize because of differences in harvester design and operation and the influence of soil conditions which are affected by site and climate conditions (Gray & Hughes, 1978). Consequently, some workers have tried to assess, under more standard conditions, the influence of levels of abuse found in practice by using for example shaking tests and drop tests. Pendulum tests, in which tubers are firmly held during impact, are similar in principle to the latter type of test but also provide information about the physical impact properties of tubers. The Gall pendulum (Gall et al., 1967) is such an instrument. Various workers have tried to relate the physical properties of the tuber measured from the rebound height of the pendulum arm, estimated by eye, with amount of damage found in the tubers after being harvested by a complete harvester (Gall et al., 1967) or damage found in the tubers, after a drop test (Umaerus & Umaerus, 1976). Although significant correlations were found between

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physical factors and damage, they did not explain more than 64 % of the variation in damage.

This paper describes the correlations found between a range of physical factors (energy absorbed, deformation of tubers, time of contact of the indentor with the tuber and non-recoverable deformation) measured electronically during impact by a more sophisticated pendulum and the amount and type of cell wall fracture damage produced directly during the test. The objective of the work was to see whether any of these physical factors, which are instantaneously displayed as readouts, would provide a rapid and accurate test of fracture damage occurring in a wide range of material under dynamic conditions similar to those found in practice.

Experimental

Material

The pendulum was tested in the field (1981) and in the laboratory (1982). In 1981, at each of 12 farms, 20 representative tubers selected from 20–30 hand-dug roots were impacted in the field. The following samples were selected from the farms which had been identified by the Potato Marketing Board (PMB) in the 1981 PMB-ADAS (Agricultural Development and Advisory Service) Damage Awareness Campaign as producing damage-susceptible tubers: Record (4 farms), Maris Piper (6 farms), Pentland Crown (1 farm), Pentland Dell (1 farm). The temperature of the tubers was recorded.

In 1982, tubers from a variety trial at the Plant Breeding Institute (PBI), Cambridge, containing some potentially damage-susceptible seedlings (ZD 7/7, ZD5/54, ZD 122/46, ZD9/4) and control cultivars (cvs Foxton, Maris Piper, Golden Wonder and Désirée) and one very susceptible cultivar, Paragon, grown at Norwich, were tested in the laboratory after storage at 5 °C. Between 11 and 15 tubers were taken per sample for impacting depending on availability.

Methods

Impact testing

Whole tubers were impacted avoiding eyes, at the mid point on the flattest possible surface of tubers (to minimize the effect of radius of curvature of tuber) by using the Food Research Institute (FRI) Portable Pendulum (Fig. 1) which is briefly described below. Full details of its design and operation are described elsewhere (Hughes et al., 1985). The pendulum, designed and built at the FRI, consists of two main parts: (1) a pendulum with an angular displacement transducer, a sample holding system and arm release mechanism, and (2) a box containing the battery-powered electronics including control and display units, connected by cable to the angular displacement transducer.

The angular displacement transducer attached to one end of the spindle is used to determine the deformation of the sample during impact (d_1), permanent deformation (non-recoverable deformation, d_2) and rebound height of the arm after impact (used to calculate energy absorbed (E_{ab}) by the tuber during impact). These data are displayed by a single digital readout and selector switch. The duration of sample penetration by the indentor (t_1) and the time taken for the indentor to return to the point of initial contact

Fig. 1. Food Research Institute Portable Pendulum.

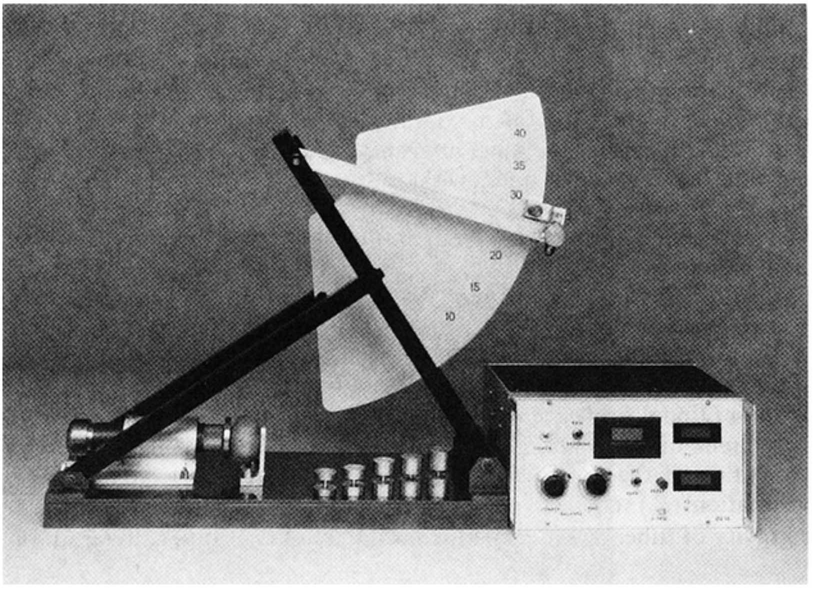


Abb. 1. Tragbares Pendel des Food Research Institute.
Fig. 1. Système pendulaire portable du Food Research Institute.

(t_2) with the tuber are shown on individual displays. The pendulum arm, whose height can be adjusted, is dropped from 30 cm, has an additional weight of 150 g and an indentor with a radius of curvature of 6.35 mm. The kinetic energy of the indentor at impact is 0.732 J and the velocity 2.602 m/s. These conditions are similar to those encountered by a 216-g tuber dropping from a height of 35 cm onto rod webs. They were chosen to produce fracture damage as opposed to black spot, which under pendulum tests occurs at lower energies and drop heights. During impact, tubers are held under a 5-kg load, by using a calibrated spring in the holding device, to prevent movement of whole tubers which could lead to errors in assessing the relationship between loss of energy on impact and dynamic tissue failure. The pendulum arm is caught by hand on its downward return to prevent a second impact.

