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A Method for Determining the Causal Relationship Between Food Texture and Physical Features in Mastication

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Abstract: Food texture is a key factor influencing palatability. This study presents a method for determining the causal relationships between measurement data and sensory evaluation results of food texture. Twelve food samples, categorized into three groups, and ten texture descriptors were selected to analyze changes in food texture during mastication. A measurement system comprising a force sensor, an accelerometer, and a microphone collected data during twelve compression cycles. Sensory evaluation data were also obtained during twelve chewing cycles using the temporary dominance sensations method. The causal relationships between feature values derived from measurement data and texture descriptors from sensory evaluations were determined using the Granger causality test with a vector autoregression model. Most identified causal relationships were found to be reasonable based on our understanding of texture perception and sensory attributes.

Keywords: Measurement, perception, food texture, Granger causality test

1. INTRODUCTION

Food texture plays a crucial role in food palatability, alongside taste and aroma [1, 2]. Since consumers primarily select food products based on their palatability, food companies need a reliable method to evaluate food texture in order to develop products with acceptable textures.

Humans perceive food texture during mastication. The mastication process breaks down the food's structure into small fragments while saliva moistens them [3]. Food texture is not perceived as a constant property throughout mastication. Therefore, an evaluation method is necessary to account for changes in food texture. One approach for evaluating food texture is Texture Profile Analysis (TPA) [4, 5]. This method measures the compression force applied to a food sample twice and extracts TPA parameters such as hardness, cohesiveness, and other attributes. While this method is useful for companies equipped with compression test machines, it primarily evaluates the texture experienced during the first two bites. Nakamoto et al. utilized the first two compression data to predict food texture [6, 7]. However, for food product design, understanding not only texture prediction but also its causality is important. Further analysis is required to determine the causal relationship between TPA parameters and food texture perception.

Sensory evaluation, in which human subjects assess food properties based on their perceptions, is also conducted in food companies. The advantage of sensory evaluation is that it provides direct human feedback. One type of sensory evaluation, known as the Temporal Dominance of Sensations (TDS) method, evaluates food properties based on time-series changes [8]. This method is considered suitable for assessing food texture. However, human subjects exhibit fluctuations in their evaluations due to variations in physical and psychological conditions. Additionally, sensory evaluation generally requires significant time and cost. If the causal relationship between measurement data and sensory evaluation data regarding food texture can be established, the measurable feature values that contribute to a specific texture will become clear, enabling the design of that texture.

To establish the causal relationship between measurement data and sensory evaluation data, this study first conducts measurements using repetitive compression tests that simulate human mastication and extracts feature values from time-series measurement data. By applying a vector autoregression model, the relationship between these feature values and sensory data evaluated through the TDS method is identified. Additionally, the Granger causality test elucidates the causal relationship between them. This causality highlights significant feature values relevant to food texture. The effectiveness of the proposed method using the autoregression model is validated through experiments.

2. METHODS

2.1. Food sample and texture

This study examines various food textures that change during mastication. Toda and Wada categorized solid foods based on their physical properties into porous foods, gel-type foods, and sponge-like foods [9]. Following this categorization, we selected twelve commercially available food samples, as listed in Table 1.

The authors examined the sample foods listed in Table 1 and discussed the food textures perceived during mastication. By focusing on the early and later stages of mastication, ten food texture descriptors shown in Table 2 were identified with reference to Hayakawa's classification [10]. The following table presents these texture descriptors along with their definitions.

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† Hiroyuki Nakamoto is the presenter of this paper.

Table 1: Food samples.

