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Original Article

Multivariate analysis of the mechanical properties of boluses during mastication with the normal dentitions

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The aim of this study was to investigate changing mechanical properties of the bolus during mastication and to quantify mechanical properties of the final bolus at swallowing. Changing mechanical properties of the bolus of three different types of foods (rice cracker, cheese and peanuts) by twelve normal dentitions were investigated by principal component analysis (PCA) on six mechanical properties (rupture energy, elasticity, viscosity, hardness, cohesiveness and adhesiveness). The raw data of cohesiveness immediately before swallowing was always constant. In all three food samples, the results by PCA on six parameters indicated that cohesiveness was independent from the remaining five parameters, and two factors were extracted on these five parameters by PCA. Furthermore, factor structure of bolus at swallowing showed no difference between the three food samples in spite of the variations in the raw data. The mechanical properties of swallowable bolus were clarified for the first time.

Key words: food bolus, mechanical properties, principal component analysis, factor analysis

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Introduction

Various methods have been employed to investigate masticatory performance, and it has been widely discussed. Manly and Braley,[1] Ishihara,[2] and Agrawal et al.[3] evaluated masticatory performance using a sieve method, while Ono et al.[4], Tanaka et al.[5] and Shiga et al.[6] demonstrated an increase in the amount of gelatin in gummy jelly during mastication. Farrel[7] focused on digestion of food. Honma et al.[8] studied bolus formation of rice crackers. Edlund and Lamm[9] proposed the use of a condensation silicone impression material as a test food to develop a method describing simply and precisely the masticatory ability of a person. Most of them, however, have mentioned an only single type of test food and considered only the particle size of the bolus. Moreover, mechanical properties of the final bolus immediately before swallowing have never been described.

Mechanical properties of food bolus should represent the feature of comprehensive masticatory performance, such as, occlusion,[10-12] masticatory muscle activity,[13-15] the functions of the tongue[16-19] and oral mucosa.[20,21] The mechanical properties of the food bolus alter by mastication in order to suit the textural attributes.[22-24] It would be difficult to evaluate masticatory performance by only a single type of food.

The mechanical properties of food alter by the process of mastication before swallowing, including comminution of food, mixing, kneading[25] and dilution with saliva.[26] Masticatory performance should be changed and fit suitable for one texture,[27,28] and the attributes of the food bolus also depend on the original texture of food. Therefore, multivariate analysis of the behavior of mechanical properties of food boluses derived from foods of various textures is required. In the present study, three different types of foods; rice cracker, cheese and peanuts were examined, and six mechanical properties of their boluses during mastication and the endpoint of mastication were analyzed in detail by principal component analysis (PCA).

The aim of this study was to investigate changing mechanical properties of the bolus during mastication and to quantify mechanical properties of the final bolus at swallowing which will be good index for evaluating total masticatory performance.

Materials and Methods

Subjects

A total of twelve subjects (eight males and four females; average age 26.6 years old) were selected by the following eligibility criteria: complete natural dentition except for occasionally missing third molars, bilateral Angle Class I molar relationships; no history of orthodontic treatment or maxillofacial surgery, lateral tooth guidance pattern of group function occlusion or cuspid-protected occlusion. Informed consent was obtained from each subject before the onset of this study.

Food samples for examination

Samples from foods of three different textures were selected: three pieces of rice crackers (Bourbon Petit Usu-Yaki, 2.4g, 30 mm×1 mm, Bourbon Co., Japan), a piece of cheese (Candy type Cheese, 5.9g, 20 mm×10 mm, Rokko Butter Co., Japan) and three pieces of peanuts (Ajitsuke rakkasei, 3.0g, 20 mm×10 mm, Irita Shokai Co., Japan) (Fig. 1 (1)). Three food samples, which had stable textures and bolus of them were suitable for measurement, were