The above physical factors were also used to calculate other impact properties, force and dynamic hardness, which have been suggested to be important in the behaviour of biological material under physical stress (Finney & Massie, 1975; Fluck & Ahmed, 1972).

Calculation of physical factors
Energy absorbed by tubers during impact (E_{ab}) is calculated from the impact kinetic energy, drop height and rebound height of the arm. Deformation of the tuber (d_1) is the distance from initial point of contact of the indentor with the tuber to the point of maximum deformation.

Permanent deformation (d_2) is the distance from the initial point of contact of the indentor with the tuber to the point of maximum deformation obtained by gently holding the pendulum arm against the tuber after impact.

The time from initial contact of pendulum with the tuber to maximum deformation is t_1.

The time taken for the indentor to return from the point of maximum deformation to the point of initial contact is t_2.

Force *(F)* is calculated as the average force:

F = effective mass of the pendulum × average deceleration of the indentor on impact.

Average deceleration of the indentor ($2d_1/t_1^2$) is calculated from the maximum deformation of the sample (d_1) and the time t_1.

Dynamic hardness (Jindal & Mohsenin, 1978) is expressed as the ratio of the energy absorbed to the volume of indentation. Volume of indentation is calculated (a) from maximum deformation of the tuber (d_1) to give dynamic hardness 1, and (b) from 'permanent deformation' (d_2) to give dynamic hardness 2.

The specific gravity of tubers is calculated from the weights of tubers in air and in water.

Damage estimation
Impacted tubers were stored at 20 °C, 60 % r.h. for 14 to 19 days prior to damage estimation.

External damage was measured on a 0 to 4 scale:
0 – no external damage,
1 – slight skin breakage (Fig. 2a),
2 – skin breakage and slight crushing (Fig. 2b),
3 – crushing and slight splitting, (<5 mm splits) (Fig. 2c),
4 – severe crushing and splitting (>5 mm splits) (Fig. 2d).

Samples damaged externally by the spherical indentor usually showed a circular pattern of damage except for splits where fissures radiated out from the circle of crushed tissue.

Internal damage was measured on tubers which were sliced transversely through the centre of the externally damaged zone, taking care not to cut along any splits. The width and depth of the damaged zone and its position relative to the skin was measured and the type of damage noted.

Internal damage occurred as one or a mixture of the following types of damage, which are similar to those described by Umaerus & Umaerus (1976):
– crushing: a discrete zone of damage, often seen as a light coloured area ringed by a distinct border of darker colour (Fig. 3a),
– cracking or internal fissures: small cracks usually radiating from the skin (Fig. 3b),
– black spot: a blue-black zone of diffuse damage, often situated at a distance below the skin (Fig. 3c) was not found in this material because of the high kinetic energy and

Fig. 2. External damage score 1 to 4 (a to d).

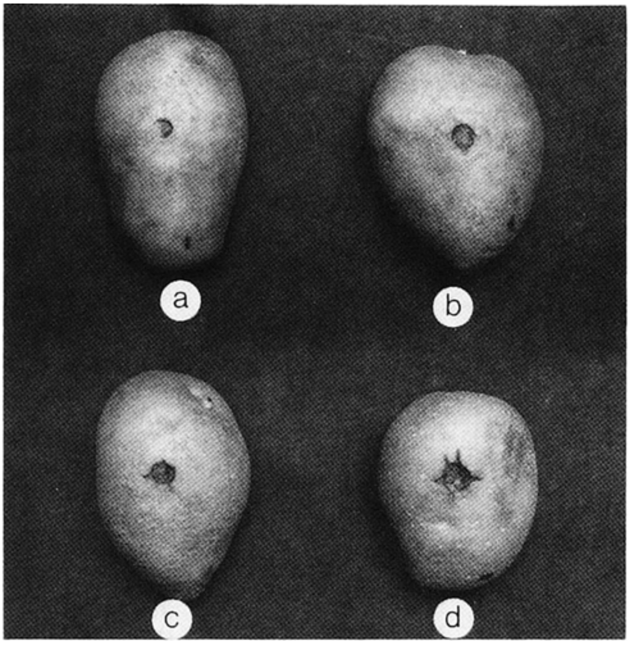


Abb. 2. Äusserlicher Schadens-Bewertungsrahmen von 1 bis 4 (a bis d).
Fig. 2. Note d'endommagement externe de 1 à 4 (a à d).

velocity chosen.

There is an important difference between black spot and the other types of damage. Whilst crushing and cracking are due to massive cell wall breakage, there is no such massive breakage with black spot. Indeed for black spot to occur only rupture of the cell membranes may be necessary.

Statistics

The statistical relationships between various factors were investigated by using the method of least squares for the production of regression lines, correlation coefficients *(r)* and coefficients of determination (r^2) which state the proportion of the variation explained by the regression lines.

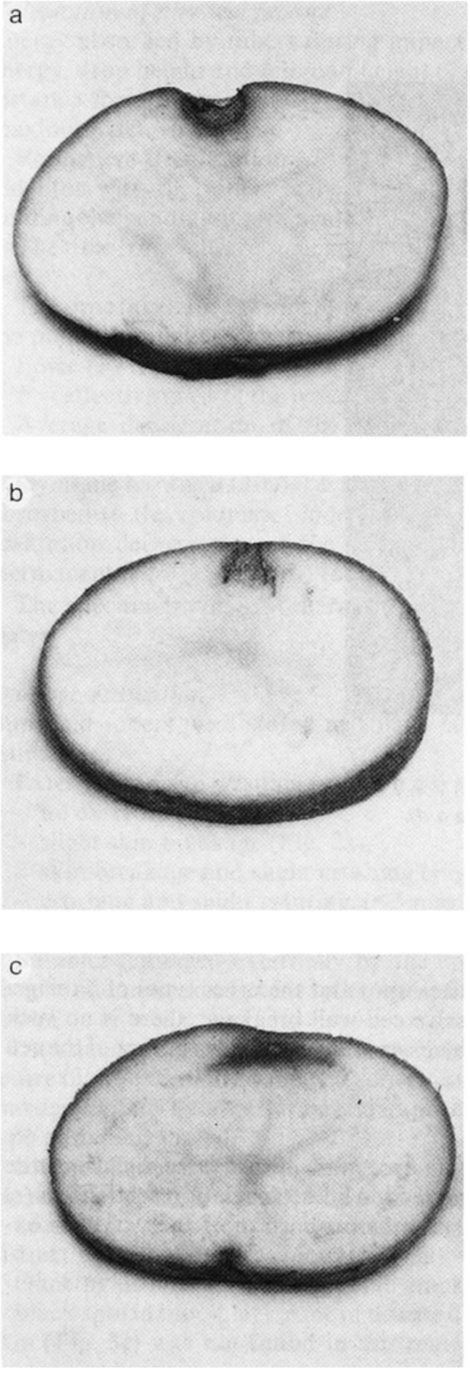


Fig. 3. Various types of internal damage.