Index	Category	Sample	Product name and company
S1	Porous	Sablé	Coconut sablé, Nissin Cisco Co., Ltd.
S2	Porous	Thick rice cracker	Salad peanuts, Seven & i Holdings Co., Ltd.
S3	Porous	Biscuit	Plain biscuit, Seven & i Holdings Co., Ltd.
S4	Porous	Thin rice cracker	Kameda usuyaki, Kameda Seika Co., Ltd.
S5	Porous	Fried dough cookies	Shiro karinto, AEON TOPVALU Co.,Ltd.
S6	Gel-type	Fish cake	Sansyoku kamaboko, Kanetetsu Delica Foods, Inc.
S7	Gel-type	Jelly	Konnyaku batake, Mannanlife Co., Ltd.
S8	Gel-type	Cylindrical cheese	Candy cheese, AEON TOPVALU Co.,Ltd.
S9	Gel-type	Red bean jelly	Yokan, imuraya co., ltd.
S10	Sponge-like	Sliced white bread	Choujuku, Pasco Shikishima Co.
S11	Sponge-like	Rice flour roll bread	Komeko roll, Pasco Shikihshima Co.
S12	Sponge-like	Chewy donut	Mochimochi ring sugar, SEVEN-ELEVEN JAPAN Co., Ltd.

Table 2: Texture descriptor and definition.

Descritor	Definition
Sakusaku	Easily broken when bitten with weak force
Zakuzaku	Fractures into layers and small particles, producing a low-frequency sound
Karikari	Short, crisp fracture requiring relatively strong force during mastication
Paripari	Thin foods that break with a relatively high-frequency sound
Gunyagunya	Flexible and elastic, maintaining its structure during mastication
Guchagucha	Mushy texture with slight stickiness during mastication
Fuwafuwa	Fluffy, light, and airy, compressible with weak force
Mochimochi	Elastic and chewy, with a slightly sticky texture
Nechanecha	Highly sticky and viscous, with low water content
Bechabecha	Sticky, viscous, and watery texture

2.2. Measurement system

To compress a food sample repetitively, a measurement system, as shown in Fig. 1, is constructed. The system primarily consists of a force sensor (MINI8/40-A, BL AUTOTEC, Ltd., Japan), a three-axis acceleration sensor (NP-3564N10, Ono Sokki Co., Ltd., Japan), a probe, a microphone (MI-1271M12, Ono Sokki Co., Ltd., Japan), a rod-type electric actuator (LEY16DA-100C, SMC Co., Japan), a portable data recorder (DR-7100, Ono Sokki Co., Ltd., Japan), and a desktop computer. The force sensor measures the normal force applied to the rod-type actuator within a range of 0 to 158 N and is connected to the desktop computer via an A/D conversion board (AIO-163202FX-USB, Contec Co., Ltd., Japan). The sampling frequency of the A/D board is 1 kHz. The acceleration sensor is fixed to the probe, as shown in Fig. 2, and the microphone is connected to the portable data recorder, recording data at a sampling frequency of 51.2 kHz. The rod-type actuator compresses the food sample via the force sensor and probe with a maximum force of 141 N and is connected to a motion controller (SMC-4DL-PE, Contec Co., Ltd., Japan) embedded in the desktop computer. The probe is cylindrical, with a diameter of 12 mm and a length of 30 mm.

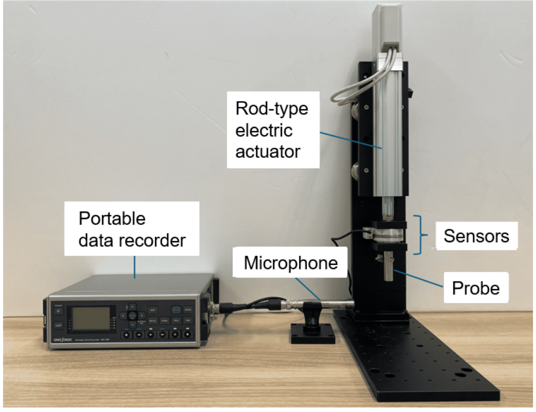


Fig. 1: Main components of measurement system.

