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Research paper

A biomechanical study on burst mechanisms of plant fruit: Stress analysis of pericarps before bursting

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ABSTRACT

Bursting of fruit is a very interesting biomechanical phenomenon because its mechanism is directly related to the plant's reproduction. A plant that produces fruit that bursts powerfully and spreads the seeds widely has the advantage of reproduction without relying on other mechanisms such as transportation of fruit by insects. The structures of many types of fruit have likely been optimized by evolution, although the structure itself appears rather simplistic. Strain energy is stored in each pericarp because of growth deformation, swelling or desiccation just before bursting. Throughout these changes, the mechanical stress of the pericarps is at equilibrium. At the instant of bursting, the stored strain energy is released very rapidly. Quick and wide motion of the pericarps in a certain direction is advantageous for throwing the seed a long distance. The motion and deformation of bursting pericarps depend on their tissue structure and mechanical stress condition just before the burst. We tracked the bursting motion by using a high-speed camera. Then we calculated the pre-burst stress generated in a pericarp of Impatiens by using the finite-element method. The boundary condition obtained by experiments using a high-speed video camera is given, and the stress was calculated using reverse deformation analysis. The stress distribution of the pericarp is effective in causing the pericarp motion to throw the seeds far away.

1. Introduction

Plant seeds are moved and distributed in a variety of ways, for example, by being carried by wind, water, insects or animals. In addition, dispersion of plant seeds by bursting fruit is a typical way of transportation that is self-active and independent of other creatures (Simons, 1992; Hara, 1994; Vogel, 2005). Fruit that can burst powerfully and spread the seeds widely offers an advantage by extending the breeding grounds of the plant in terms of natural selection. Therefore, the bursting of fruit from living plants represents a natural selection of bursting mechanisms, and appears to be

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mechanically and structurally optimized (Schulgasser and Witztum, 1995). A recent study of bursting fruit reported the transfer of kinetic energy and gravitational potential energy from fruits to seeds, and the launch angle of the seeds (Hayashi, 2009). However, the strain energy or stress distribution on the pericarp was not considered in this paper, even though it is most essential factor in creating the driving force of explosive seed. The bursting motion of pericarps causes the seeds to be thrown far and wide, and it strongly depends on the stress conditions just prior to bursting. In a mechanical context, the pre-burst stress is considered as a residual stress. Residual stress should be avoided in a productive industry, e.g. welding or casting, because it often causes unexpectedly high stress. In contrast, in a living organism, residual stress is often adopted to achieve favorable stress conditions. For example, it is well known that stress concentration is cancelled by residual stress in the outer wall of an artery (Fung, 1990). Therefore, studying residual stress in living organisms is important in understanding their exceptional biomechanical functions.

The residual stress of bursting fruit is probably optimized to facilitate a bursting motion that leads to a wide spatial distribution of the seeds. To clarify specific bursting mechanisms, it is necessary to evaluate the residual stress distribution within the fruit. Therefore, the aim of this study was to obtain the residual stress or pre-burst stress generated in fruit pericarps. Impatiens were cultured, and their fruit pericarps investigated. The shapes of Impatiens pericarps before and after bursting are shown in Fig. 1. The fruit of Impatiens has five pericarp sheets. The pericarp sheets are interconnected, with boundaries stiffer than the pericarp body. Based on visual observations, the bursting process of the fruit can be described as follows. The pericarps start to absorb water and swell during the bursting season. Pericarp sheet deformation is restrained by the connection to the adjacent sheet, and thus the swelling generates mechanical stress within the pericarps. Once a pericarp boundary is ruptured by the stress, the pericarp sheets released from the restraint deform quickly and throw the seeds outward. In this study, pericarp bursting motion was tracked using a high-speed video camera. In addition, the pre-burst stress distribution of a pericarp was evaluated using a finite-element method based on the pericarp shape before and after bursting.

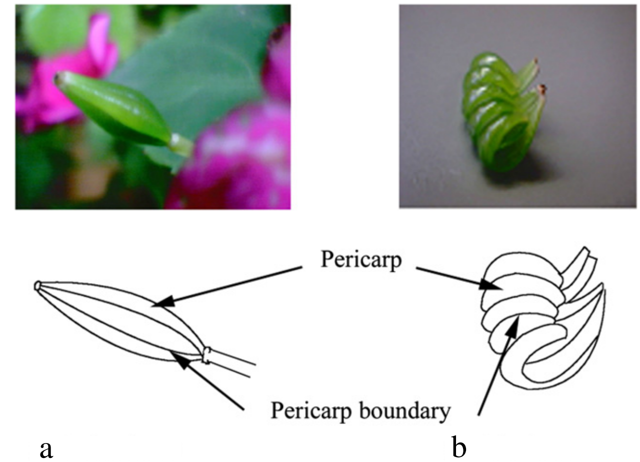

Fig. 1 – Impatiens fruit and pericarp boundary before and after bursting: (a) before bursting, (b) after bursting.

2. Materials and method

2.1. *Tracking the bursting motion of Impatiens pericarps*

The bursting motion of Impatiens fruit is difficult to observe because it is a high-speed motion of the order of milliseconds. To capture the motion, we used a high-speed video camcorder (nac Image Technology, MEMRECAM fx-k3) capturing 300 frames per second. An example of bursting motion images of fruit is shown in Fig. 2. In the experiment, a fruit was picked with its stalk just before bursting, and the stalk of the fruit was fixed on a steel pin using adhesive tape.

We extracted tracks of three-dimensional pericarp motion during bursting of the fruit. Curves of a pericarp boundary were drawn based on images recorded by two high-speed video cameras from orthogonal directions. Two-dimensional coordinate values of specific points on the pericarp boundary were obtained from the two cameras, and three-dimensional coordinates of these points were calculated. Each curve was obtained using three-dimensional NURBS (Non-Uniform Rational B-Splines) using the point coordinates. The time sequence of the curves was used for calculation of the pre-burst stress of the pericarp using finite-element analysis.

2.2. *Micro-CT scanning, CAD modeling and finite-element analysis*

A CT scan of the pericarp was carried out using micro-CT (Hitachi Medical Co., MCT-CB100MF) before and after bursting to obtain the precise shape of the pericarps. We constructed CAD models of the pericarp before and after bursting based on the micro-CT images, and then finite-element models were created. The direction of the CT scan and examples of CT images are shown in Fig. 3. The interval between CT scans was around 0.1 mm. More than 150 section images were obtained parallel to the longitudinal axis of the pericarp before and after bursting. CAD models of the pericarp based on the CT images are shown in Fig. 4. The models were created using V-CAT (RIKEN), an image-processing software for creating STL data or volumetric CAD data from sequential tomographic images. V-CAT has been developed by the V-CAD project (Kase et al., 2003). The outer and inner surfaces of the pericarps were precisely determined by numerous polygons in STL format in the CAD models. We focused on a pericarp that had a ruptured boundary at the time of burst, and extracted polygon data of the pericarp from the CAD models. Finite-element models were created using MENTAT (MSC Software), a predecessor of the finite-element analysis software MARC. Polygon data of the pericarp was input into MENTAT, and finite-element models were constructed that were fitted to the polygons of the pericarp surface. Hexahedral and tetrahedral solid elements were used for the modeling. Fig. 5 shows the finite-element models of the pericarp before and after bursting. Both models have the