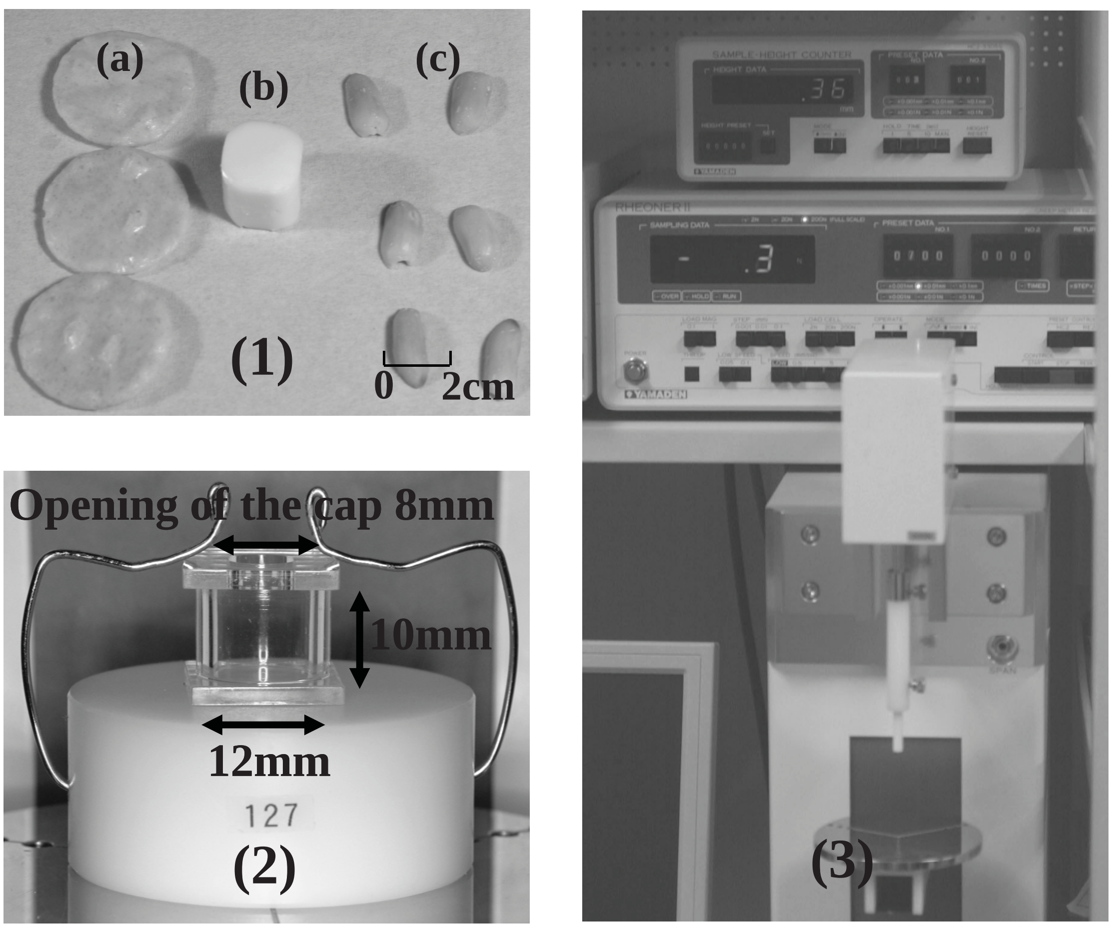

Fig. 1. Food samples, experimental container and experimental device
(1) 3 food samples, (a) Rice cracker (b) Cheese (c) Peanuts (2) Experimental container (3) Experimental device (the creep meter RHEOMETER II, RE3305)

selected according to the criteria of Yanagisawa et al.[29]

The amount of food samples for the experiment was determined between the maximum for natural mastication and the minimum for examination.

