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Research Note

Analytical study of turgor pressure in apple and potato tissues

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ABSTRACT

Mechanical injuries are the main cause of damage (such as bruising) and loss of quality of fruit and vegetables, occurring mainly from mechanical forces during compression, vibration and impact loads. Apples and potatoes are susceptible to external and internal pressures, which causes bruising and fracture in soft tissues. The study of turgor pressure and the compressive stiffness of apple and potato tissues is essential to understand their fracture strength against external and internal pressures. In the present study, a generalized form of a strain energy function is proposed, and a relation between turgor pressure and stretch ratio is developed by considering its appropriate form. It is considered that the tissues are isotropic, incompressible, homogeneous, and show hyperelastic behavior. The Levenberg–Marquardt algorithm was used for regression analysis to calibrate the material constants by correlating predicted and experimental values of turgor pressure and stretch ratio for apple and potato tissues. A good fit of the developed relation to experimental data was obtained with the coefficients of determination of 98.02% for apple and 98.0% for potato.

1. Introduction

A large percentage of water is contained in fruit and vegetables (Vaclavik and Christian, 2007), which is responsible for turgidity in soft tissues. To determine the quality of food products, it is important to understand the effect of turgor pressure in the cells. The cellular conglomerate in fruit and vegetables is composed of the parenchyma cells, which are fluid-filled and thin-walled shells. Each cell is composed of a cell wall surrounding the cytoplasm, nucleus, and a vacuole which contains over 90% of the cell's liquid (Pitt, 1982). The cell wall is semipermeable to water and certain solutes; it is also able to hold water under pressure by having a high internal concentration of solutes (Nobel, 1974; Pitt, 1982). The high concentrations of solutes inside the cell dilute the internal water as compared to that outside. By osmosis, water can move into the cell through the semipermeable membrane. Water diffusion inside the cell, therefore, reduces its concentration gradient (Roberts, 2007). The solutes cannot cross the membrane and remain inside the cell. Further, as water enters into the cell, the cell starts to swell and a pressure is generated on the cell wall. This pressure is known as turgor pressure (Wayne, 2009).

The study of turgor pressure for tissues was provided, initially, by Nilsson et al. (1958), who derived the relation between tissue rigidity and turgor pressure for infinitesimal deformation. Lin and Pitt (1986) performed experiments on apple and potato samples, and found the effect of turgor pressure on the failure strain, failure stress, tissue stiffness and failure mode in soft tissue. Under constant uniaxial loading, potato tissues decrease the failure susceptibility (Niklas, 1982) and reduce its strength at high turgor pressure (Hiller and Jeronimidis, 1996). Turgor pressure and temperature influence the mechanical properties of apple and potato tissues. Bajema et al. (1998b) investigated the effect of turgor pressure and temperature on the dynamic failure properties of potato tissues. Zdunek et al. (2008) analyzed the potato tissues and observed that failure mode of the tissues between cell wall rupturing and cell–cell debonding can be changed by changes in turgor pressure and temperature. Turgor pressure and cell size have a great effect on the wall elasticity of plant cells (Steudle and Ulrich, 1977), and potato tissue cracking (Konstankiewicz and Zdunek, 2001). An acoustic emission (AE) method was used to analyze failure conditions (Konstankiewicz and Zdunek, 2001) and fracture properties (Zdunek et al., 2008) of potato tissues with different turgor pressure and cell size distribution.

In many studies, turgor pressure was adjusted by soaking the potato and apple tissues (Lin and Pitt, 1986), potato tissues (Scanlon et al., 1996; Bajema et al., 1998a; Laza et al., 2001; Alvarez et al., 2000), tomato tissues (Jackman et al., 1992) and melon and kiwifruit tissues (Sajnin et al., 1999) in mannitol solutions of various concentrations. The influences of turgor pressure on pear tissues (De Belie et al., 2000a), red cabbage cells (De Belie et al., 2000b) and apple tissues (Alamar et al., 2005; Oey et al., 2007), have also been investigated. It was adduced that macroscopic mechanical

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behavior of fruit and vegetables depends on microscopic properties. The effect of higher turgor pressure was reported by Pitt and Chen (1983) on failure strain, failure stress and tissue stiffness of apple and potato tissues, and further, it was concluded that the increase in turgor decreases the failure strain while failure stress remains unaffected. Oparka and Wright (1988) analyzed the effect of cell turgor pressure on sucrose partitioning in potato tuber tissues. Increment in turgor pressure reduces the failure stress and strain under axial compression (Bajema et al., 1998a).

To study the effect of turgor pressure on cellular structure, most work has been done experimentally. A very low number of studies are available which deal with the problem mathematically. The aim of the present study was therefore two-fold: first, to propose a generalized form of a strain energy function for hyperelastic tissues, and second, to develop a mathematical relation between turgor pressure and stretch ratio by using an appropriate form of the proposed generalized strain energy function (SEF).