a. Internal crushing – *innerliche Quetschung – écrasement interne*
b. Internal cracks – *innerliche Risse – éclatement interne*
c. Blackspot – *Schwarzfleckigkeit – noircissement interne*

Abb. 3. Verschiedene Typen innerer Beschädigung.
Fig. 3. Différents types d'endommagement interne.

Results

Damage

Damage ranged from severe external damage and deep internal cracks (sample 1) to material showing only slight surface damage and slight internal crushing (sample 21) (Table 1, Figs 4, 5 and 6). Most tubers showed some form of external damage (Table 1) with the least being found in Record, a cultivar known to have low susceptibility to external damage (Anon., 1974). Although all the tubers showed internal damage, its form and extent varied considerably between samples and the form appeared to be associated with the severity of external damage (Table 1 and Fig. 4). For example, in this range of cultivars and seedlings, material showing the least external damage tended to have

Table 1. Percentage tubers showing particular types of damage and tuber temperature at impact (ranked according to energy absorbed during impact; see Fig. 4).

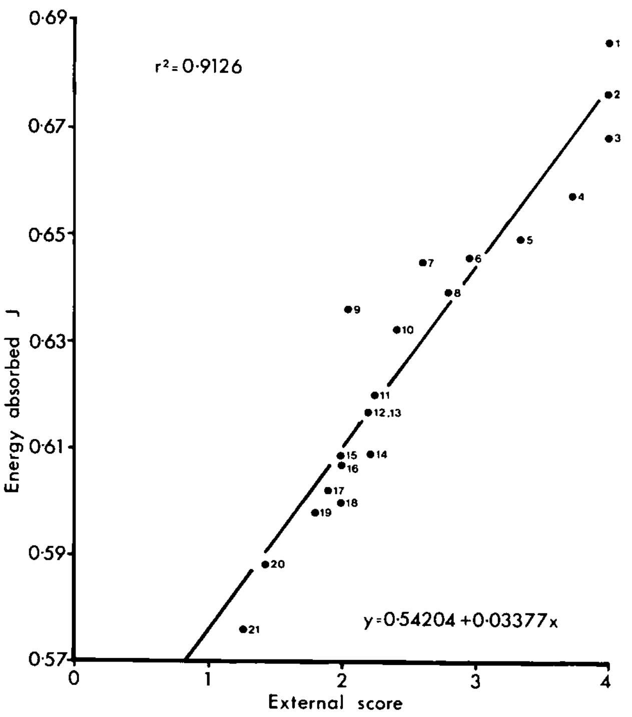
Cultivar[1]	Damage (%)[2]			Tuber temperature[6]
	external damage[3]	internal crushing[4]	internal cracking[5]	
1 ZD7/7 (L)	100	0	100	5.0
2 Paragon (L)	100	0	100	5.0
3 ZD5/54 (L)	100	0	100	5.0
4 ZD122/46 (L)	100	7	93	5.0
5 ZD9/4 (L)	100	0	100	5.0
6 Maris Piper (F)	100	5	95	8.0
7 Maris Piper (F)	100	0	100	7.5
8 Maris Piper (F)	100	10	90	8.2
9 Pentland Crown (F)	95	5	95	7.5
10 Pentland Dell (F)	100	15	85	5.0
11 Maris Piper (F)	100	0	100	11.6
12 Maris Piper (F)	100	5	95	9.5
13 Maris Piper (F)	100	0	100	6.0
14 Record (F)	95	43	57	14.4
15 Record (F)	95	20	80	6.0
16 Foxton (L)	100	57	43	5.0
17 Désirée (L)	100	45	55	5.0
18 Maris Piper (L)	100	57	43	5.0
19 Golden Wonder (L)	100	33	67	5.0
20 Record (F)	95	60	40	12.7
21 Record (F)	90	95	5	15.0

[1] *Sorte - Variété;* [2] *Schaden (%) - Endommagement (%);* [3] *Äusserer Schaden - Endommagement externe;* [4] *Innere Quetschung - Écrasement interne;* [5] *Inneres Reissen (Scheren) - Éclatement interne;* [6] *Knollentemperatur - Température du tubercule*

Tabelle 1. Knollen mit bestimmten Arten von Schaden und Knollentemperatur beim Aufschlag (Rangfolge entsprechend absorbierter Energie während des Aufschlages; siehe Abb. 4).
Tableau 1. Types d'endommagement en % de tubercules atteints et température des tubercules au moment de l'impact (classement réalisé par rapport à l'énergie absorbée durant l'impact; voir fig. 4).

damage of the internal crushing type (samples 20 and 21). However, as the extent of external damage increased, the crushing type of damage was generally replaced by a mixture of crushed and cracked tissue and finally cracking alone (samples 1, 2 and 3). As the severity of external damage increased, the depth of damage also tended to increase, particularly at the highest severity of external damage where internal damage occurred as fissures as opposed to crushed zones (Table 1, Figs 4, 5 and 6). In all cases, the internal damage was situated immediately below the impacted zone. External score, width and depth were poorly correlated one with another in individual tubers but were better correlated on a mean basis.

Fig. 4. Relationship between energy absorbed and external score (means).

