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Patterns Observed in the First Chew of Foods with Various Textures

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Pressure distribution during the chewing of food with molars was measured using a multiple-point sheet sensor, and compared with results from an instrumental compression test. The sensor system detected the masticatory pressure with many sensing cells so that masticatory force and contact area between food materials and the lower teeth were directly measured. Masticatory pressure of five foods (white bread, raw carrot, cracker, rice cracker and Yokan) for fourteen healthy adults was measured, and the different pressure patterns related to the texture were discussed. Masticatory force *versus* time curves were characterized by each sample, although they varied largely by subject. Two peaks appeared in the masticatory curves of carrot and Yokan, more peaks were shown in cracker and rice cracker, but the first peak was missing for the bread mastication. The first peak corresponded to sample rupture, therefore the active pressure defined as the force divided by the contact area was found to reflect the breaking stress of the samples. Similar to the results of mechanical tests, brittle cracker and rice cracker showed a lower breaking force within a short time at the first peak. The last peak appearing just before teeth opening was similar to the maximum masticatory force for bread, cracker, rice cracker and Yokan, and did not correspond with the breaking force of samples. The order of the active pressure at the last peak was similar to that of stress values at very high strain measured in a compression test. The maximum force detected during one chew is not always measured in a normal instrumental test.

Keywords: mastication, intra-oral force, food texture, multiple-point sheet sensor, breaking stress

Texture is known to be a very important factor determining the attributes of food (Szczesniak & Kleyn, 1963) and it therefore affects the quality and preference of foodstuffs (Matsumoto & Matsumoto, 1977). Texture evaluation is required for quality control as well as in the research and development of new food products. We can classify the measurement methods of texture into two: subjective or sensory evaluation, and objective or mechanical testing using an instrument (Yamano, 1994). When humans eat food, pressure is generated between the upper and lower teeth as the jaw closes. General mechanical tests of food materials measure the pressure at different compression strains by an instrument such as an Instron universal testing machine. Though mechanical tests sometimes repeat the compression twice or more as chewing movements, the pressure at the first chew is most influenced by the original texture of samples. Both the instrument tests and human mastication seem similar, however, mechanical tests often fail to identify food texture. We assume that the differences in compression speed and direction, temperature, moisture, sensing systems etc. in an instrument test are responsible for the difference in results (Kohyama, 2000). We therefore introduce a new technique, which is a direct measurement of human mastication, to evaluate the texture and to complement mechanical testing and sensory evaluation (Kohyama, 2000). This method establishes an objective value, which is aimed at approximating the human sense of texture, since the process used to test food is human mastication.

Measurement of pressure on human teeth during chewing is one direct method. Masticatory force has been measured with a micro pressure sensor attached to a tooth (Bearn, 1973; Tornberg *et al.*, 1985; Hagberg, 1987; Takahashi & Nakazawa, 1987; Miwa, 1995). Since studies of most previous authors used sensors glued on or embedded in an artificial tooth, measurements on subjects who do not use dentures to determine general mastication were difficult (Kohyama, 2000). A multiple-point sheet sensor can conveniently be used for many subjects without dental treatment (Kohyama & Nishi, 1997; Kohyama *et al.*, 2000; Kohyama & Sakai, 2001; Kohyama *et al.*, 2001). Bite force distribution for crackers with incisors showed their crispy character and the order of maximum force was different from that observed in an instrument test (Kohyama & Nishi, 1997). The breaking force of tough kelp did not influence the maximum force at first chew with molars (Kohyama *et al.*, 2000; Kohyama & Sakai, 2001). We guessed that the independence of masticatory pressure on the sample hardness is observed in tough samples, whose high breaking strain makes them difficult to break with one chew. On the other hand, the masticatory force and the peak time of the first chew with molars for some gels corresponded well to the breaking force and deformation in a mechanical test (Kohyama *et al.*, 2001). Food texture seems to be the factor deciding conformity or nonconformity between masticatory pressure and mechanical results. Unlike kelp, many foodstuffs break during the first chew.

This study aimed to clarify the effects of food texture on the pressure of the first chew with molars. Sample foods ranging widely in texture were chosen. Takahashi and Nakazawa (1987) measured chewing force patterns of various foods using a micro-pressure transducer in an artificial tooth of one subject. They classified food samples into four groups by the masticatory force

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patterns observed in the first chew. We chose bread from their group A, Yokan (a sweet agar gel made with azuki-bean paste) from B, raw carrot from C, and rice cracker from D. Cracker was added as it was previously studied on incisor biting (Kohyama & Nishi, 1997). The parameters of the masticatory measurement were compared with those of a mechanical compression test.

