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Impact characterization of agricultural products by fall trajectory simulation and measurement

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ABSTRACT

Since 40 years, artificial fruits or dummies are built similar to real agricultural produce in order to measure mechanical load caused due to harvest and post-harvest handling systems. As shown by Praeger et al., 2013 the evaluation of how close these electronic fruits reflect real products impact behavior has been largely neglected during their design.

The paper dealt with development of a test method for comparison of elastic characteristics of real potato tubers and of dummy materials (built based on 2 component polyurethane elastomers) falling on metal or plastic materials. Therefore, the trajectory of the produce center of the whole drop process was simulated based on measurements with a miniaturised 3-axis accelerometer inside the samples, force measurements at the impact position and videos made with a high speed camera of the fall and rebound process. A simulation model of the impact was developed and impacts were characterised by forces, coefficients of restitutions, accumulated energy and deformation features obtained by quasi- rigid body impact simulations. Exemplary impact characteristics are presented for real potatoes of different water status and artificial tuber dummies using force-deformation courses and coefficients of restitution. The testing procedure showed to be useful for the systematic design of optimised dummy materials, for instance based on polyurethane elastomers, for a highly realistic replication of impact performance of real fruit and to improve the applicability and accuracy of dummies in field measurements. The drop tests and simulations for tuber dummies and real potatoes showed a wide range of impact characteristics when falling onto steel. In general, impact forces of the currently used dummies were higher and deformations were reduced compared to those of potato tubers. One dummy tested in this study showed impact characteristics widely similar to potato tuber material.

1. Introduction

Mechanical impacts during harvest and postharvest processes have been widely recognised as the primary cause of external and internal damages on potato tubers (Peters, 1996; Brook, 1996). Particularly during transport and handling, most bruise damages are caused by acting forces. Especially impact dynamic forces are critical, and their intensity is higher in magnitude and frequency than static forces (Mohsenin, 1986). The accumulated impact energy after severe mechanical damage affects complex metabolic processes (Strehmel et al., 2010) that result in bruising damages (e.g. blackspot bruising). In conjunction with intensity and duration of mechanical impacts, several intrinsic factors of potato tubers, such as specific gravity, water status or potassium content, have been identified as critical factors of bruise development (Mc Garry et al. 1996; Linus-Opara and Patare, 2014).

Besides increasing tuber temperature during handling, the most efficient approach to prevent mechanical damage and considerable economic losses is to optimise the entire process by minimizing the numbers and the intensity of impacts. Therefore, potential equipment related risk zones, such as fall heights, transport velocities or impact surface cushioning materials, need to be located. Since 40 years, much research efforts have been directed to the development and the application of automated impact recording devices, the so called *pseudo-* or *electronic-fruits* (other terms used: *dummies*, *artificial tubers*, *instrumented devices* or *spheres, impact recording devices* etc.). Such devices have been used for investigations on potato (Molema et al., 2000), tomato (Arazuri et al., 2010), apple (Hyde 1997), peach (Ahmadi et al., 2010), citrus (Ortiz et al., 2011) or for small fruits such as blueberry (Yu et al., 2011a, 2011b).

An artificial tuber essentially involves wireless sensors, such as 3-axial accelerometers (Bollen, 2006), tactile sensors (Herold et al., 2001) or strain-gauges (Müller et al., 2008), battery and electronic equipment (e.g. amplifiers, bridges etc.) with low power consumption, and a data logger that records data over time. Currently, available

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Nomenclature

AMU	Acceleration measuring unit
COR	Coefficient of restitution
w	Reduced water content of 5%
$\Delta t_F = 0.0001$	Force sensor sampling rate, s
$\Delta t_a = 0.00033$	AMU sampling rate, s
Δt	$= \Delta t_a = 0.00033$, s
h_1	fall height = 0.25 m
$h2$	Rebound height
v_1	velocity before impact
v_2	velocity after impact
g	gravitational acceleration = 9.81 ms^{-2}
m	mass of test samples
n	fitting force value interval
$tfall$	fall time, s
$\hat{t}_{1\_imp\_a}$	absolute time of the first acceleration value, s
$t_{1\_imp\_F}$	relative time registered by the force sensor, s
$\hat{t}_{imp\_end}$	time at the end of impact, s
t_{end}	end time of simulation
TA	time-acceleration lookup table
e_h	determination of COR by simulation
e_{vid}	determination of COR by high-speed videos
e_A	determination of COR by fusion of force data and simulation
δ_r	permanent deformation
δ_m	maximum penetration

implementations and prototypes of such devices support high impact registration (up to 500 g) with high sampling rates (up to 10 kHz).