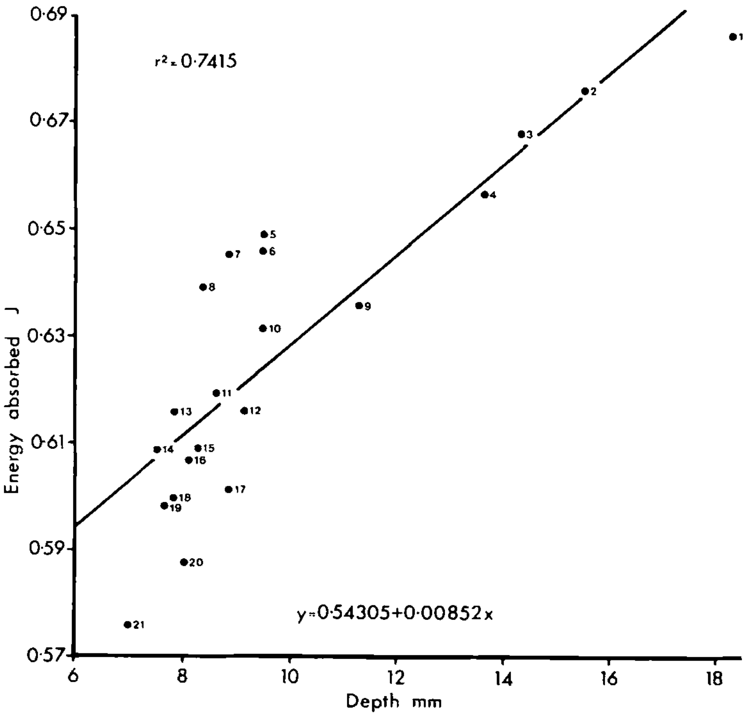


Energy absorbed (J) - *Absorbierte Energie* - *Énergie absorbée;* External score - *Äusserliche Bewertung* - *Note externe*

Abb. 4. Beziehung zwischen absorbierter Energie und äusserliche Bewertung (Mittelwerte).
Fig. 4. Relation entre énergie absorbée et note externe (moyenne).

Physical factors
A wide range of readings was obtained in these samples for all the physical factors – energy absorbed, d_1, t_1, t_2, $t_1 + t_2$ and d_2. The range of energy absorbed can be seen in Fig. 4. These factors are inter-related and highly correlated for individuals and means (Tables 2 and 3) since – with the exception of d_2 which measures directly the amount of non-recoverable deformation – they reflect in one way or another energy absorbed during impact:
– d_1 (depth of deformation during impact) will be influenced by the firmness of the tuber and the structural damage, both of which will influence the energy absorbed;

Fig. 5. Relationship between energy absorbed and depth of damage (means).

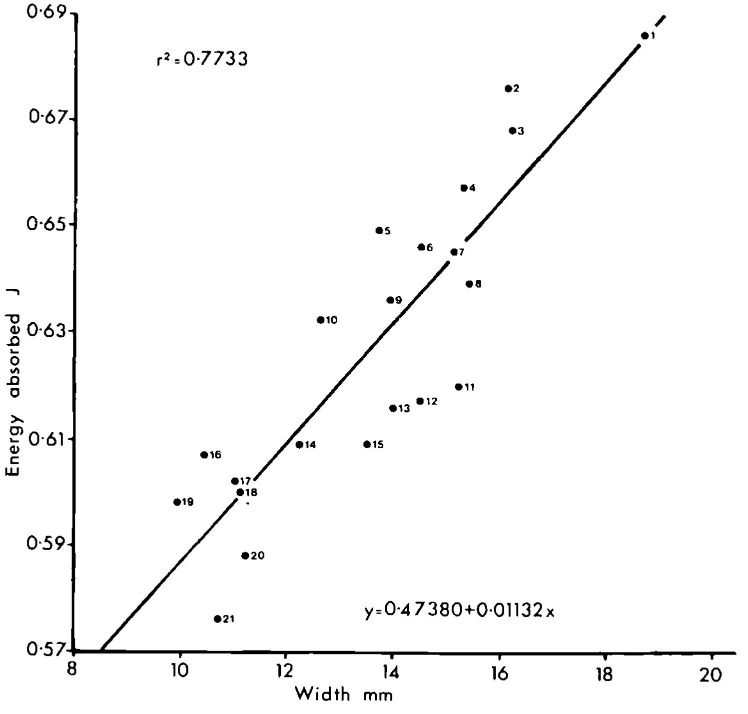


Energy absorbed (J) – *Absorbierte Energie – Énergie absorbée;* Depth (mm) – *Tiefe – Profondeur*

Abb. 5. Beziehung zwischen absorbierter Energie und Tiefe der Beschädigung (Mittelwerte).
Fig. 5. Relation entre énergie absorbée et profondeur de la zone endommagée (moyenne).

- t_1, as a measure of the time of contact of the indentor with the tuber during deformation, will be related to d_1 and thus to energy absorbed;
- t_2, as a measure of the time taken for the indentor to leave the tuber, will be influenced by the residual elastic properties of the tuber and will be related to damage occurring and thus to energy absorbed;
- $t_1 + t_2$ will be highly correlated with t_1 and t_2 and, as a measure of the total time of contact with the tuber, will reflect the damage occurring and the energy absorbed;
- d_2 is a measure of immediate non-recoverable deformation and will be influenced by the total structural damage that has occurred during impact; it gives the best correlation with energy absorbed and is, not surprisingly, highly correlated with the other physical factors.

Fig. 6. Relationship between energy absorbed and width of internal damage (means).



Energy absorbed (J) – *Absorbierte Energie* – *Énergie absorbée;* Width (mm) – *Seitliche Ausdehnung – Largeur*

Abb. 6. Beziehung zwischen absorbierter Energie und seitliche Ausdehnung der Beschädigung (Mittelwerte).
Fig. 6. Relation entre énergie absorbée et largeur de la zone endommagée (moyenne).

Table 2. Correlation matrix of individual tubers.