Experimental device and container

A creep meter RHEONER II (RE3305; load cell: maximum load 2N; Yamaden Co., Japan; Fig. 1 (3)) was used for measurement. A cylindrical plunger (diameter, 5 mm) was used, and the container comprised an acrylic plate (18 mm×18 mm) and a ring (inner diameter, 12 mm; height, 10 mm) that was covered with another acrylic plate with a hole (diameter, 8 mm) in the center for the plunger to pass through (Fig. 1 (2)). The size of the container complied with the method of measuring the hardness of the food particles in the elderly person who has some difficulty in mastication and swallowing. This method was established by the Ministry of Health and Welfare Japan.[30] The size of the container was scaled down for our examination.

By an axial compression test, creep test and texture profile analysis, we obtained raw data with regard to six parameters: rupture energy, elasticity, viscosity, hardness, cohesiveness and adhesiveness.

Axial compression test

Rupture energy was measured by the axial compression test. Each sample was placed within the ring and was compressed with the plunger at a constant speed of 1.0 mm/sec. The force was measured every 0.08 seconds. Rupture energy was measured from the resultant compression curve and was determined when the plunger reached a depth of 8 mm into the sample.

Creep test

Elasticity and viscosity were measured by the creep test under axial compression for 1 minute at a constant compression speed of the plunger, i.e., 5 mm/sec. The force was arranged within the range which keeps linearity between stress and strain. This linearity was determined to hold for deformations of less than 20%, and the optimal force for each sample was 0.005–0.2 N.

Texture profile analysis[31]

Instrumental texture profile data were obtained after subjecting the sample to compression twice. The samples were compressed to 67% of their primary height using a cylindrical plunger (diameter, 5 mm) at a speed of 1 mm/sec. The texture profile parameters were determined as follows (Fig. 2):

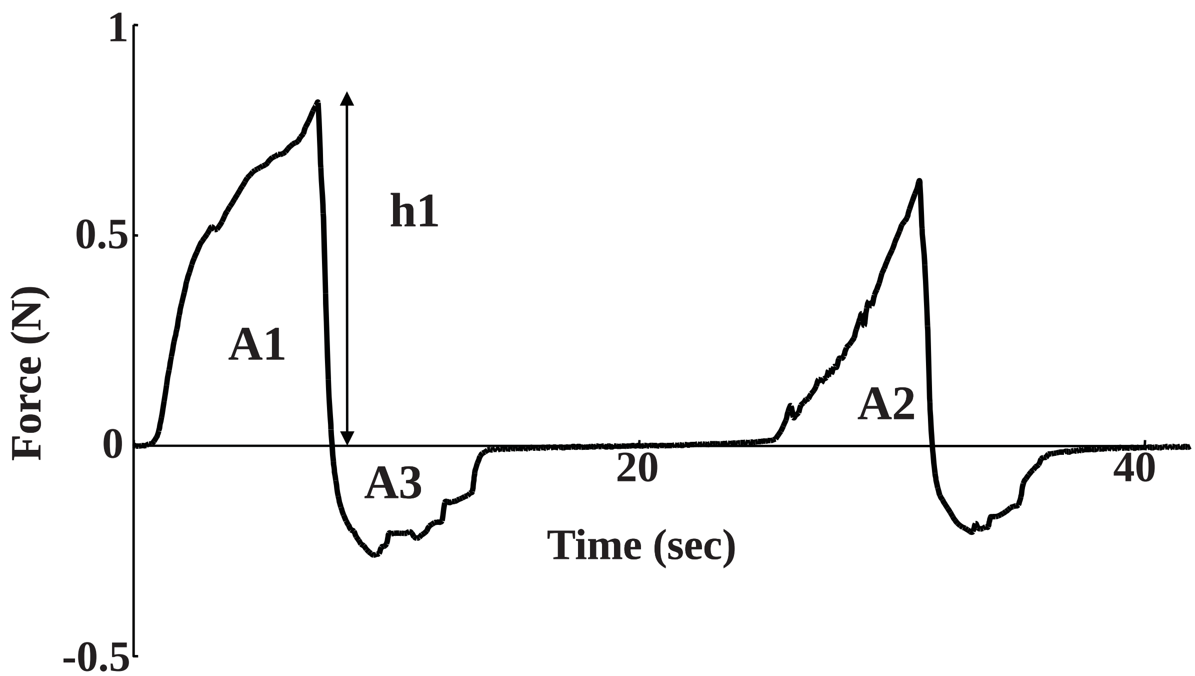

Fig. 2. Parameter of texture profile analysis
h1=Hardness, A2/A1=Cohesiveness, A3=Adhesiveness

(1) Hardness (N) was defined as "the maximum force required for compressing the sample" and was calculated as the peak force of the first compression of the sample.

