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REVIEW

Characterization of Cucumber Cultivars by Mechanical Stress Distributions during the Compression Process

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Abstract

Firm, crispy and crunchy texture is an important factor of plant-based foods. Pre- and post- failure processes of cucumber cultivars were examined to explore the mechanical properties that determine cultivar-specific crispy and crunchy texture. Spatial distribution of mechanical properties, which can be a very important characteristic in relation to food textural quality, was visualized and characterized for the mechanically complex and heterogeneous structure of cucumber fruits. A multiple-point sheet sensor system, which shows time series of spatial stress distribution on a sample, successively demonstrated the characteristics of the stress distribution in each tissue of cucumbers and its differences among cultivars during the prefailure process of compression tests. For the postfailure process, it was confirmed how fractures occur, as either a major global fracture event or a number of sequential small local fractures. The two-dimensional information about postfailure events enabled us to relate the structural fracture phenomenon to the force-strain property of each cultivar. This technique is applicable to other food materials to explore the relationships among their mechanical properties, structure, and texture.

Discipline: Food
Additional key words: failure, fracture, structure, texture, tissue

Introduction

Texture is an important factor in our appreciation of food. Over the past two decades, interest in controlling the textural quality of plant-based foods has been increasing for both fresh and processed foods[29]. In the case of cucumber fruit, superior textural quality is desired when selecting cultivars for pickled products or for the fresh market[11]. Consumers prefer a firm, crisp and crunchy texture[13,14,21,26]. However, little is known about the relationship between cucumber textural quality and internal structural characteristics[11,24].

Most natural food material has a mechanically complex and heterogeneous structure and is frequently anisotropic as well[2,10,22]. Thus, the stress distribution during compression in both the prefailure and postfailure regions of the force-deformation curve may be anisotropic and inhomogeneous in many foods. Mechanical stresses are distributed in a complex manner in plant organs[27]. In the case of cucumber, the fruits consist of three principal tissues, skin (exocarp), flesh or parenchyma (mesocarp), and seed cavity (endocarp). The texture of cucumbers is influenced by the nature of these constituent tissues[4,26]; thus attempts have been made to distinguish the mechanical properties of specific tissues within the cucumber[7,26]. However, the tissue distribution should not be the same among cultivars[7]. The high level of these complexities, the mechanical heterogeneity and anisotropy within and between the tissues, are inherent in the plant organ; thus single-point measurements are inadequate to reveal its multifactorial nature.

Spatial distribution of mechanical properties in foods can be a very important characteristic in relation to food texture quality. Techniques of visualizing global internal quality such as MRI (Magnetic Resonance Imaging) and EM (electronic microscope) can provide useful insight into the many structural aspects of raw and processed food, which leads us to a better understanding of texture[12,30]. Similar concepts may apply to the mechanical

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aspects that arise from the structure but move one step further toward texture. To “see” the mechanical properties as a distribution map can offer valuable information. We established a new approach for mapping the distribution of mechanical properties on foodstuff[7–9,16,17]. It is useful especially for plant-based food which has complex structures consisting of several different tissues.

The multiple point sheet sensor (MSS) system (Fig. 1a), which can ascertain the planar stress distribution on the sample, was introduced into food texture study in 1997[16]. As a standard type (named I-Scan50R), the 1,936 stress-sensing points are aligned as an X-Y coordinate system with 44 × 44 grids covering the sensor surface. This system reveals the stress of each coordinate with a planar resolution of 1.27 mm. The saturated pressure is about 3.5 MPa. Details of the sensing mechanism and basic regulations on food measurement are available elsewhere[16,20].

To map the distribution of mechanical properties on foodstuff, this system was used together with a compression tester[7–9,16,17]. During a cross-sectional sample on the MSS, the sample is uniaxially compressed by an Instron universal testing machine, and the loading on the sample is recorded by the MSS system (Fig. 1a). Data is basically a time series of two-dimensional stress distribution maps (44 × 44 matrices) acquired at each time point. Therefore, we can know the change of stress distribution pattern on the entire cross-sectional area during a compression in process.