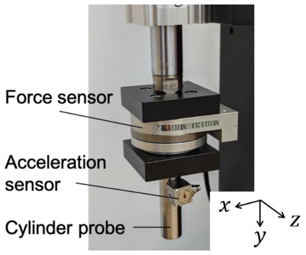


Fig. 2: Force and acceleration sensors.

2.3. Measurement and feature values

A food sample is shaped into approximately a 12-mm diameter and placed in a container with an inner diameter of 13 mm. The measurement system compresses the food sample with the probe twelve times and simultaneously records force, acceleration, and sound pressure. The size of sample is ten.

2.3.1. Feature values of force

An illustration of force data is presented in Fig. 3. Typical force data for a single compression are shown on the right side of Fig. 3. The force data obtained from repetitive compressions are divided into two-compression segments, labeled as the 1st data, the 2nd data, and so on. The latter half of the 1st data and the former half of the 2nd data overlap. Feature values are calculated from the two-compression data. The definitions of the feature values, based on TPA [4], are listed in Table 3.

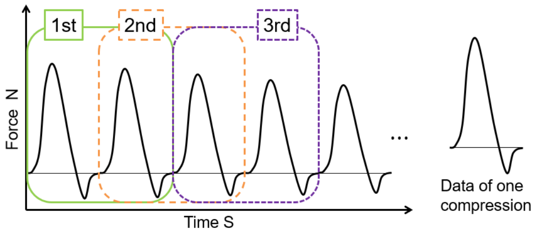


Fig. 3: Force data of repetitive compressions and division into the two-compression data.

2.3.2. Feature values of acceleration

First, the acceleration data are divided into two-compression segments, similar to the force data. Then, three feature values–the maximum absolute y-axis acceleration m/s^2, the number of peaks, and the mean magnitude of three-axis acceleration m/s^2–are calculated from the acceleration data. The y-axis acceleration corresponds to the direction of the compression motion as shown in Fig. 2.

2.3.3. Feature values of sound pressure

Sound pressure data are also divided into two-compression segments. To remove external noise, the sound pressure data are set to zero when the force data are zero. After that, loudness and sharpness are calculated from the sound pressure data.

2.3.4. Experimental condition

In the experiment, a sample is placed in a container with a diameter of 13 mm. The measurement system compresses the sample twelve times. The compression velocity is 10 mm/s, and the compression rate is 80%. At each compression interval, 0.036 ml of water is manually added to the sample using a syringe, totaling 0.4 ml. The horizontal distance between the probe and the microphone is 25 mm.

2.4. Sensory evaluation

During mastication, major changes in food texture occur. To record these changes, the TDS method is applied [8]. This study was approved by the Ethics Committee of the Kobe University Graduate School of System Informatics (No. R05-04) in accordance with the Helsinki Declaration.

In this sensory evaluation, a user interface that comprises the start and end buttons, the buttons labeled texture descriptors, and elapsed time is displayed on a laptop computer. A human subject operates the buttons. The subject places a sample in their mouth and clicks the start button to initiate the sensory evaluation. After the click, the interface emits a sound every 1.5 seconds. The subject chews the sample in synchronization with the sound and selects one of the texture descriptors to indicate the dominant texture at any moment. If the perceived texture changes, the subject clicks the corresponding new texture descriptor. The chewing process is repeated twelve times. Once the subject has swallowed the food bolus, they click the stop button. The laptop computer records the time and the selected texture descriptors.

In the calculation process of the TDS method, the recorded data are first standardized along the time axis. Then, a dominance rate for each texture is calculated from the standardized data. The probability level P_0 and the 5% significance level P_s are expressed as follows.

$$P_0 = \frac{1}{n_p}. \tag{1}$$

$$P_s = P_0 + 1.645\sqrt{\frac{P_0(1-P_0)}{n}}, \tag{2}$$

where n_p represents the number of the texture descriptors, n is defined as (the number of subjects $\times$ the number of trials for each subject). The dominance rate exceeding the significance level is considered indicative of a significant texture.