Materials and Methods

Samples White bread (Sun Royal, Yamazaki Baking Co., Ltd., Tokyo) sliced 20 mm thick was hollowed out by a ring cutter with a diameter of 25 mm. Fresh raw carrot bought in a local market and Yokan (Hon-Neri, Yamazaki Baking Co., Ltd) were cut into cylinders 25 mm in diameter ×10 mm thickness. Crackers (Yamazaki Nabisco Co., Ltd., Tokyo) and unflavored rice crackers (Akita Inafuku Beika Co., Ltd., Akita) were kindly made by the manufacturers the same size with a diameter of about 25 mm.

These sample sizes were chosen because they were found easy to chew with molars in a preliminary test. A small sample is difficult to find in the oral cavity, and is sometimes swallowed without chewing if it is soft. A wider and thicker sample is difficult for subjects with a small mouth to bite with molars.

Mechanical test A compression test of each sample was carried out using a universal testing apparatus (Instron 5564) with a flat probe (2580 mm^2) at a constant speed of 1 mm/s. Test temperature was 23°C as same as that for the mastication experiments. Stress was calculated as the detected load divided by the initial cross-sectional area of a sample to delete the effect of the original size. Strain was the ratio of deformation to the initial height. Initial slope of the stress-strain curves was determined at 1% strain. The sample breaking point was set as the first reduction in stress observed. The breaking energy was defined as the area under the stress-strain curve up to breaking.

Masticatory pressure measurement Fourteen healthy subjects (7 men and 7 women, age 29.6±7.6 years) without functional problems in mastication voluntarily participated in this experiment.

Masticatory pressure was measured with an ISCAN system (Nitta Corp., Osaka). The hardware was remodeled in order to speed up the sampling rate mentioned in a previous paper on cracker biting (Kohyama & Nishi, 1997). The new system can measure a high sampling rate to 1200 Hz (Azuma, 2001). A sensor sheet called "MSCAN2" was specially designed to measure masticatory force with one side of the molars, and is composed of 243 sensing points forming a grid of 2 mm pitch on a flexible plastic film with a saturated pressure of 4 MPa (Kohyama *et al.*, 2001). Each sensor is calibrated with a fixed load applied by the Instron apparatus.

Since crisp samples like fresh crackers loose their textural characteristics very rapidly within 0.2 or 0.3 s from the beginning of a bite (Kohyama & Nishi, 1997), a fast sampling rate was required. A low sampling rate made the force-time curves of mastication smooth, because the sample breaking points were not detected. We recorded mastication force at various sampling rates up to 1200 Hz in a preliminary test (Azuma, 2001). The smoothing effect was not observed at a rate of 600 Hz for low moisture foods, but 100 to 200 Hz was fast enough for gel-type foods. Therefore, the sampling in this study was carried out at 600 Hz for carrot, cracker and rice cracker, and at 200 Hz for bread and Yokan.

A cylindrical sample was attached to the sheet sensor with adhesive tape. Subjects inserted the sample on the sensor sheet between the upper and lower first molars of their habitual chewing side themselves without touching it with their fingers, and then normally chewed the sample twice. The 5 foods were tested in random order, and each sample was replicated more than twice. Masticatory pressure detected by 92 sensing cells under the samples before the second chew was analyzed.

The following parameters were calculated from the masticatory curves: peak force, time, contact area between samples and teeth, and active pressure (force divided by the contact area) at the peak, duration of the force, cycle time (period from the beginning of the first chew to beginning of the second), impulses (time-integral of the force) during the first chew and up to the first peak, initial slope, and mean slope (slope of a straight line from the onset to the first peak).

Statistical analyses were done using an SPSS package (ver. 9.0J for Windows).

Results

Mechanical test Figure 1 and Table 1 show the results of the mechanical test.

The high initial slope of the curves for rice cracker and raw carrot showed their hard texture. A peak was often, although not always, observed for carrot at strain around 70% in Fig. 1. White bread and Yokan, in contrast, showed smooth stress-strain curves with low initial slope, indicating they were soft.

Rice cracker showed many peaks in stress, which formed a zigzag pattern in the stress-strain curves, indicating its crispy characteristics. Cracker also showed the zigzag pattern at low strain ranges to about 20% and a smoother curve was observed at high strain ranges. The first decrease in stress observed at very small strain evidenced that the two samples were brittle. The higher stress value for rice cracker than that for cracker indicated it was the harder of the two. A 1 kN load cell used in this mechanical test did not allow measurement at strain ranges higher than around 60% for rice cracker and 90% for cracker.