After getting the data, we can determine regions of interest on the map and extract the mechanical properties of these targeted regions[6,8]. This function is available to obtain the mechanical properties of each tissue when the sample consists of several different tissues[8]. This system provides us voluminous amounts of information simultaneously, which was not available in commonly used single-point measurements. Multiple-point stress measuring opens new possibilities for approaching the mechanical testing of food texture.

Visualization and characterization of planar stress distributions in cucumber cultivars

Texture perception occurs during the dynamic process of food breakdown in the mouth[30]. Biting and chewing foods normally involve substantial deformation and breakdown of the food structure[19]. Fig. 1b shows typical force-strain curves of a cross-section of two cucumber cultivars during the compression test. Destructive food material deforms in an approximately elastic manner during the prefailure process when a uniaxial compressive force is applied. The initial major fracture event is accompanied by rapid release of stored energy. This initial fracture is followed by the postfailure process, which includes a series of fractures at lower stresses and the final steep ascent of force[1,5,23]. Perception of the mechanical attributes of food involves both prefailure deformation and postfailure behavior[18,22]. In following sections, the planar stress distribution of pre- and post-failure processes were visualized and characterized for Japanese cucumber cultivars.

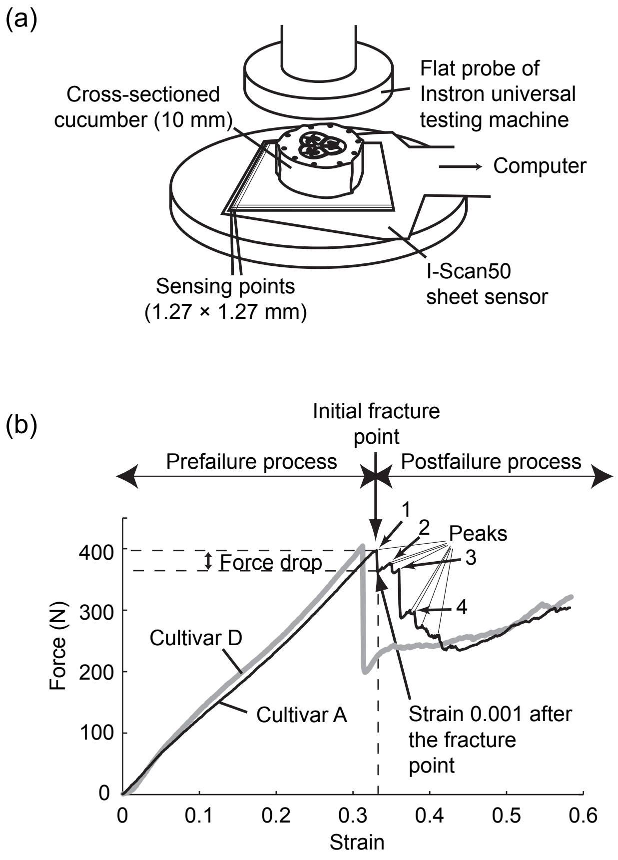

Fig. 1. Force-strain curves measured by the MSS

(a) A cross-sectioned sample (10 mm thick) on an I-Scan50 sensor was compressed by an Instron universal testing machine at a constant speed of 1 mm/s.

(b) Typical examples are shown for cultivars A (black line) and D (gray line). Several terms are also indicated in the illustration (in the case of cultivar A).

1. Prefailure deformation to initial fracture

The two-dimensional stress distribution during prefailure deformation and at the initial fracture has been examined for four cucumber cultivars A, B, C, and D (Table 1)[7,8]. These four cultivars were similar in stress and strain at the initial fracture; thus they can not be significantly differentiated in conventional measures[7]. The characteristic features of each cultivar could be deciphered