	E_{ab}	d_1	d_2	t_1	t_2	$t_1 + t_2$	external score	width	depth	tuber weight	s.g.
E_{ab}	1.0										
d_1	0.7664	1.0									
d_2	0.8996	0.8844	1.0								
t_1	0.8022	0.9063	0.8670	1.0							
t_2	0.8425	0.8183	0.8811	0.7889	1.0						
$t_1 + t_2$	0.8646	0.8670	0.9102	0.8630	0.9913	1.0					
external score[1]	0.8453	0.7279	0.8339	0.7564	0.7189	0.7532	1.0				
width[2]	0.6990	0.5929	0.6996	0.6601	0.6455	0.6722	0.6146	1.0			
depth[3]	0.5647	0.6061	0.6062	0.5559	0.6387	0.6443	0.4883	0.5020	1.0		
tuber weight[4]	-0.0259 n.s.	-0.2500*	-0.1930 n.s.	-0.1925 n.s.	0.1672 n.s.	0.1787 n.s.	0.1048 n.s.	-0.0031 n.s.	0.0536 n.s.	1.0	
s.g.[5]	-0.5208	-0.6086	-0.5901	-0.5531	0.5654	0.5834	0.4932	-0.2896**	-0.3710	-0.1024 n.s.	1.0

Unless otherwise stated $P < 0.001$ - *Wenn nicht anders angegeben $P < 0.001$ - $P < 0.001$ sauf indication contraire;* **$0.001 < P < 0.01$; *$0.01 < P < 0.05$; n.s. not significant - *nicht signifikant - non-significatif.*

E_{ab} - energy absorbed - *Absorbierte Energie - Énergie absorbée;* d_1 - maximum deformation - *Maximale Deformation - Déformation maximum;* d_2 - permanent deformation - *Permanente Deformation - Déformation permanente;* t_1 - time of initial contact of pendulum with tuber - *Zeit des initialen Kontaktes des Pendels mit der Knolle - Temps de contact initial du pendule avec le tubercule;* t_2 - time taken for the indentor to return from the point of maximum deformation to initial point of contact - *Zeit der Rückkehr des Schlagbolzens vom Punkt der maximalen Deformation zum initialen Kontaktpunkt - Temps pris par l'outil pour retourner du point de déformation maximum au point de contact initial.*

[1] *Äusserliche Bewertung - Note externe;* [2] *Breite (seitliche Ausdehnung) - Largeur;* [3] *Tiefe - Profondeur;* [4] *Knollengewicht - Poids du tubercule;* [5] *Spezifisches Gewicht - Poids spécifique*

Tabelle 2. Korrelationsmatrix bestimmter Knollen.
Tableau 2. Matrice de corrélation effectuée à partir des mesures sur chaque tubercule.

Table 3. Correlation matrix of sample means.

	E_{ab}	d_1	d_2	t_1	t_2	$t_1 + t_2$	external score	width	depth	tuber weight	s.g.
E_{ab}	1.0										
d_1	0.8708	1.0									
d_2	0.9529	0.9514	1.0								
t_1	0.8971	0.9705	0.9493	1.0							
t_2	0.9284	0.9609	0.9737	0.9311	1.0						
$t_1 + t_2$	0.9324	0.9736	0.9797	0.9554	0.9973	1.0					
external score[1]	0.9553	0.8975	0.9657	0.9636	0.9379	0.9415	1.0				
width[2]	0.8794	0.8113	0.8795	0.8717	0.8322	0.8494	0.8153	1.0			
depth[3]	0.8611	0.8857	0.9072	0.8414	0.9584	0.9456	0.8488	0.7640	1.00		
tuber weight[4]	-0.2752 n.s.	-0.4625*	-0.4523*	-0.4334*	-0.4330*	-0.4379*	-0.4078 n.s.	-0.3435 n.s.	-0.3473 n.s.	1.0	
s.g.[5]	-0.7258	-0.7880	-0.7756	-0.7886	-0.7495	-0.7657	-0.8095	-0.5791**	-0.6613	-0.2154 n.s.	1.0

Significance, E_{ab}, d_1, d_2, t_1, t_2, [1] [5] *Siehe Tabelle 2 - Voir tableau 2*

Tabelle 3. Korrelationsmatrix für die Mittelwerte der Proben.
Tableau 3. Matrice de corrélation effectuée à partir des moyennes des échantillons.

Relationship between damage and physical factors
Because of the inter-relationships between these various physical factors, good correlations were found between them and external damage. These correlations were not as good with width or depth of damage alone (Tables 2 and 3).

The physical factors giving the highest correlation with damage were d_2 and energy absorbed. Both these factors will be influenced by the total amount of damage produced during impact and the correlations are slightly improved when multiple correlations are

Table 4. Multiple correlations of damage against physical factors measured during impact of individual tubers.

	External score + depth[1]	External score + width[2]	External score + depth + width (damage rating)[3]	Depth + width
E_{ab}	0.8630	0.8753	0.8825	0.7414
d_1	0.7825	0.7509	0.7895	0.6919
d_2	0.8645	0.8670	0.8827	0.7592
t_1	0.7860	0.7958	0.8094	0.7093
t_2	0.7909	0.7639	0.8087	0.7410
$t_1 + t_2$	0.8171	0.7986	0.8368	0.7601

$P < 0.001$ in all cases - *in allen Fällen - dans tous les cas*

[1] *Äussere Bewertung + Tiefe - Note externe + profondeur;* [2] *Seitliche Ausdehnung - Largeur;* [3] *Schadensbewertung - Taux d'endommagement*

Tabelle 4. Multiple Korrelation von Beschädigung gegen physikalische Faktoren, während des Aufschlages auf einzelne Knollen gemessen.
Tableau 4. Corrélations multiples entre les endommagements et les facteurs physiques au cours de l'impact calculées à partir des mesures sur chaque tubercule.

Table 5. Multiple correlation of means of damage against physical factors measured during impact.