(2) Cohesiveness was calculated as A2/A1 (A1 and A2 represent the integrated energy required for the first and the second compression, respectively).

(3) Adhesiveness (J/m^3) was calculated as the integration of the negative energy between the first and second compressions.

Experimental procedure

The food boluses were maintained at 37.0 °C through the experiment.

The number of natural chewing strokes until swallowing was counted for each food sample in each subject. During mastication, subjects were prohibited partial swallowing.

The point immediately before swallowing was defined as the last point.

The first point was defined as the point when hardness of food samples became measurable by load cell (2N) for the first time.

The point which was the middle number of chewing strokes between the first and last points was termed as the middle point.

The chewing strokes of each point were determined (Table 1 (a) (b) (c)). Samples in the oral cavity were naturally pitted out by the subjects. The bolus was almost evenly divided into two, and placed into two containers. It in one container was used for the axial compression test (for measurement of rupture energy) and the other, for the creep test and texture profile analysis (measurement of the remaining five parameters). This procedure was repeated three times at each point.

Statistical analysis

Statistical analysis was carried out by a one-way analysis of variance (ANOVA) followed by a Tukey multiple range test at a 5% level of significance to compare the first with the middle point, the middle with the last point (SPSS 12.0J, SPSS Japan Inc.). In this case, each point name was decided as the independent variable and the six parameters were the dependent variables.

The means and standard deviations of all the variables were calculated. A correlation matrix was obtained from normalized data. PCA and factor analysis were used to obtain the dependence structure for a set of variables. PCA of the data was performed using

Table 1(a) The number of chewing strokes of rice cracker

Subject	First point	Middle point	Last point
1	25	31	38
2	15	20	26
3	20	27	33
4	21	27	33
5	15	18	21
6	15	21	27
7	24	29	34
8	16	23	30
9	20	25	30
10	20	28	36
11	16	23	30
12	20	28	36

Table 1(b) The number of chewing strokes of cheese

Subject	First point	Middle point	Last point
1	15	20	24
2	11	17	23
3	14	27	40
4	13	17	21
5	16	20	24
6	14	21	28
7	17	26	35
8	8	12	16
9	10	18	26
10	13	18	23
11	12	20	28
12	16	30	44

Table 1(c) The number of chewing strokes of peanuts

Subject	First point	Middle point	Last point
1	18	22	26
2	15	20	25
3	19	22	25
4	17	19	21
5	16	21	26
6	18	21	24
7	20	25	30
8	12	14	16
9	16	20	24
10	12	17	22
11	21	26	31
12	23	31	39