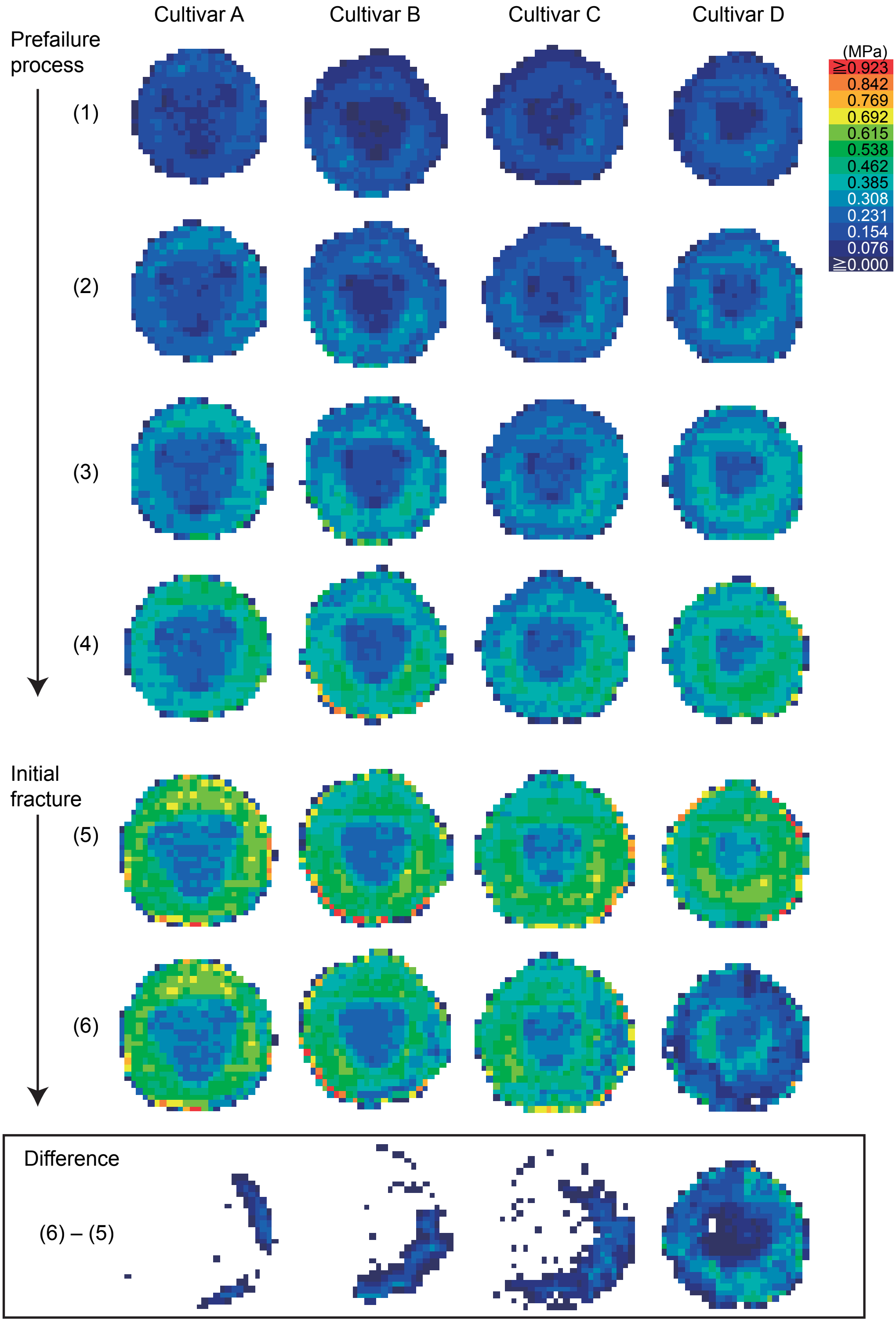

Fig. 2. Typical two-dimensional stress-distribution maps for four cultivars
The prefailure process includes (1) 0.1, (2) 0.15, (3) 0.2, and (4) 0.25 strains. Initial fracture consists of (5) fracture point and (6) strain 0.001 after the fracture point; the difference between them (6) – (5) is also shown in the bottom box. Each square represents one 1.27 × 1.27 mm sensing point. The stress scale is provided on the right side.

