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Technical section

Dehydration of core/shell fruits

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ABSTRACT

Dehydrated core/shell fruits, such as jujubes, raisins and plums, show very complex buckles and wrinkles on their exocarp. It is a challenging task to model such complicated patterns and their evolution in a virtual environment even for professional animators. This paper presents a unified physically-based approach to simulate the morphological transformation for the core/shell fruits in the dehydration process. A finite element method (FEM), which is based on the multiplicative decomposition of the deformation gradient into an elastic part and a dehydrated part, is adopted to model the morphological evolution. In the method, the dehydration pattern can be conveniently controlled through physically prescribed parameters according to the geometry and material of the real fruits. The effects of the parameters on the final dehydrated surface patterns are investigated and summarized in detail. Experiments on jujubes, wolfberries, raisins and plums are given, which demonstrate the efficacy of the method.

1. Introduction

A core/shell fruit consists of a surface thin exocarp, a middle thick sarcocarp and a central hard stone. On the surface of some dehydrated core/shell fruits, such as jujubes, wolfberries, raisins, etc., rough and undulating patterns can be noticed comparing with their fresh states. The dehydration process is often related to a dramatic morphological transformation from an initial smooth and full configuration to a final rough one with many random, intricate and reticular undulations, as shown in Fig. 2 for the morphological evolution of a jujube at different dehydrated stages. To model such patterns in animations or movies seems to be a big challenge for an artist. On one hand, the artist can manually add the complicated details to a fruit model through classical texture mapping techniques (normal mapping or displacement mapping). However, it seems difficult, even for an experienced artist, to model the surface pattern evolution for an arbitrary realistic fruit using an empirical mathematical tool, since the buckles may merge together to a bigger one or divide into smaller ones during dehydration. On the other hand, the data driven methods rely on carefully captured images and measurements [1] and need to build up a mathematical model by studying the dehydration process of real fruits. However, the buckling morphology in each fruit may differ from each other because of the differences in their geometry and material. Also, it is an expensive and labor intensive work to collect morphological data via experiments.

In animation production, physically-based methods have been proven to be very successful in simulating the phenomena, such as fire [2], fluid [3] and, even fruit senescence [4]. In the physical view, dehydration is related to many complex processes, such as water transport, evaporation and material remodeling, and the mechanism for inducing the final morphology roots from the local material instabilities. Comparing with traditional instability problems, which are mostly induced by mechanical loadings, the dehydration-induced buckling should be attributed to the internal volume shrinkage due to the water loss. So the volumetric growth theory developed in recent years, which aims to handle the deformation and stress for solids with a growing mass, could be adopted to model the phenomena. The related work will be briefly reviewed in the next section. Following the idea in the growth mechanics, a general continuum theory aiming to characterize morphogenesis of dehydrated core/shell fruits is elaborated and the corresponding FE model is also introduced with aim to simulate the dehydration-induced morphological transition for general core/shell fruits. The model offers the users several parameters to control the shape and material of the core/shell fruits, such as the material ratio, the exocarp thickness, the stone size and the overall shape parameters. The parameter effects on

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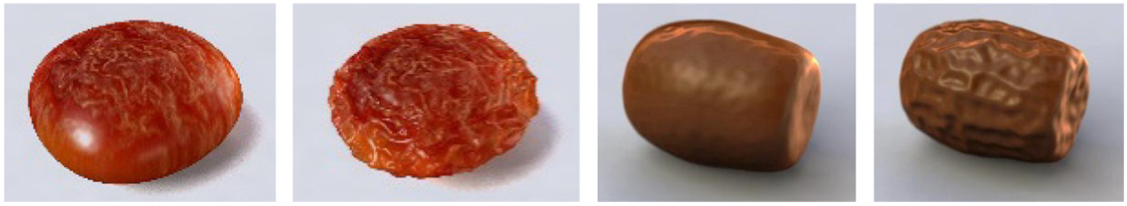

Fig. 1. Simulation results for the dehydrated plum and jujube.