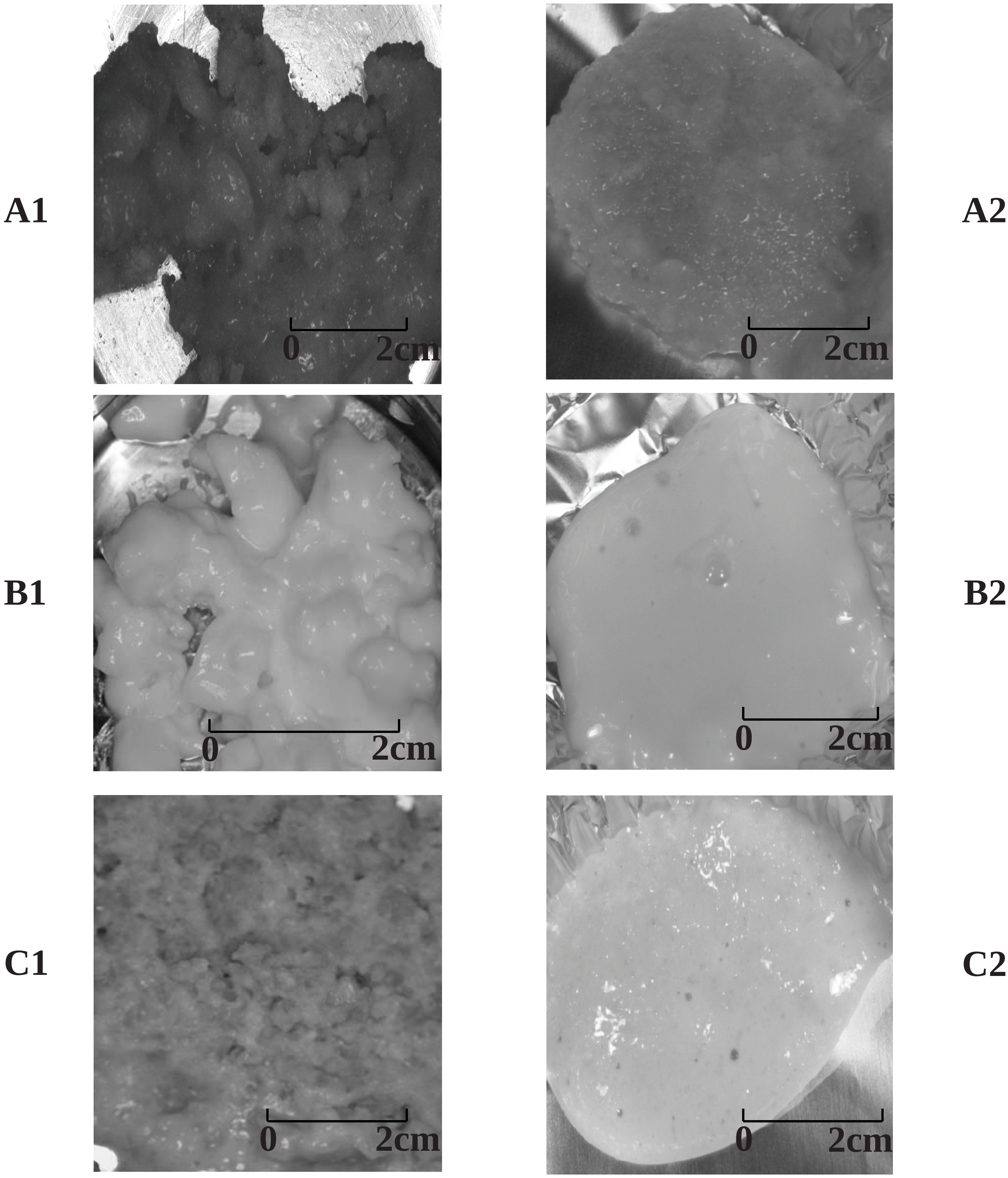

Fig. 3. Examples of food bolus
Rice cracker at the first point (A1), Rice cracker at the last point (A2), Cheese at the first point (B1), Cheese at the last point (B2), Peanuts at the first point (C1) and Peanuts at the last point (C2)
In all 3 food samples, the food bolus was digested at the last point.

STATISTICA (StatSoft Inc., USA).

Ethical Review Board

This study was approved by the Institutional Ethical Review Board of Tokyo Medical and Dental University (Approval number: 202; March 22, 2006).

Results

The change of mechanical properties of boluses as the progress of mastication

In case of rice cracker, rupture energy significantly decreased during the transition from the first to the middle point (F-value = 10.73; P-value < 0.001).

The elasticity of cheese decreased linearly throughout the process (F-value = 72.09; P-value < 0.001). In contrast, the viscosity of all three samples decreased during each point of transition (Rice cracker: F-value = 19.16; P-value < 0.001, Cheese: F-value = 41.79; P-value < 0.001, Peanuts: F-value = 16.26; P-value < 0.001).