Carrot and Yokan showed a higher breaking strain than cracker or rice cracker. Bread did not show any decrease in force to 98% strain, indicating it was difficult to break in the mechanical test. Except for bread, breaking stress of raw carrot was the high-

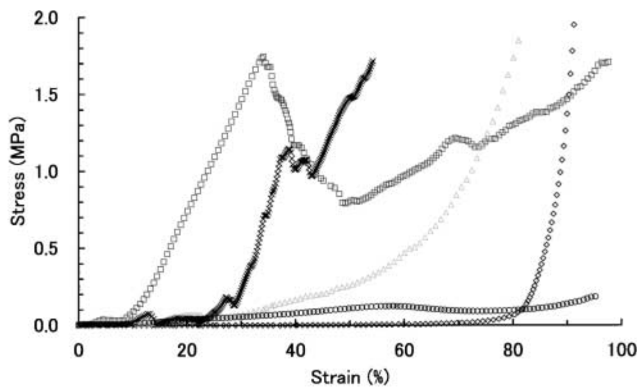

Fig. 1. Typical stress-strain curves in the mechanical test. Symbols: ◇; white bread, □; raw carrot, △; cracker, ×; rice cracker and ○; Yokan (agar gel with azuki-bean paste).

Table 1. Size and mechanical characteristics of samples.

Parameter	Bread	Carrot	Cracker	Rice cracker	Yokan
Cross sectional area (mm^2)	443.4 a	466.9 b	511.5 c	546.5 d	437.0 a
Height (mm)	17.4 d	10.6 c	4.2 a	6.0 b	10.6 c
Breaking stress (MPa)	>24 d	1.68 c	0.01 a	0.02 a	0.12 b
Breaking strain (%)	>98 e	35.3 c	7.3 b	3.7 a	57.9 d
Breaking energy (MPa)	>60 d	24.23 c	0.03 a	0.05 a	2.77 b
Mean slope up to breaking (MPa)	>24 d	4.78 c	0.12 a	0.53 b	0.20 a
Initial slope (MPa)	0.031 ab	0.225 bc	0.082 b	0.222 c	0.009 a
Stress at 5% strain (MPa)	0.000 a	0.020 c	0.006 b	0.016 c	0.001 a
Stress at 10% strain (MPa)	0.000 a	0.148 c	0.009 b	0.023 b	0.004 b
Stress at 30% strain (MPa)	0.001 a	1.431 d	0.081 c	0.215 c	0.046 b
Stress at 50% strain (MPa)	0.003 a	1.198 d	0.252 c	1.163 d	0.099 b
Stress at 70% strain (MPa)	0.013 a	1.160 d	0.815 c	>2 e	0.097 b
Stress at 90% strain (MPa)	1.750 b	1.567 ab	>2 c	>2 c	0.123 a
Hardness	soft	hard	soft	hard	soft
Fracturability	unbreakable	less brittle	brittle	brittle	less brittle

Mean values of more than 12 replicates.
Different letter following mean values shows significant difference ($p<0.05$) among samples as determined by Dunnett's T3 test.

est. As the breaking stress of Yokan was low, the breaking energy and mean slope were also low. Bread and Yokan curves crossed between 80 and 90% strain. At very high strain, stress values increased steeply for all samples, but Yokan still exhibited the lowest stress.

Mechanical characteristics (hardness and fracturability) of the five samples are briefly shown in the last two rows of Table 1.

Masticatory curves Figure 2 shows typical force-time curves of the five samples. The masticatory force is defined as the sum of force over the 92 cells beneath the samples. As shown in the mechanical compression, rice cracker had a zigzag pattern until the last peak appeared. Cracker exhibited a similar zigzag pattern at the early stage and smooth curves with a maximum force later. The two samples showed many peaks in masticatory force, but the maximum value was observed at the last peak. Carrot and Yokan showed two peaks in most cases, but white bread showed only one peak at the latter position.