	External score + depth[1]	External score + width[2]	External score + depth + width (damage rating)[3]	Depth + width
E_{ab}	0.9600	0.9710	0.9726	0.9270
d_1	0.9276	0.9080	0.9315	0.9100
d_2	0.9798	0.9787	0.9876	0.9521
t_1	0.9145	0.9332	0.9374	0.9131
t_2	0.9868	0.9451	0.9879	0.9708
$t_1 + t_2$	0.9814	0.9520	0.9845	0.9658

$P < 0.001$ in all cases - *in allen Fällen - dans tous les cas*

[1] [3] *Siehe Tabelle 4 - Voir tableau 4.*

Tabelle 5. Multiple Korrelation der Mittelwerte der Beschädigung gegen physikalische Faktoren, während des Aufschlages gemessen.
Tableau 5. Corrélations multiples entre les moyennes des endommagements et les facteurs physiques mesurés au cours de l'impact.

calculated incorporating depth or width or both depth and width with external score (Tables 4 and 5). Improvements in correlations are also found when multiple regressions are calculated for the relationship between other physical factors and damage (Tables 4 and 5).

None of the impact properties - force, dynamic hardness - derived from the physical factors obtained during impact, gave as good a correlation with damage (Tables 6 and 7) as did energy absorbed or d_2 (Tables 2, 3, 4 and 5).

Temperature influences damage susceptibility (Gray & Hughes, 1978) and consequently tuber temperature should be standardized in variety assessment trials. However, temperature does not have a direct effect on energy absorbed in the pendulum test since the relationship between damage and energy absorbed was not improved when temperature was included in the multiple regression.

Table 6. Correlations and multiple correlations of physical factors calculated from impact properties of means.

	External score[1]	Depth[1]	Width[2]	External score + depth + width (damage rating)[3]
Force[4]	-0.7508	-0.6267	-0.8167	0.8365
Dynamic hardness[5] 1	-0.8156	-0.7645	-0.7458	0.8343
Dynamic hardness 2	-0.8101	-0.6188	-0.8354	0.8890

$P < 0.001$ in all cases - *in allen Fällen - dans tous les cas*

[1] [3] *Siehe Tabelle 4 - Voir tableau 4;* [4] *Stärke (Kraft) - Force;* [5] *Dynamische Festigkeit - Dureté dynamique*

Tabelle 6. Korrelationen und multiple Korrelationen physikalischer Faktoren, von Schlageigenschaften aus Mittelwerten berechnet.
Tableau 6. Corrélations et corrélations multiples entre les facteurs physiques, calculées à partir des moyennes des caractéristiques d'impact.

Table 7. Correlations and multiple correlations of physical factors calculated from impact properties of individual tubers.

	External score[1]	Depth[1]	Width[2]	External score + depth + width (damage rating)[3]
Force[4]	-0.6153	-0.3636	-0.5703	0.6618
Dynamic hardness[5] 1	-0.6049	-0.4656	-0.4818	0.6414
Dynamic hardness 2	-0.6321	-0.3581	-0.5988	0.6864

$P < 0.001$ in all cases - *in allen Fällen - dans tous les cas*

[1] [3] *Siehe Tabelle 4 - Voir tableau 4;* [5,6] *Siehe Tabelle 6 - Voir tableau 6*

Tabelle 7. Korrelationen und multiple Korrelationen physikalischer Faktoren, von Schlageigenschaften bestimmter Knollen berechnet.
Tableau 7. Corrélations et corrélations multiples entre les facteurs physiques, calculées à partir des caractéristiques d'impact pour chaque tubercule.

Discussion

These experiments show that both the energy absorbed during impact and d_2 predict, with a high degree of accuracy, the total amount of fracture damage produced during impact. These two factors also give a better prediction of the total amount of damage than other impact factors such as force and dynamic hardness, which have been used by other workers in assessing the mechanical properties of agricultural commodities with varying degrees of success (Nelson & Mohsenin, 1968; Mohsenin, 1970; Fluck & Ahmed, 1972; Jindal & Mohsenin, 1978).

The poorer correlations found between force and damage than between energy absorbed and damage may be because we calculated force from average decelerations and not from peak values measured by an accelerometer (as did Nelson & Mohsenin (1968)). Furthermore the relationship between force and damage and between dynamic hardness and damage may have been influenced by the different types of damage produced, i.e. crushing compared to cracking.

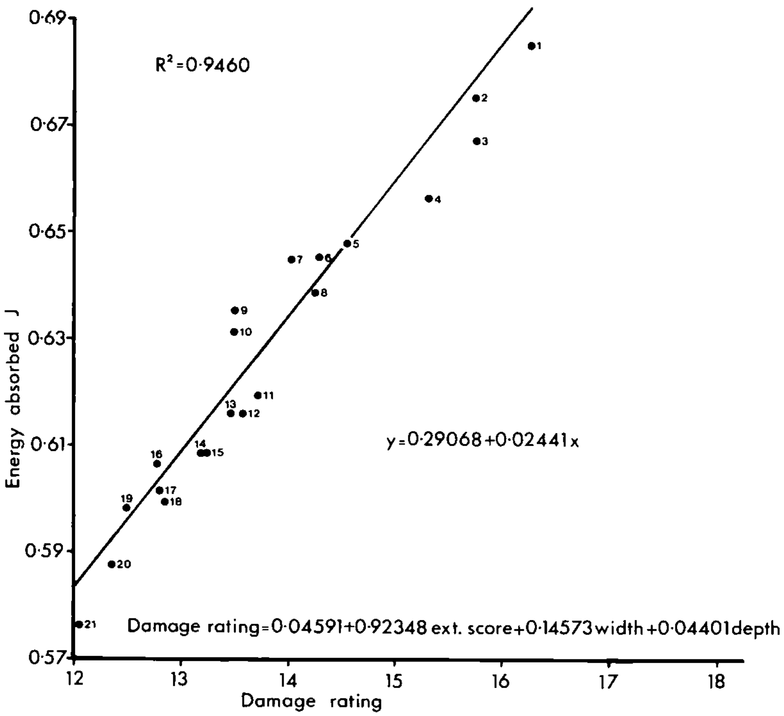
d_2 correlates well with total cell wall fracture possibly because it is a measure of non-recoverable deformation which itself is a measure of total cell wall fracture under the point of the indentor. Nonetheless, d_2 has a subjective element in its measurement since the pendulum arm after impact is held gently by hand against the tuber. However, energy absorbed, which gives nearly as good correlations as d_2, is possibly a better physical measurement for predicting the damage produced under an impact test because, firstly, it does not have a subjective element and, secondly, it can be obtained instantaneously from the readout. Energy will be absorbed by tubers as they deform and as external and internal structural damage occurs. Thus excellent correlations are found between this factor and structural damage. External score alone explains 91 % and 72 % of the variation respectively for means and individuals. Although internal damage - as depth, width, or depth plus width - does not give as good a correlation as external score, consideration of these internal measurements can improve the plotted data. For example, if samples 1, 2 and 3 are examined (Fig. 4) it can be seen that these are clustered since they have the maximum score possible (4). However, when internal dimensions were used in multiple regressions by using external score plus width and depth (damage rating), these 3 samples separated out well (Fig. 7) and the correlation was slightly improved (95 % vs. 91 %) perhaps partly because the maximum score for external damage is 4 and that with hindsight this scale should have been extended.