Table 1. General characteristics of cucumber cultivars described by plant breeders

Cultivar	Characteristics
A	Normal cultivar for eating raw; firm flesh, large and soft seed cavity, juicy, suited for growing in greenhouses
B	Normal cultivar for eating raw; firm flesh, large and soft seed cavity
C	Normal cultivar for eating raw; firm flesh, small seed cavity
D	Normal cultivar for eating raw; firm flesh, small seed cavity, clean break by biting

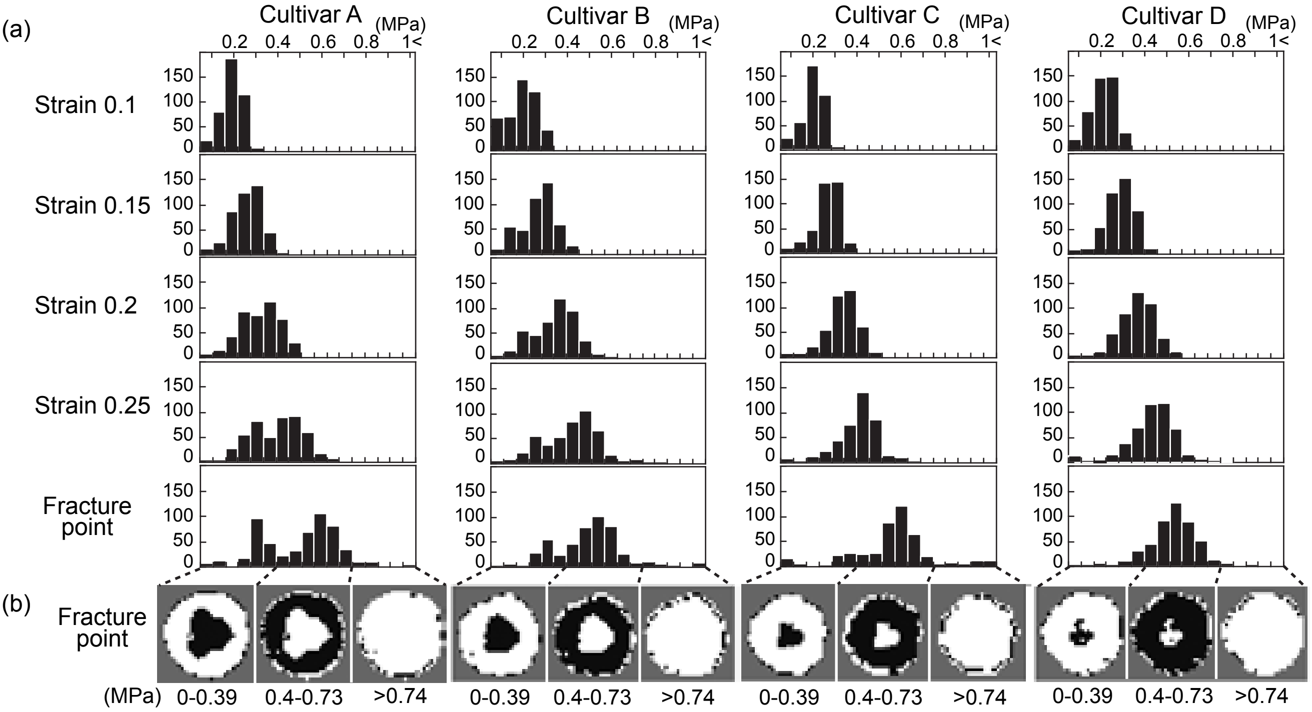

Fig. 3. (a) Stress histograms for four cultivars, for the frames of 0.1, 0.15, 0.2, 0.25 strains, and fracture point
X axis: Stress (MPa). Class values are 0.076, 0.134, 0.191, 0.249, 0.306, 0.363, 0.421, 0.478, 0.535, 0.593, 0.650, 0.707, 0.765, 0.822, 0.879, 0.937, and 0.994 <. Y axis: Number of the sensing points that detect stress.
(b) The positional characteristics of stress distribution at fracture point
The stress class levels are low (0 to 0.39 MPa, shown in black), middle (0.4 to 0.73 MPa, shown in black) and high (> 0.74 MPa, shown in black).

by the unique perspective of the planar stress distribution for each scanning frame. The planar stress distributions for frames 0.1, 0.15, 0.2, and 0.25 strains and the fracture point (around 0.3 strain) are shown for the four cultivars (Fig. 2, (1) to (5)). A stress histogram of all sensing points that detected any stress was also prepared (Fig. 3).