The sheet sensor system can also indicate contact area between teeth and food materials. Figure 3 shows contact area *versus* time curves of the examples in Fig. 2. The contact area is defined as the product of one cell area (4 mm^2), and the number of cells detecting non-zero pressure among the 92 cells under the samples. These are much narrower than the cross-sectional area shown in Table 1, because the human teeth were smaller than the samples. The maximum values of the contact area seemed to depend on the tooth size of each subject, therefore they were generally close for one person. Yokan showed lower contact area during the chew. The timing observed the maximum area was

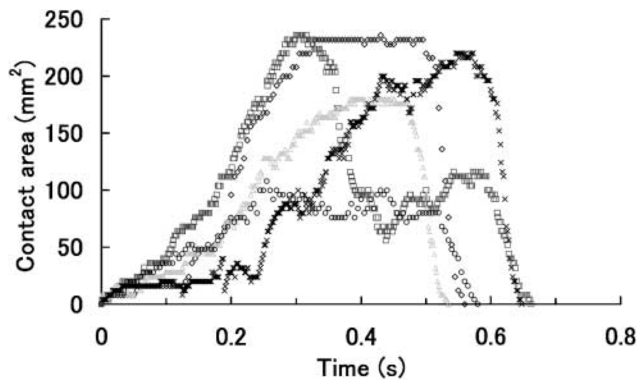

Fig. 3. Typical patterns of the contact area observed in the first chew of five samples. Contact area is defined as product of one cell area (4 mm^2) by the number of active cells detecting non-zero pressure among the 92 cells. Symbols: ◇; white bread, □; raw carrot, △; cracker, ×; rice cracker and ○; Yokan.

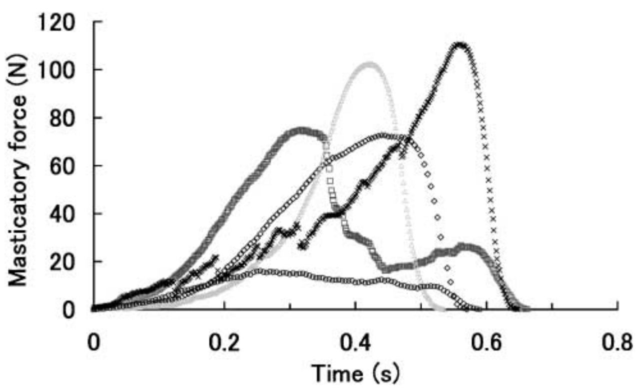

Fig. 2. Typical force-time curves in the first chew of five samples. Masticatory force is defined as sum of force detected by 92 sensing cells. Symbols: ◇; white bread, □; raw carrot, △; cracker, ×; rice cracker and ○; Yokan.

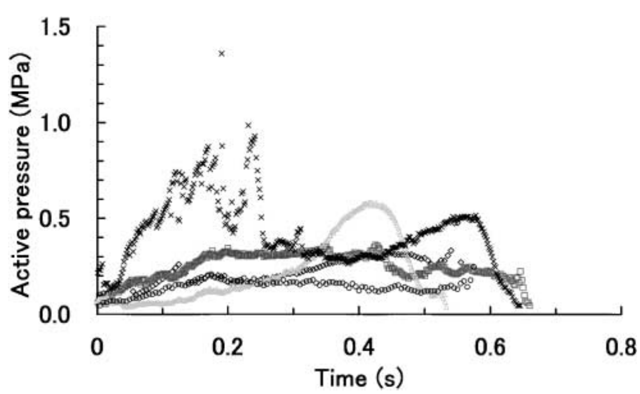

Fig. 4. Characteristics of the active pressure observed in the first chew of five samples. Active pressure is defined as the masticatory force divided by the contact area. Symbols: ◇; white bread, □; raw carrot, △; cracker, ×; rice cracker and ○; Yokan.

early for carrot, late for cracker and rice cracker, and a prolonged period for bread.

During mastication, both the force and contact area changed. An example of the active pressure, defined as the force divided by the contact area, is shown in Fig. 4; this was observed in the first chew shown in Figs. 2 and 3. The value of active pressure for rice cracker was the most scattered in the first 0.3 s of mastication by fracture of the sample, and the maximum value was very high. The scattered pattern of the active pressure did not synchronize with the zigzag pattern of masticatory force. The active pressure of cracker and rice cracker showed a peak at the same timing of the last peak in the force-time curve (Fig. 2), while that of bread remained almost constant, unlike the masticatory force. Yokan also showed a flat pattern like bread, but the value of active pressure was lower.

We used the maximum values, the first peak in masticatory force curves as peak1, and the last peak as peak2 for further analysis. Since there is only one peak at the latter position for bread, the analysis of the first peak was done with 4 other samples. Table 2 is the results of the two-way analysis of variance (ANOVA) of the fourteen subjects and five samples. Differences among subjects and samples were significant for all the parameters in Table 2. Active pressure at the first peak showed comparatively weaker subject dependence than other parameters.