Dry matter or specific gravity has sometimes been shown to be correlated with resistance to fracture-type damage (Umaerus & Umaerus, 1976) possibly because of increased tuber density influencing energy absorbed during impact, the sandbag effect (Schoorl & Holt, 1983). However, these results show that the correlation within individual tubers and fracture damage (as external score) is poor, explaining less than 24 % of the variation (Table 2), which may suggest that the relationship found for mean values which explains nearly 66 % of the variation (Table 3) is largely indirect and not causal.

Although bigger tubers, because of their increased kinetic energy when dropped, may damage more than small tubers during harvesting, these results show that tuber size does not influence their intrinsic susceptibility to fracture damage, at least within the size range chosen for this experiment.

Other workers have also used pendulums for predicting susceptibility to mechanical

Fig. 7. Relationship between energy absorbed and damage rating (means).



Energy absorbed (J) - *Absorbierte Energie - Énergie absorbée;* Damage rating - *Schadensbewertung - Taux d'endommagement*

Abb. 7. Beziehung zwischen absorbierter Energie und Schadensbewertung.
Fig. 7. Relation entre énergie absorbée et taux d'endommagement.

damage of potatoes. For example, the Gall pendulum has been used to predict mechanical damage of cultivars by using complete harvesters (Gall et al., 1967) and in the screening of varieties damaged in drop tests (Umaerus & Umaerus, 1976). These tests are involved with correlating damage produced under particular conditions with physical measurements obtained under another set of conditions (pendulum). The relatively poor although significant correlations found by these workers, which at best explain only 64 % of the variation, may be due to the above factor or to inherent difficulties in measuring damage or to deficiences in either the pendulum or measurement of rebound height of the arm which is estimated by eye. In both instances, the pendulum data are related to energy absorbed by the tuber during impact (rebound of pendulum arm) and the test is described as a dynamic hardness test (Umaerus & Umaerus, 1976). However, it is not entirely clear, for example, whether dynamic firmness or dynamic tissue strength is being measured, since no detailed information is given on the amount and type of damage produced by the pendulum during the various impact tests.

In the work described here, the correlation is between energy absorbed by the tuber during impact and the amount of cell wall fracture in the same tuber under test. Under the conditions operating in this experiment, which reproduce some of the conditions found in practice (equivalent to 216 g tuber falling 35 cm onto a rod web), the samples of different susceptibility were widely separated and the types of damage found in practice were reproduced, ranging from samples showing little skin damage with some internal crushing (Record) to samples showing considerable external and internal cracking (e.g. Pentland Crown and Paragon). The types of damage produced by the pendulum are similar to those found in the SMAK classification (Umaerus & Umaerus, 1976) for field damage.

The FRI Portable Pendulum provides a highly accurate and instantaneous prediction (on the basis of energy absorbed) of the dynamic tissue strength of potatoes (i.e. their susceptibility to cell wall fracture) under a given set of impact conditions. The readouts can also be connected to a computer to present and store the information automatically. If used with the appropriate control cultivars, it would be possible to use this equipment in breeding programmes rapidly to screen out seedlings which are more susceptible to fracture damage than currently acceptable cultivars. The need to screen for damage susceptibility may increase as the genetic base to breeding programmes is widened using parental material whose characteristics – certainly with respect to quality – are unknown. This test may be compared roughly to the bolt test which is used for screening but where damage has to be measured.

The portable pendulum may also have a use in field trials in assessing the effect of husbandry factors on the susceptibility of potatoes to fracture damage. Up to the present, damage assessment has often been carried out on tubers off harvesters which has its disadvantages, as has already been discussed.

The pendulum may furthermore have a use in assessing, prior to harvest, the susceptibility of a crop to damage and thus possibly permitting the optimum time to be selected to minimize losses due to damage.

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Zusammenfassung

Beziehung zwischen physikalischen Merkmalen von Knollen, gemessen bei Pendelschlag-Versuchen und Bruchschädigung der Knollen

Physikalische Eigenschaften von Knollen (absorbierte Energie – berechnet aus der Schlaghöhe des Pendelarms – als Deformation und Kontaktzeit des Bolzens mit der Knolle) wur-

den während des Schlages elektronisch mittels tragbaren FRI-Pendels mit Winkelverschiebungsvorrichtung in seiner Spindel (Abb. 1) gemessen. Das Ziel war herauszufinden, ob Messung irgendeines der physikalischen Faktoren (welche sich unmittelbar darstellen liessen) akkurate Schätzungen der Höhe an Bruchschaden in Knollen als Folge des Schlags unter gleichen physikalischen Bedingungen wie denjenigen bei der Ernte erlauben.