2. Materials and methods

2.1. Experiments

The tissues considered in the present study were from 'Ida Red' apples and 'Idaho' potatoes. In the present work, experiments on apple and potato tissues conducted by Lin and Pitt (1986) have been used for validation of the study. Apples and potatoes were kept in cold storage before testing. Both apples and potatoes were divided into sections and then cylindrical samples were cut from the flesh side of the sections. Cell turgor pressure was manipulated by soaking the cylindrical samples into mannitol solutions of concentrations from 0.0 to 0.8 M for apple and 0.0 to 0.5 M for potato. An Instron Universal testing machine was used for a compression test (for more details, see Lin and Pitt, 1986).

2.2. Mathematical formulation

It is supposed that the tissues of apple and potato are composed of identical parenchyma cells which are uniform in thickness and mechanically homogeneous. Therefore, when a uniform compressive stress is applied to the tissues, each cell in the tissue is subjected to an equal load (Pitt and Chen, 1983). Consequently, the fluid inside the cell generates the pressure (turgor pressure) on the cell wall. Further, as stress increases, turgor pressure increases within the cell and cell walls start to stretch. In more turgid cells, if the external stress on the cellular conglomerate increases slightly, the cell wall stretching exceeds its strength and cell wall rupture occurs (Segerlind and Dal Fabbro, 1978; Dal Fabbro et al., 1980; Pitt and Chen, 1983).

2.2.1. Strain energy function (SEF)

In our previous work (Singh et al., 2013), a mechanical model was developed to present the relation between cell wall stretch ratio and tension for apple and potato tissues. To develop the aforementioned relation, the following strain energy function was proposed

$$W = \left(\frac{C_1}{2b}\right)[\exp(b(I_1-3))-1] + \left(\frac{C_2}{2}\right)(I_2-3)^2 \quad (1)$$

where the dimensionless constant $b>0$ is a stiffening parameter, and C_1 and C_2 are material constants (for more details, see Singh et al. (2013)).

2.2.2. Generalization of SEF

The study of mechanical properties of hyperelastic material has been a topic of interest for many decades. Numerous strain energy functions have been developed for the characterization of hyperelastic materials (detail is given in Singh et al. (2013)). In this context, a more general form of strain energy function (1) can be proposed as

$$W = \left(\frac{A}{b}\right)[\exp(b(I_1-3))-1] + \left(\frac{B}{m}\right)(I_2-3)^m \quad (2)$$

where A and B are the material constants, which can be determined by experimental data, and m is any natural number. This function satisfies the necessary requirement of normalization conditions (Holzapfel, 2000), which states that W should vanish in the reference configuration where $I_1 = I_2 = 3, I_3 = 1$ i.e. $W(\mathbf{I}) = 0$; and W increases with deformation i.e. $W \geq 0$.

On expanding the exponential term, Eq. (2) can be written as

$$W = \left(\frac{A}{b}\right)\left[\sum_{n=1}^{\infty}\left(\frac{b^n}{n!}\right)(I_1-3)^n\right] + \left(\frac{B}{m}\right)(I_2-3)^m \quad (3)$$

Now we are in the position where we can acquire several strain energy functions from Eqs. (2) and/or (3). For the different values of m and n, Eqs. (2) and/or (3) can be reduced into several previously developed strain energy functions. A concise list is given in Table 1.

2.2.3. Constitutive equation

Several strain energy functions have been reported in the literature for characterization of biological tissues. To study the mechanical properties of apple and potato tissues, however, as shown by Singh et al. (2013), the more appropriate form of strain energy function can be procured from Eq. (2) corresponding to $m = 2$. In the present study, therefore, we will model our problem by considering the following form of strain energy function

$$W = \left(\frac{C_1}{2b}\right)[\exp(b(I_1-3))-1] + \left(\frac{C_2}{2}\right)(I_2-3)^2 \quad (4)$$

where $A = C_1/2$ and $B = C_2$.

Table 1
Reduced form of strain energy function (2) and/or (3) into several well known strain energy functions.

Values of m and n	Reduced strain energy function	Reduced strain energy function is equivalent to strain energy function of
$m \to \infty$	$W = (A/b)[\exp(b(I_1-3))-1]$	Fung (1967) and Humphrey and Yin (1987)
$m \to \infty, n = 1$	$W = A(I_1-3)$	Neo-Hookeano model Rivlin (1948)
$m \to \infty, n = N$	$W = (A/b)\sum_{n=1}^{N}(b^n/n!)(I_1-3)^n$	Yeoh (1990)
$m = 1$	$W = (A/b)[\exp(b(I_1-3))-1] + B(I_2-3)$	Veronda and Westmann (1970)
$m = 2$	$W = (A/b)[\exp(b(I_1-3))-1] + (B/2)(I_2-3)^2$	Singh et al. (2013)
$m = 1, n = 1$	$W = A(I_1-3) + B(I_2-3)$	Mooney (1940)
$m = 1, n = 2$	$W = A(I_1-3) + (Ab/2)(I_1-3)^2 + B(I_2-3)$	Isihara et al. (1951)
$m = 1, n = 3$	$W = A(I_1-3) + (Ab/2)(I_1-3)^2 + (Ab^2/6)(I_1-3)^3 + B(I_2-3)$	Biderman (1958)