With a goal of showing texture effects on mastication, the mean values of more than two replicates for each subject were analyzed by repeated measures ANOVA to compare samples. The sample differences were significant as shown in Table 3.

The maximum force appeared near peak2 except for carrot, whose maximum force was close to peak1. The maximum value differed from 35 N for Yokan to 125 N for rice cracker. Variation in the active pressure was smaller from 0.253 MPa to 0.660 MPa, because the value was affected by both the force and contact area. The maximum contact area was close to that at the first peak for carrot and Yokan, and that at peak2 for bread, cracker and rice cracker.

The force required to break the samples by mastication, indicated by the peak force1, was high for carrot. Cracker and rice cracker showed low values of peak force1 with small contact area and within short periods, indicating their brittle characters. The values of active pressure at peak1 increased in the order of Yokan, cracker, carrot and rice cracker. Both the force and con-

Table 2. ANOVA results of mastication of 5 samples.

Parameter	$F_{subject}$	p	F_{sample}	p	$F_{subject×sample}$	p
Peak force1	7.782	0.000	297.281	0.000	3.435	0.000
Time at peak1	26.977	0.000	93.196	0.000	4.223	0.000
Contact area at peak1	6.052	0.000	389.121	0.000	3.163	0.000
Active pressure at peak1	1.982	0.032	56.167	0.000	1.436	0.089
Peak force2	40.047	0.000	166.524	0.000	5.192	0.000
Time at peak2	63.799	0.000	36.659	0.000	4.685	0.000
Contact area at peak2	13.959	0.000	113.393	0.000	2.585	0.000
Active pressure at peak2	34.881	0.000	121.375	0.000	4.031	0.000
Maximum force	34.231	0.000	107.486	0.000	5.659	0.000
Time at maximum force	76.514	0.000	24.169	0.000	6.871	0.000
Maximum contact area	15.684	0.000	77.037	0.000	2.274	0.000
Active pressure at maximum force	34.888	0.000	124.413	0.000	5.470	0.000
Duration	84.603	0.000	33.607	0.000	6.947	0.000
Cycle time	81.188	0.000	31.257	0.000	5.564	0.000
Impulse	36.239	0.000	43.736	0.000	4.091	0.000
Mean slope up to peak1	9.212	0.000	47.211	0.000	3.466	0.000
Initial slope	5.156	0.000	11.720	0.000	4.059	0.000
Impulse up to peak1	7.608	0.000	110.754	0.000	3.525	0.000

Table 3. Sample effects on masticatory parameters.

Parameter	F_{sample}	p	Bread	Carrot	Cracker	Rice cracker	Yokan
Peak force1 (N)	90.737	0.000	—	76.6 c	7.8 a	18.1 b	12.8 b
Time at peak1 (s)	16.439	0.000	—	0.339 d	0.089 a	0.144 b	0.212 c
Contact area at peak1 (mm^2)	105.141	0.000	—	222 c	34 a	39 a	119 b
Active pressure at peak1 (MPa)	35.347	0.000	—	0.341 c	0.214 b	0.457 d	0.118 a
Peak force2 (N)	23.821	0.000	68.0 b	33.0 a	112.3 c	124.3 c	32.8 a
Time at peak2 (s)	7.779	0.001	0.374 ab	0.557 c	0.368 a	0.510 bc	0.449 b
Contact area at peak2 (mm^2)	18.168	0.000	175 b	97 a	183 b	184 b	104 a
Active pressure at peak2 (MPa)	30.079	0.000	0.389 b	0.291 a	0.590 c	0.654 c	0.252 a
Maximum force (N)	18.590	0.000	74.8 b	83.6 b	112.3 c	124.8 c	34.6 a
Time at maximum force (s)	3.245	0.019	0.370 a	0.384 a	0.368 a	0.508 b	0.382 a
Maximum contact area (mm^2)	33.114	0.000	192 b	231 c	188 b	190 b	134 a
Active pressure at maximum force (MPa)	22.452	0.000	0.389 b	0.366 b	0.590 c	0.660 c	0.253 a
Duration (s)	4.839	0.002	0.536 abc	0.685 c	0.487 a	0.643 bc	0.586 b
Cycle time (s)	5.900	0.001	0.978 bc	1.064 c	0.800 a	0.941 b	0.989 bc
Impulse (N·s)	7.639	0.001	17.3 ab	16.9 b	20.5 b	29.0 c	9.0 a
Mean slope up to peak1 (N/s)	12.243	0.001	—	316.3 c	128.9 b	171.0 b	67.6 a
Initial slope (N/s)	3.214	0.040	66.0 b	142.6 b	117.7 b	118.2 b	33.1 a
Impulse up to peak1(N·s)	24.613	0.000	—	9.29 c	0.51 a	1.23 b	1.22 ab

Mean values of 14 subjects are shown.