Eine Reihe von Proben (Tabelle 1), die sich beträchtlich in ihrer Anfälligkeit gegen Bruchschaden unterschieden, wurden mittels statischer Kraft von 5 kg (zur Verhinderung der Knollenbewegung) festgehalten und mittels Pendelarm mit Schlagbolzen und einem Halbmesser der Krümmung von 6,35 mm, einer kinetischen Energie von 0,732 J und einer Geschwindigkeit von 2,602 m/s beschädigt. Diese Beschädigungen sind einer Knolle von 216 g äquivalent, die 35 cm fällt. 14–19 Tage lang bei 20 °C gelagerte Knollen wurden an der Schlagstelle untersucht und die äusserliche Beschädigung in einer 0 bis 4-Skala unterteilt (Abb. 2); ferner wurde die innere Breite und Tiefe der Beschädigung gemessen.

In diesem Material ergab sich eine sehr breite Spanne bei der Schadenshöhe (Tabelle 1; Abb. 3, 4, 5 und 6), ähnlich dem Typ von Bruchschaden unter Freilandbedingungen (Quetschungen, Risse und Bruch). Eine breite Spanne von Auslegungen (Abb. 4) fand sich für die physikalischen Faktoren, welche zueinander in Wechselwirkung standen und miteinander hoch korreliert waren (Tabellen 2 und 3). Höchste Korrelationen zwischen physikalischen Faktoren und Schädigung wurden generell zwischen Beschädigung und jeglicher Art von absorbierter (Tabellen 2 und 3; Abb. 4, 5 und 6) oder permanenter Deformierung der Knolle (Tabellen 2 und 3) gefunden, welche beispielsweise 91 und 93 % der Variation in der extremen Bewertung erklären. Eine geringfügige Verbesserung der Korrelationen ergab sich bei Berechnung multipler Regressionen für physikalische Faktoren gegen äusserliche Bewertung + Tiefe der inneren Schädigung + seitlicher Ausdehnung der inneren Schädigung (Tabellen 5 und 6) (Schadensabstufung). Eine Verbesserung bei der Differenzierung zeigte sich bei absorbierter Energie gegen Schadensabstufung (Abb. 7) bei Proben mit einer mittleren äusserlichen Bewertung von 4 (Abb. 4). Andere physikalische Faktoren wie Kraft und dynamische Festigkeit, welche aus den oben genannten direkten Ablesungen berechnet werden können, ergaben schlechtere Korrelationen von Beschädigung sowohl mit absorbierter Energie als auch permanenter Deformation (Tabellen 6 und 7).

Das tragbare Pendel erlaubt eine höchst akkurate und schnelle Vorhersage der Gesamthöhe von Bruchschaden (auf der Basis absorbierter Energie), der an Knollen unter präzise kontrollierten Bedingungen entsteht, und stellt deshalb eine direkte Testvorrichtung für Prüfungs- und Züchtungsprogramme sowie Sortenversuche zur Ermittlung von Material dar, welches gegen Bruchschaden anfälliger als gegenwärtig akzeptable Sorten ist. Es könnte auch in Feldversuchen zur Ermittlung der optimalen Erntezeit verwendet werden.

Résumé

Relations entre les propriétés physiques des tubercules mesurées par des tests d'impacts pendulaires et les endommagements par fracture

Les propriétés physiques des tubercules (énergie absorbée-mesurée par le rebond du bras pendulaire - déformation et temps de contact de l'outil avec le tubercule) sont mesurées électroniquement, au cours de l'impact, en utilisant le système pendulaire portable FRI muni dans son axe d'un transducteur de déplacement angulaire (fig. 1). L'objectif est d'évaluer quelles mesures de ces caractéristiques physiques (instantanément visualisées) pourraient fournir une estimation précise du niveau d'endommagement par fracture des tubercules soumis à un impact dans des conditions physiques semblables à celles de la récolte.

Un ensemble d'échantillons (tableau 1), de sensibilité à l'endommagement par fracture très variable, est fermement maintenu par une force statique de 5 kg (afin d'empêcher le mouvement du tubercule) et percuté par la tête de l'outil fixé au bras pendulaire d'un angle de courbure de 6,35 mm, d'une énergie cinétique de 0,732 J et d'une vitesse de 2,602 m/s. Ces conditions correspondent à celles d'un tubercule de 216 g tombant de 35 cm. Après stockage des tuber-

cules pendant 14-19 jours à 20 °C, l'endommagement externe est évalué sur une échelle de 0 à 4 (fig. 2) et la largeur et la profondeur de la zone endommagée sont mesurées.

Ces lots ont présenté une très grande variabilité au niveau des endommagements (tableau 1, fig. 3, 4, 5 et 6) semblables à ceux observés au champ (écrasement, fissure, éclatement). Un grand nombre de mesures (fig. 4) concernant les facteurs physiques se sont révélées fortement correlées entre-elles (tableau 2 et 3). Les caractéristiques physiques les plus correlées avec les endommagements sont en général l'énergie absorbée (tableau 2 et 3, fig. 4, 5, 6) ou la déformation permanente du tubercule (tableau 2 et 3) qui expliquent respectivement 91 et 93 % de la variation de la note d'endommagements externes. Une légère amélioration des corrélations est obtenue quand les régressions multiples pour chaque facteur physique sont calculées en prenant en compte la note d'endommagement externe + la profondeur + la largeur de l'endommagement interne (tableau 5 et 6) (taux d'endommagement). On constate une amélioration de la séparation des échantillons de note moyenne 4 (fig. 4) lorsque l'on considère l'énergie absorbée par rapport aux taux d'endommagement (fig. 7). D'autres caractéristiques physiques telles que la force et la dureté dynamique calculée à partir des lectures directes, sont moins nettement correlées avec les endommagements que l'énergie absorbée ou la déformation permanente (tableau 6 et 7).

Ce système pendulaire portable fourni une prévision très précise et instantanée (à partir de l'énergie absorbée) du taux d'endommagements par fracture de tubercules soumis à un impact dans des conditions précises. Il peut être utilisé comme test direct dans des programmes de sélection ou des essais variétaux, afin de séparer les lots plus sensibles aux endommagements que les variétés généralement acceptées. Il peut également servir dans des essais de plein-champ ou même à la ferme pour déterminer la date optimale de récolte.

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