The stress-distribution map indicated that the stress distribution of the cucumber cross-sections was uneven. Comparing the frame images or histograms of the same strain among the cultivars, it was noted that breed specificity was clearer at higher strain levels (Fig. 3). When the strain was small, the histograms of all the cultivars exhibited a monophasic distribution and a similar mode of distribution. When the strain reached 0.2 and above, cultivars C and D maintained monophasic distributions; however at the same strain levels, cultivars A and B displayed diphasic distributions. In cultivars A and B, the new second peaks appeared at the lower side of the stress axes, while the first peaks existed at the same class as monophasic distributions.

To demonstrate the positional characteristics of stress distribution, the stress classes were trisected into “low” (0 to 0.39 MPa), “middle” (0.4 to 0.73 MPa) and “high” (> 0.74 MPa) levels (Fig. 3). The sensing points belonging to the high group were at the exterior of the sample corresponding to the skin. The low group sensing points were at the center and outmost edge of the sample corresponding to the seed cavity. The sensing points of the middle group were in between these two groups corresponding to the flesh. The distribution of the low group at the outmost edge was attributed to the effect of sample edges.

There were significant differences in the regional distribution of the low stress group between cultivars; cultivars A and B were large whereas cultivars C and D were small[8]. With this in mind, the diphasic distribution in histograms of cultivars A and B can be explained to result from the larger seed cavities and their low stress, making the regions of low stress relatively large and consisting of the second peak at lower stress. For cultivars C and D, the monophasic distribution in the histograms resulted from smaller seed cavities that made the regions of low stress relatively small and thus the histograms did not consist of the second peak at lower stress.

Several studies reported the mechanical properties of various cucumber tissues. Thompson et al. (1982)[26] conducted penetration tests for different positions in cross-sectional slices of cucumber, and showed that the tissue was firmer near the skin and became progressively softer toward the seed area. In addition, they demonstrated that penetration force for exocarp was larger than that for mesocarp by differentiating exocarp peak from mesocarp peak within a single penetration curve[25]. These previously reported mechanical features of cucumber tissues were clearly captured using the MSS system. Compared to the puncture tests, this analysis method has the merit of revealing the mechanical properties and their geometrical distribution simultaneously.

The MSS system successively demonstrated the characteristics of the two-dimensional stress distribution in each tissue of cucumbers and its differences among cultivars during the prefailure process of compression tests. The planar stress distribution of a whole cross-sectional area will offer useful information about the textural properties of heterogeneous tissues.

2. Postfailure process

In this section an attempt is made to examine the postfailure process of cucumber cultivars, taking into consideration the heterogeneity and anisotropy of plant tissues, to explore the mechanical properties that determine cultivar-specific crispy and crunchy textures.

The two-dimensional stress distributions for the load drop after the initial fractures for the four cultivars were analyzed. Stress-distribution maps were prepared for the fracture point, strain 0.001 after the fracture point, and the difference between them (Fig. 2, (5), (6), (6)-(5)).

These three maps, particularly the difference map, revealed where and how much the stress changed on the sample surface during the load drop of the initial fracture. The stress map of strain 0.001 after the fracture point revealed the location and intensity of the initial fracture. The stress change occurred primarily at the flesh and skin regions in all the cultivars; it rarely occurred at the central seed cavity region. A new small crack-like zone of low stress appeared for cultivar A, whereas low stress expanded over almost the entire region on cross-sections of cultivar D. The stress map for the difference between the fracture point and strain 0.001 after the fracture point illustrated these phenomena more clearly. The stress changed in a broad area for cultivar D, while it changed locally and in a small area for the cultivar A.

The initial fracture event occurred locally for cultivar A, with a significantly smaller area and load changes than the other cultivars[9]. In addition, there were many peaks after the initial fracture point[9]. This arose from sequential repetition of small local fractures as sample compression progressed (Fig. 1b, black line). Fig. 4 is a typical distribution map of the stress difference between the local peak and strain 0.001 after the local peak for each load drop. The distribution of the substantial stress difference was local for each map, and the locations of sizable stress differences shifted among these maps. It was speculated that the local fracture occurs in sequence at a location where a