Different letter following mean values shows significant difference (p<0.05) between samples determined by paired sample t-test.

Table 4. Correlation coefficients among the masticatory parameters.

Parameter	Time1	Area1	AP1	PF2	Time2	Area2	AP2	Duration	Cycle time
Peak force1	0.487 c	0.840 c	0.367 c	–0.255 b	0.216 b	–0.345 c	–0.212 b	0.177 a	0.199 a
Time at peak1		0.525 c	0.159 a	–0.075	0.861 c	–0.124	–0.050	0.845 c	0.842 c
Contact area at peak1			–0.042	–0.467 c	0.215 b	–0.510 c	–0.438 c	0.177 c	0.258 b
Active pressure at peak1				0.276 c	0.190 a	0.239 b	0.282 c	0.190 a	0.100
Peak force2					0.223 b	0.821 c	0.971 c	0.237 b	0.081
Time at peak2						0.197 a	0.238 b	0.990 c	0.923 c
Contact area at peak2							0.734 c	0.226 b	0.052
Active pressure at peak2								0.251 b	0.095
Duration									0.922 c

a; $p<0.05$, b; $p<0.01$, c; $p<0.001$

tact area decreased at peak2 for carrot, but increased for other samples. No clear breaking point was observed for bread. The maximum value of active pressure was higher than Yokan, lower than cracker and rice cracker, and similar to carrot.

The integral and differential properties of the masticatory curve, that is, the impulse and slope values, showed the same tendency as force, since the duration and cycle time of mastication did not significantly vary with sample texture. The impulse values up to the first peak for cracker, Yokan and rice cracker were low, that for carrot was intermediate, and that for bread was so high it was not determined.

Correlation coefficients between pairs of samples of each parameter in the masticatory recording were calculated (Table 4). For the first peak, many combinations were significantly correlated like the force and the time at peak1, but the area and active pressure were independent. For peak2, significant correlation was observed in all the combinations. The magnitudes of the force and contact area at the first peak and those at peak2 were negatively correlated. The four variables related to time (times at peak1 and peak2, duration and cycle time in Table 4) were highly correlated ($p<0.05\%$) with each other.

Discussion

Mechanical test To compare with the force produced during mastication, a simple compression test up to very high strain was used as the mechanical test. When humans chew food, the upper and lower teeth close and often come in contact. An instrumental test to 100% compression strain is required, however, we had to stop before 100% to protect the load cell from breakage. This test successfully showed repeated breakings after the breaking point clearly shown in rice cracker (Fig. 1), as observed in mastication measurement (Fig. 2). In a high strain range, the stress and strain shown in Table 1 and Fig. 1 involved large error because they were based on initial values of cross sectional area and height. This technique was used for convenience in order to standardize the size of each sample, as size adjustment of various food samples was difficult. Without samples of brittle rice cracker and cracker, a puncture test might be preferable as stress value at a high strain is interpreted more easily. Stress-strain curves for the two samples in a puncture test are difficult to measure, because after breaking, ruptured samples are scattered.

Bread was not broken by a compression of less than 98% strain as shown in Table 1, therefore the breaking stress and energy were the highest among the five. Bread consists of many cells with air as true of rice cracker and cracker, however, the flexible cell walls were not broken easily and generated a smooth curve. Bread showed the lowest stress value at a low strain range, while the stress at a very high strain rose steeply.

Patterns in masticatory force Takahashi and Nakazawa (1987) measured chewing force patterns of various foods with one subject and categorized the masticatory force patterns observed in the first chew. Our results (Fig. 2) were similar to theirs and were commonly observed in the 14 subjects in this study. Bread showed only one peak, Yokan had a smooth masticatory curve with two peaks, raw carrot showed two steep peaks, and rice cracker exhibited many small peaks. Cracker was not tested by Takahashi and Nakazawa (1987), but its texture is crisp and as brittle as rice cracker, and the masticatory force pattern was like that of rice cracker. Since cracker is not as hard as rice cracker, the many peaks were less steep. In previous studies on masticatory force, the curve shape was not shown (Tornberg *et al.*, 1985; Hagberg, 1987; Miwa, 1995). Masticatory curves of biscuit and apple reported by Bearn (1973) resembled those of cracker and carrot in this study, respectively. This study evidenced the grouping of masticatory patterns was common for healthy adults, even though individual ways of mastication also affected the magnitude of force and duration.