Ten male subjects, aged 23.7 ± 1.2 years, participated in the sensory evaluation using the TDS method. All subjects practiced using the TDS interface and understood the definitions of the texture descriptors in advance. Samples were provided in one-bite sizes. The order of the samples was randomized, and the number of evaluations consisted of three sets, with each set comprising twelve samples.

2.5. Model and causality test

2.5.1. Vector autoregression model

This study employs the vector autoregression (VAR) model to analyze the causality between sensory evaluation values and measured feature values. The first-order VAR model for food textures and feature values is formulated as follows:

$$\mathbf{y}_t = \mathbf{c} + \mathbf{A}^{(1)}\mathbf{y}_{t-1} + \epsilon_t, \tag{3}$$

where $\mathbf{y}_t$ is an n-dimensional vector at time t, $\mathbf{A}^{(1)}$ is an $n \times n$ matrix with a lag of 1, $\mathbf{c}$ is a constant vector, and $\epsilon_\mathbf{t}$ is a disturbance term. Here, n represents the total number of one texture and feature values, and t denotes t-th chewing time. By employing the VAR model, the causal relationship is analyzed using the Granger causality test.

2.5.2. Granger causality test

The Granger causality test assumes the stationarity of sequential data. Therefore, the augmented Dickey-Fuller (ADF) test is used to check for stationarity. First-order differencing is applied to the TDS data and the normalized feature values to remove the trend. Through this process, the length of the data is reduced by one. If the ADF

Table 3: Definition of feature values of force data.

Feature value	Definition
Hardness N	Maximum force applied during the first compression
Brittleness N	Maximum force drop before reaching the peak force during the first compression
Adhesive force N	Maximum absolute force in the negative direction during the separation of a compressed sample
Adhesiveness J	Area of the negative force during the separation of a compressed sample
Springiness %	Ratio of the time to the second peak to the time to the first peak
Cohesiveness %	Ratio of the positive area during the second compression to the positive area during the first compression

test fails to confirm the stationarity of the full-length data, the data length at which non-stationarity is rejected at a 5% significance level is used for the Granger causality test.

3. RESULT AND DISCUSSION

3.1. Measurement experiment

The system measured force, acceleration, and sound pressure of food samples through twelve compressions and analyzed the feature values based on the measurement data. The feature values of sablé are shown in Fig. 4. Since the feature values were calculated from two-compression data, the horizontal axes of the plots start from the second compression. Most feature values gradually changed through compression iterations.

3.2. Sensory evaluation

The TDS curves calculated from the sensory evaluation data are shown in Fig. 5. The curves that exceed the significance level, represented by the horizontal red dashed line, indicate dominant textures. Overall, the dominant food texture of the samples changed twice or three times during mastication. For example, the biscuit in Fig. 5c exhibited sakusaku during early mastication and nechanecha in the later stage. Fish cake and jelly, shown in Fig. 5f and 5g, transitioned from gunyagunya to bechabecha. Roll bread in Fig. 5k displayed three textures: fuwafuwa, mochimochi, and nechanecha. The texture changes varied depending on the sample.

3.3. Granger causality test

The Granger causality test was performed on the VAR model using the TDS data and measured feature values. This test was conducted on the data within the range where the stationarity of the differenced series was confirmed. A few examples of causal graphs are shown in Fig. 6a and 6b present graphs of sablé, where the sakusaku texture of sablé exhibited causal relationships with hardness and brittleness. The nechanecha texture of sablé had a causal relationship with hardness. These results appear reasonable in terms of our texture perception. The sakusaku texture of thick rice crackers in Fig. 6c demonstrated nine causal relationships, except for adhesive force and the number of peaks, indicating a complex relationship between texture and physical properties. The guchagucha texture of cheese was causally linked to brittleness, adhesiveness, and loudness, as shown in Fig. 6d. The mochimochi texture of donuts in Fig. 6e exhibited causal relationships with adhesiveness, cohesiveness, and springiness. These relationships are also considered reasonable.