The spherical or ellipsoidal shaped electronic fruits most commonly used in potato harvest and postharvest process are IS 100 and I.R.D (Techmark, Inc., Lansing, USA), PTR-200 (Bioteknisk Institut, Aarhus, Denmark), Smart Spud (Sensorwireless Inc., Charlottetown, Canada) and TuberLog (ESYS, Berlin, Germany). The applicability of these devices was mainly analysed in scientific research. In practice, however, they have demonstrated relatively limited performance. Van Canneyt et al. (2003) emphasised the necessity to gain better knowledge about the real characteristics of instrumented potato devices, such as sensitivity considering specific contact zones, relationships between impact forces and acceleration signals, and reproducibility of results etc. One of the major constraints for a meaningful practical application is the considerable difference between real tuber and electronic fruits impact performance, which restrict the usability of obtained data for damage analyses of real tubers.

Praeger et al., 2013 studied number of impacts and impact acceleration values during runs in a processing line simulator and a drop simulator. They found significant differences between real potato tubers and different types of artificial fruits.

Several authors investigated the physical properties of electronic fruits and real potatoes. The elastic behavior was described mainly by the static modulus of elasticity (Young's modulus) and coefficient of restitution (COR). The static modulus of elasticity is characterized by the force of resistance against deformation – i.e. the stiffness. It is suitable for characterization of impacts of homogenous isotropic materials (Gonzales-Montellano et al., 2012). The coefficient of restitution is expressed by the ratio of rebound energy to impact energy. Analyses of the energy balance during fall tests (COR-determination) provided useful criteria for characterization of impacts and bruise susceptibility of biological produces (Ahmadi et al. 2016; Stropek and Golacki, 2016).

Both properties are specific for different kinds of fruit and, because of biological nature, they can be more or less variably. Therefore, the imitation of elastic behavior of fruit is difficult, and it is not sufficiently arrived until now.

Studman and Pang (1990) indicated difficulties in relating electronic fruit data to actual fruit damages. Analyzing the impacts of the IS 100 instrumented sphere with a high-speed camera, Hyde et al. (1992) observed apparent differences between the motion of real and of electronic tubers when passing through potato packing lines. Some physical properties of the sphere, such as shape, weight and elasticity, are not corresponding to those of potato tubers. Especially the sphere's relatively high modulus of elasticity in connection with high restitution coefficient increased the chance of bouncing. Molema et al. (2000) have claimed that, due to their lower stiffness, real tubers absorb more energy in comparison to the IS100 spherical device. Moreover, in Dutch ware-potato handling-chains tubers are usually lighter and smaller than the IS. Therefore penetration of the tubers into the material they impact and the resulting peak-acceleration will be less, compared to impacts caused by the IS 100.

To avoid the inadequacy of the synthetic materials during impact measurments on agricultural products, the miniaturised 3-axial acceleration measuring unit (AMU) called MIKRAS (ESYS, Berlin, Germany) was developed (Geyer et al., 2009). The AMU has the size of a AA-battery and can be directly implanted in real produces such as potatoes, apples, asparagus, pickling cucumbers etc. In contrast to electronic fruits, acceleration measurements with the implanted system reflect the influence of the specific tissue properties on measurements (Geyer et al., 2009). Variations in tissue properties between different produce types and also within the same produce, e.g. due to changes during storage can be considered. The modulus of elasticity of stored potato tubers, for example, declined by approx. 3 MPa during 7 months storage (Praeger et al., 2009).

Notwithstanding the advantages of the implanted AMU, it has not been commercialised yet because of its complicate handling (implanting procedure) under practical conditions. Therefore, further investigations of electronic fruits are necessary, in particular studies about their impact properties.

The main goal of the presented studies was to develop a new method, a simultaneous measurement of impact acceleration and force, for characterization of impact behaviour. This unique method can be used as a basis for further development of measuring devices with mechanical properties similar to real produces. The AMU was implanted into plastic tubers with different mass, Shore-hardness and Modulus of elasticity, and in real potato tubers with different mass and elastic parameters (to consider biological variability). The tubers fitted with the AMU were used for impact experiments using a fall station fitted with an impact force sensor and high-speed camera. For the characterization of impacts, the parameters forces, coefficients of restitution, accumulated energy and force-deformation characteristics were determined. To observe indirectly measurable characteristics (impact velocity, deformation), quasi-rigid body impact simulations were applied, which were based on acceleration and force data measurements. Impacts from defined height on both steel and cushion plastic surfaces were evaluated.

2. Material and methods

The experimental study consists of following steps:

- Fall experiments to collect data of laboratory impacts, i.e. acceleration sensors (AMU), impact force (fall simulator) and video (high speed camera).
- Simulation, i.e. mechanization of AMU data to calculating the entire trajectory of the centre of mass of test samples during impact experiments.
- Computation and comparison of impact characteristics: 1. Fusion of