The masticatory curve of crackers was similarly jagged in the first 0.3 s as that of fresh cracker bitten with incisors (Kohyama & Nishi, 1997). However, thereafter the force increased to peak2. The steep increase was not observed in incisor biting. This difference seems to be caused by differently shaped molars and incisors. Since molars are wider than incisors, broken particles of brittle food are easily held between the upper and lower molars, and repeatedly contact the upper teeth. On the contrary, thin incisors rarely keep food particles. This phenomenon is similar to that observed in mechanical compression tests using a flat plate and a wedge- or a cone-shaped probe.

Since the first peak was not observed for bread, which never broke in the mechanical test and did not always break in the masticatory recording, this peak seemed to reflect the fracture of the main structure of the samples. After breaking the sample with the teeth, the masticatory force decreased for at least a short time, since the resistance from the broken pieces was less than before the breaking. Bread never showed this decrease in force until the jaw opened. The smooth peak during the first mastication was also observed for kelp, which is difficult to cut even with several chews (Kohyama *et al.*, 2000; Kohyama & Sakai, 2001), though the peak force was much higher than that of bread. Observations showed that bread was not broken.

As cracker showed a similar pattern to rice cracker, and bread a similar pattern to kelp, the pattern seems to be determined by sample fracturability rather than hardness. The masticatory curve of Yokan resembles that of three surimi gels (Kohyama *et al.*, 2001), though the values of two peak forces of Yokan are much lower than those observed in the gels. We assume that the smooth pattern with two peaks is commonly found in chewing gel-type foods.

The magnitudes of the force and contact area at the first peak and those at peak2 did not show positive correlations, suggesting that the first and last peaks in masticatory force were not influenced by a common factor. As the first peak corresponds to the sample breaking, the last must not be related to the breaking. We can also state that the maximum force is neither of these two peaks, since the maximum point appeared early in carrot and late in bread, cracker and rice cracker as shown in Table 3.

Contact area and active pressure The sheet sensor system is useful to show not only the patterns in masticatory force influenced by food texture but also the contact area between teeth and food materials.

Since the area of one sensing cell of the MSCAN2 is 4 mm^2, the derived contact area can provide only an estimate of tooth contact area and is larger than the true value. This is why the shape of the contact area curves shown in Fig. 3 is not smooth. However, the precision of the measured contact area, which may involve an error on the order of 4 mm^2s is considered sufficient because the differences in contact areas were larger among samples.

In all the subjects and samples, both the masticatory force and the contact area decreased to zero simultaneously with opening of the teeth after the first occlusion in mastication.

The maximum contact area appeared close to the first peak for carrot and Yokan, and at peak2 for bread, cracker and rice cracker. The former two samples became smaller pieces after breaking. In contrast, cracker and rice cracker in the latter group contained low moisture, but after breaking small pieces absorbed saliva rapidly and the bolus volume increased gradually. This is the reason the contact area increased between peak1 and peak2.

This sensor shows the active pressure of mastication, while the other intra-oral devices (Bearn, 1973; Hagberg, 1987; Takahashi & Nakazawa, 1987) measure the force applied by a tooth but do not give the active pressure because they have only one pressure sensing point.

Humans with natural dentition have two kinds of mechanoreceptors; one is in the periodontal membrane and the other is neuromuscular spindles in the masticatory muscles (Boyar & Kilcast, 1986; Lavelle, 1988). We hypothesize that the active pressure itself rather than the sum of force applied to foods directly stimulates mechanoreceptors in the periodontal ligament and gives information on the hardness of food, because a micro receptor could not detect macro force received from one mouthful. The masticatory force acts as the resistance to the neuromuscular spindles and also influences total periodontal assessment. These hypotheses must be confirmed in combination with other physiological techniques.

Individual differences and sample texture Masticatory parameters largely depended on the subject, because masticatory habits were individual depending on teeth shape, size, and chewing rhythm. Except for active pressure at peak1, parameters showed strong subject dependence. It is common for the significance level of subject differences to be very low (p<0.05%) as reported by Kohyama and Sakai (2001). It was unusual that weak subject dependence (p=3.25%) and a lack of interaction between subject and sample were observed in active pressure at the first peak in the present study. This suggests that the first peak was influenced more by the sample texture than individual mastication. Depending on the size and shape of individual apparatuses, the peak force and contact area at the first peak varied with the subject, but the active pressure did not.