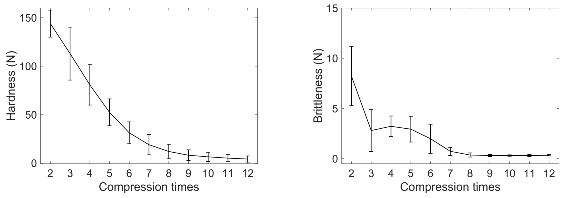
Table 4: Causal relationship between sample's texture and feature values.

Index	Texture	Feature value
S1	Sakusaku	Hardness, brittleness
	Nechanecha	Hardness
S2	Sakusaku	Except for adhesive force, num. of peaks
	Nechanecha	Adhesiveness
	Bechabecha	Brittleness, cohesiveness
S3	Sakusaku	Hardness
	Nechanecha	Adhesive force
S4	Paripari	Brittleness, springiness
S5	Karikari	Hardness
	Zakuzaku	Hardness
	Bechabecha	Brittleness, springiness
S6	Gunyagunya	Adhesive force
S7	Gunyagunya	Springiness, max. peak
S8	Guchagucha	Brittleness, adhesiveness, loudness
S9	Guchagucha	Adhesive force
	Nechanecha	Cohesiveness
S10	Fuwafuwa	Cohesiveness
	Nechanecha	Brittleness
S11	Fuwafuwa	Brittleness
	Mochimochi	Max. peak, mag. acc.
S12	Mochimochi	Adhesiveness, cohesiveness, springiness

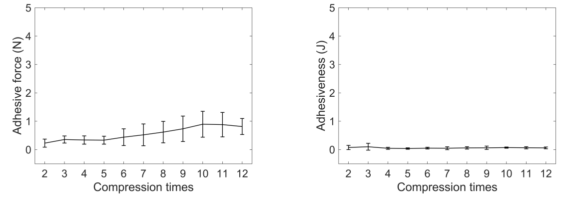
The causal relationships are summarized in Table 4. The causal relationships between most textures and feature values, whose significant differences were confirmed using the TDS method, have been verified.

3.4. Discussion

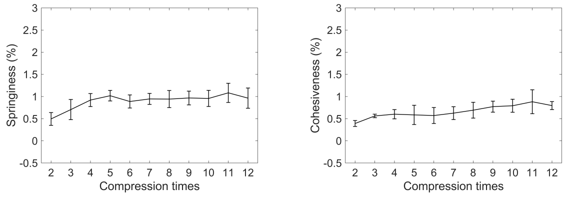
Regarding the feature values shown in Fig. 4, hardness and brittleness were highest at the second compression and gradually decreased over the compression iterations. In contrast, adhesive force gradually increased. These results indicate that the bolus formed as the fracture progressed through compression. The feature values of acceleration and sound pressure showed that only the second and third compressions exhibited high values, suggesting that the acceleration sensor and microphone



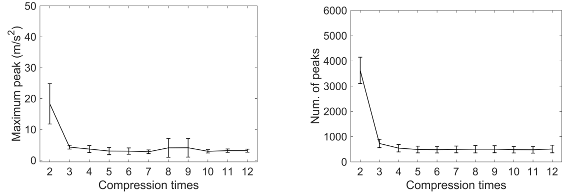
(a) Hardness. **(b)** Brittleness.



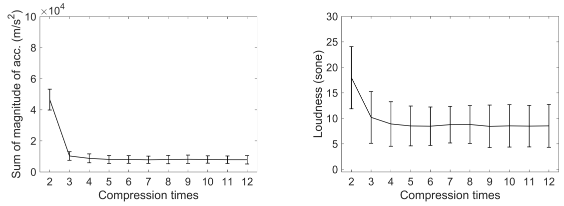
(c) Adhesive force. **(d)** Adhesiveness.