Fig. 2. The morphologies of a real jujube at different dehydrated stages. The jujube is dehydrated in the normal temperature and pressure.

the final buckling patterns are also summarized from a broad range of surface deformations. An artist could adjust the above mentioned physical parameters to control the surface patterns of dehydrated fruits. Experiments on several kinds of fruits, such as jujubes, wolfberries, raisins and plums, demonstrate the visual accuracy of the simulation. Fig. 1 shows a preview of the results.

2. Related work

Modeling the evolution of wrinkles in animation is not a new problem. Until now, there are many works centering on this subject, such as the energy-based method to model the distinct wrinkle shapes [5], the approach using the stretch tensor of coarse animation output to model the wrinkles of cloth objects [6] and the combination model of embedded thin shell with coarse finite element lattice [7]. However, little research works exist for the modeling of dehydration-induced deformation of fruits in animation, which shows unique characteristics compared with the wrinkles on clothes and faces. First of all, the driving force to initiate the surface wrinkles in dehydration is the volumetric shrinkage, rather than the mechanical pressure, which seems unable to be embedded into the animation model in the traditional methods. Meanwhile, the surface wrinkles on a dehydrated fruit could be random with different sizes and orientations as indicated earlier in Fig. 2 and no physically-based methods have been proved to be efficient to handle such complicated patterns in animation. In addition, in some traditional methods, such as the embedded thin shell model [7], a lot of nonintuitive parameters should be prescribed, which could prevent an artist from making an animation efficient. The continuum-based model presented in the current work could be a choice to overcome the above problems.

The dehydration process shows large similarities with the growth of biological tissue which has been intensively investigated in recent years. Comparing with traditional engineering materials, such as steel and concrete, the deformation of biomaterials could be actively induced by the redistribution of internal materials, such as the Venus flytrap [8] and ice plant seed capsules [9]. The dehydration process intrinsically belongs to such kinds of phenomena, which is related to a mass loss due to the water evaporation. Several methods have been developed to model the morphological evolution due to the mass or volume growth in soft solids. Most of them inherited the general framework developed by Rodriguez et al. [10], where a multiplicative decomposition of the deformation gradient into an elastic part and a growth part was introduced and found to be effective for stress-dependent finite mass growth. Now, the method has been applicable to characterizing the morphological evolution of biomaterials. Dervaux et al. [11] studied the morphogenesis of thin hyperelastic plates, where the cockling of paper and surface instabilities of grass blades were explained theoretically. Ben Amar and coworkers [12,13] investigated the wavy morphologies on the inner surface of tubular organs, such as airway and intestine, which shows that the multiplicative approach is effective to handle the growth-induced instabilities. In the numerical aspect, Feng and coworkers utilized the finite thermal strain to replace the growth deformation tensor and investigated the surface wrinkling of core–shell soft structures [14,15] and the morphological folding of esophageal mucosa [16]. In their work, the buckling modes obtained by numerical results show good agreement with the analytical results and the influence of geometrical and material parameters on the surface buckling patterns is also investigated. The methodology offers a practical tool to simulate the volumetric growth of biomaterials. However, their work is limited to consider some simple cases and most details about the simulation are omitted. For instance, the fruit shape is not always spherical and some fruits, such as jujubes and plums, contain stones inside the sarcocarp, which have considerable influence on the final wrinkling patterns. In addition, the length and depth of the buckles in a high-stress state need more examination in order to characterize the process of dehydration for animation production.

In addition, other physically-based methods were also proposed to deal with morphological evolution. For example, to simulate the deformation in the biological aging and decay process of fruits, Kider et al. [4] introduced equivalent springs with decreasing lengths and stiffness to replace the volumetric shrinkage in fruit meat due to water loss, so that the surface layer simulated using the nCloth solver in Maya could produce the effects that occur during decay. Their model is based on several assumptions on the surface layer and internal volume and whose justification to produce the complicated deformation during