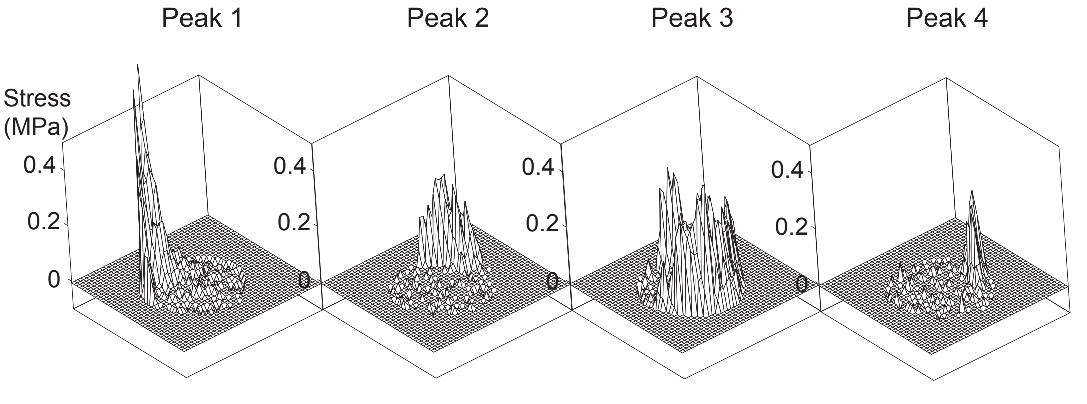

Fig. 4. Distribution maps of the stress difference between the local peak and strain 0.001 after the peak for each load drop for cultivar A (corresponding to the peaks 1, 2, 3, and 4 in Fig. 1b)

Each square represents one 1.27 × 1.27 mm sensing point.

fracture has not yet occurred. While this measurement only indicates the qualitative relationship between the load drop and stress distribution, it enables the observation of a structural fracture during a series of load drops for the first time.

Cultivar D exhibited opposite tendencies for the parameters of initial fracture and the postfailure process to those of cultivar A. Area and load changes at initial fracture were significantly larger for cultivar D[9]. Thus, a global fracture event could occur on the entire cross-sectional area at the initial fracture. This was confirmed visually by the stress-distribution map of the difference between these two time points, in which there was only a small area with no stress change at the center of the cross-section that the seed cavity occupied (Fig. 2, cultivar D). The peak numbers after the initial fracture were significantly smaller[9]. It was presumed that a large global fracture occurred at the time of the initial fracture of this cultivar, followed by several small fractures.

The textural characteristic of cultivar D is firm but brittle with crispy flesh. Sudden and complete propagation of a crack (a clean break) is characteristic of the preferred texture for raw cucumbers in Japan. The fracture characteristic of this cultivar was that a few large fractures occurred globally. The load dropped abruptly after the initial fracture. A similar event may occur during incisal biting in the human mouth. These sudden drops in the applied load rate, which are detected by the jaw-closing muscles and sensors in the soft tissues around individual teeth[28], may produce the perception of a clean break for this cultivar.

From the two-dimensional stress-distribution map, it was confirmed how fractures occur, as either a major global fracture event or a number of sequential small local fractures. The two-dimensional information about postfailure events enabled it to relate the structural fracture phenomenon to the load-strain property of each cultivar. This technique is applicable to other food materials to explore the relationships among their mechanical properties, structure, and texture.

Conclusion

Texture perception is an important factor in consumer sensory appreciation. Texture is defined by the international standard ISO 5492 as "All the mechanical, geometrical and surface attributes of a product perceptible by means of mechanical, tactile and, where appropriate, visual and auditory receptors." A foodstuff cannot have texture, only particular mechanical (and other) properties which are involved in producing sensory feelings or texture notes for the human being during the act of chewing the foodstuff[15]. For better understanding the nature of food texture, we should research texture-inducing properties[15] such as fundamental knowledge of the factors which manifest themselves as texture[3]. We should focus on not only mechanical, geometrical and surface properties, but also its spatiotemporal, heterogeneous and time-induced changes as well. Stress distribution measurements using the I-Scan system can give rise to a new perspective for these properties, that is, visualization of the spatiotemporal change of heterogeneous and anisotropic food structure. As demonstrated here, the effective use of this information contributed to a better understanding of the texture of plant-based foods. This approach contrasts with previous attempts to measure texture-related properties, which are basically single-point measurements. Texture is a multisensory and complex property still largely unknown. The characterization of stress distribution maps could provide new approaches to a better understanding of the texture of edible plant organs and to controlling plant development and product quality.

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