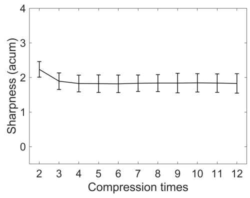
(e) Springiness. **(f)** Cohesiveness.



(g) Max. peak of acceleration. **(h)** Num. of acceleration peaks.



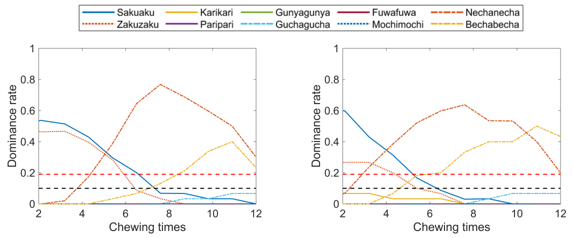
(i) Sum of magnitude of acceleration. **(j)** Loudness.



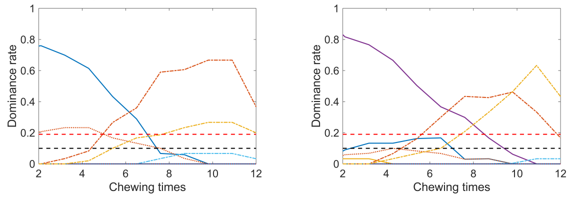
(k) Sharpness.

Fig. 4: Feature values of sablé. The error bar indicates the range of the standard deviation.

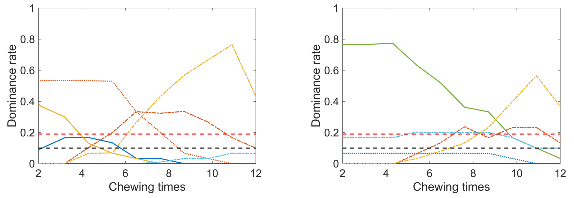
captured the sample's fracture during the initial stage. Although the results are not presented in a graph, the measured forces of the fish cake and jelly remained largely unchanged throughout repeated compressions, which was reflected in their hardness. In contrast, the forces of the bread and roll bread were weak and lacked adhesive force even during the initial stage of compression. These findings suggest that the absence of adhesive force influenced the perception of the fuwafuwa and mochimochi textures of the breads. Overall, the measurement system effectively captured the physical characteristics of the sample foods.



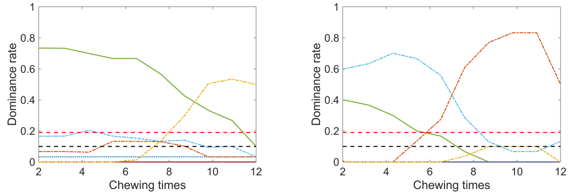
(a) S1: Sablé. **(b)** S2: Thick rice cracker.



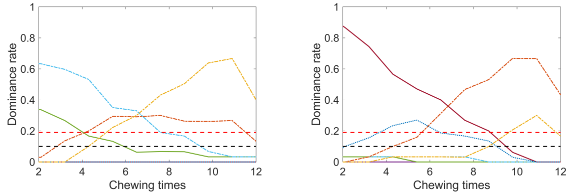
(c) S3: Biscuit. **(d)** S4: Thin rice cracker.



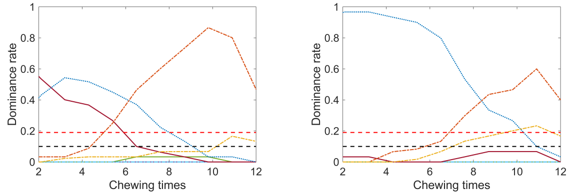
(e) S5: Fried dough cookies. **(f)** S6: Fish cake.



(g) S7: Jelly. **(h)** S8: Cheese.