As shown in Table 3, significant differences were noted in the time related parameters. The strong correlation among four variables related to time shown in Table 4 suggests the existence of individual rhythm. That evidence suggests that chewing time in the first chew varied with samples. Previous reports mentioned that sample texture did not affect the duration or cycle time of the first chew (Takahashi & Nakazawa, 1987; Kohyama & Sakai, 2001) or early stage of mastication (Miwa, 1995). Chewing rhythm for the entire mastication process is individual and seems difficult to modify by texture, since a pattern or rhythm generator in the brainstem of the individual controls it (Thexton, 1992). Assuming that humans masticate all the samples in the same way, cycle time is similar for all foods, and a thicker sample requires a longer duration, so that the order of the duration and thickness also are similar. The results of this study indicated the duration is independent on the sample thickness as shown in Table 1, and food texture strongly influenced both the speed of the first bite and the force.

No correlation was observed between bread and other samples, but there were significant correlations between any two of the other samples in peak2 and impulse. Bread was a unique sample among the five, perhaps due to its unbreakable character.

Relationships between mechanical test and masticatory recording The active pressure at the first peak is an important variable in identifying sample fracturability, and it relates to the breaking stress in the mechanical test. The order of time at the first peak and the breaking strain were the same, even though speed of mastication was not constant. Unlike instrumental compression, which operates at a constant speed, masticatory movement is complex. However, it is evident that a longer period until the first peak in the masticatory curves corresponds to greater deformation at the breaking point. The time to the first peak in the masticatory curves and breaking strain in the mechanical test correlated with each other, including bread, that did not show a clear breaking point.

The impulse in the masticatory curve is considered analogous with the energy in a mechanical test under a constant compression speed. The impulse values up to the first peak were low in cracker, Yokan, and rice cracker, intermediate in carrot, and very high in bread (Table 3), tendencies closely similar to the breaking energy shown in Table 1. For the mean slope up to breaking, the masticatory curves and the stress-strain curves in the mechanical test tended to be similar.

It is known that the initial slope obtained from a mechanical test gave Young's modulus relating to sample hardness. In this study the initial slope of the masticatory curves shown in Table 3 also expressed the hardness, though the variation was smaller than that in the mechanical test. The irregular shape of human teeth, and variable and fast compression speed in mastication are believed to easily allow errors in measurement. In addition, changes of temperature and moisture in the mouth may also cause differences from an instrumental test.

A peak in masticatory force appeared just before jaw opening (peak2). The values of peak force and active pressure at peak2 (Table 3) corresponded well with the stress values observed at a high strain in the mechanical test (Table 1). We speculate that the resistance to peak2 may relate to sample toughness. Further study combining sensory evaluation and mastication recording is needed to clarify this.

Maximum masticatory force often appeared later than the breaking point. The maximum force for all samples but carrot was observed at peak2 when the upper and lower teeth were almost in contact. The peak force, contact area and active pressure varied with the sample, and also depended on the individual. Those parameters may be important for recognition of the mechanical characteristics during mastication. We measured mechanical stress at a very high strain, and found that the order was similar to the active pressure at peak2. Mechanical tests with a clearance condition to almost zero are practically difficult, because a pressure sensor might be broken. Missing information from peak2 of the masticatory curves will cause differences between an instrumental test and human mastication.

The maximum or peak values in masticatory force have been reported (Bearn, 1973; Tornberg *et al*., 1985, Hagberg, 1987; Takahashi & Nakazawa, 1987; Kohyama *et al*., 2000; Kohyama & Sakai, 2001), but in many foods, this is not the force required for food breaking commonly examined in a mechanical test. The force at the first peak in a masticatory curve corresponding to the breaking force is not detectable unless the masticatory force was measured continuously and a masticatory curve was drawn. This is an important point in designing a sensing tool to measure food texture during mastication.

Conclusion

We studied force and contact area during the first chew of five food samples with different textures. The first peak in the masticatory curve represented rupture of the sample. As true of the results of mechanical tests, less brittle samples showed higher rupture force and longer period to the first peak. The value of active pressure at the first peak of masticatory force well corresponded with the breaking stress of samples, but depended less on the subject. The active pressure observed just before jaw opening corresponded to the stress values measured under high strain compression. The maximum force in the first chew appeared just before tooth opening in many cases, but was at the first peak for raw carrot. The results suggest that the maximum force measured during one chew does not correspond to any simple parameter observed in a mechanical test.

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