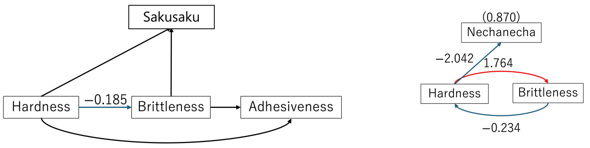
(i) S9: Red bean jelly. **(j)** S10: White bread.



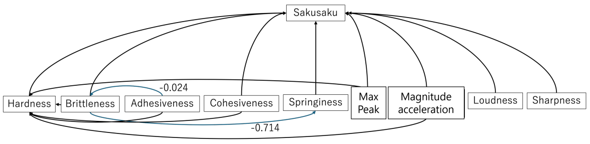
(k) S11: Roll bread. **(l)** S12: Chewy donut.

Fig. 5: TDS curves. The horizontal black and red dashed lines represent the probability and significance levels, respectively.

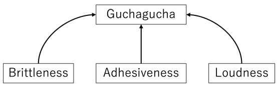
The TDS method demonstrated that most samples exhibited two dominant textures during mastication, corresponding to the early and later phases. The number of chewing cycles required for the transition between these textures varied depending on the sample. As shown in Fig. 5f and 5l, some samples maintained their early-phase textures for an extended duration, whereas others,



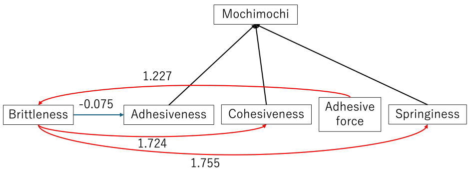
(a) Sakusaku of sablé (S1). **(b)** Nechanecha of sablé (S1).



(c) Sakusaku of thick rice cracker (S2).



(d) Guchagucha of cheese (S8).



(e) Mochimochi of donut (S12).

Fig. 6: Causality graph examples. The values of the arrows denote partial regression coefficients. The red and blue arrows denote positive and negative coefficients, respectively.

as illustrated in Fig. 5b and 5k, transitioned to the later-phase texture relatively quickly. While the TDS method is commonly used for evaluating taste and aroma, it is also considered an effective approach for visualizing textural changes. The TDS curves of the twelve samples used in this study exhibited distinct variations, confirming through the data that subjects perceived unique textural characteristics.

The results of the causality test confirmed causal relationships for the texture of all food samples. However, certain textures–such as the bechabecha of thin rice crackers (S4) and the nechanecha of cheese (S8)–exhibited high dominance rates in the TDS method but did not demonstrate causality. Most of the confirmed causal relationships were deemed reasonable based on our understanding of texture perception and sensory attributes. For instance, the sakusaku of sablé (S1) was associated with hardness and brittleness, while the mochimochi of donuts (S12) correlated with adhesiveness, cohesiveness, and springiness. On the other hand, some causal relationships appeared less intuitive, such as the association between bechabecha in S5 and brittleness and springiness, as well as the relationship between fuwafuwa in S11 and brittleness. These textures corresponded to data with minimal variations in feature values, suggesting that enhancing the sensitivity of the measurement system could be a potential solution. Additionally, even for the sample texture, different causal relationships were observed depending on the feature values, indicating that the nuances of texture might vary depending on the food sample, even within the same category. While the samples were categorized into three groups for this study, further refinement of texture definitions within more narrowly defined categories is warranted. Overall, the proposed process using the Granger causality test on the sensory evaluation and measurement data successfully determined the causal relationship between textures and feature values.

4. CONCLUSIONS

This study presented a method for analyzing food texture to determine the causal relationships between measurement data and sensory evaluation results. Through experiments, the VAR model and the Granger causality test were used to identify these relationships. Most of the identified causal links were found to be reasonable based on our understanding of texture perception and sensory attributes. We believe that these causal relationships can be applied to the design of food textures. In future studies, the causal relationships examined in this research will be extended beyond Japanese texture terminology, as we aim to apply this method to different languages.

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