The hardness of all three samples apparently decreased during both points of transition (Rice cracker: F-value = 17.75; P-value < 0.001, Cheese: F-value = 99.84; P-value < 0.001, Peanuts: F-value = 13.31 P-value < 0.001).

In case of rice cracker, cohesiveness increased during both points of transition (F-value = 41.98; P-value < 0.001), and in cheese, cohesiveness remained unchanged throughout the experiment (F-value = 2.75; P-value = 0.07), and adhesiveness clearly decreased during both points of transition (F-value = 36.04; P-value < 0.001). The cohesiveness of the peanuts clearly increased during the transition from the middle to the last point (F-value = 12.18; P-value < 0.001) (Table 2 (a) (b) (c)).

Coefficient of variation of each test

The cohesiveness immediately before swallowing was always approximately 0.5 (coefficient of variation (CV): 0.1~0.15); however, the CVs of the remaining five parameters varied considerably (Table 3).

Principal component analysis
PCA of all six parameters

In all three food samples, the first two principal components extracted from the correlation matrix of all six parameters explained more than 75% of the variance (Table 4 (a)). The scree plot indicated a stepped offset between the second and third eigenvalues.

Table 2 (a) The raw data of rice cracker *: significantly different from the middle point by Tukey HSD(p < 0.05)

Point		Rupture energy (J/m^3)	Elasticity (Pa)	Viscosity (Pa•s)	Hardness (N)	Cohesiveness	Adhesiveness (J/m^3)
First	Average (SD)	1.58×10^{4}* (1.08×10^{4})	5.65×10^{4}* (4.33×10^{4})	3.91×10^{5}* (2.60×10^{6})	0.67* (0.46)	0.45* (0.07)	2.62×10^{3}* (1.50×10^{3})
Middle	Average (SD)	9.61×10^{3} (6.98×10^{3})	2.93×10^{4} (2.07×10^{4})	2.30×10^{6} (1.57×10^{6})	0.40 (0.34)	0.54 (0.07)	2.54×10^{3} (1.65×10^{3})
Last	Average (SD)	7.04×10^{3} (6.07×10^{3})	1.39×10^{4} (6.61×10^{3})	1.01×10^{6}* (5.69×10^{5})	0.19* (0.12)	0.59* (0.06)	1.57×10^{3}* (1.16×10^{3})

Table 2 (b) The raw data of cheese *: significantly different from the middle point by Tukey HSD(p < 0.05)

Point		Rupture energy (J/m^3)	Elasticity (Pa)	Viscosity (Pa•s)	Hardness (N)	Cohesiveness	Adhesiveness (J/m^3)
First	Average (SD)	4.29×10^{4}* (1.02×10^{4})	1.71×10^{5}* (5.00×10^{4})	2.28×10^{7}* (1.45×10^{7})	1.38* (0.31)	0.49 (0.07)	7.19×10^{3}* (3.09×10^{3})
Middle	Average (SD)	2.38×10^{4} (1.05×10^{4})	1.12×10^{5} (6.24×10^{4})	1.15×10^{7} (8.46×10^{6})	0.86 (0.38)	0.52 (0.07)	5.09×10^{3} (2.28×10^{3})
Last	Average (SD)	9.36×10^{3}* (6.61×10^{3})	3.38×10^{4}* (3.71×10^{4})	3.35×10^{6}* (3.67×10^{6})	0.34* (0.19)	0.54 (0.07)	2.47×10^{3}* (1.39×10^{3})

Table 2 (c) The raw data of peanuts *: significantly different from the middle point by Tukey HSD(p < 0.05)

Point		Rupture energy (J/m^3)	Elasticity (Pa)	Viscosity (Pa•s)	Hardness (N)	Cohesiveness	Adhesiveness (J/m^3)
First	Average (SD)	1.49×10^{4}* (7.39×10^{3})	6.16×10^{4} (6.12×10^{4})	1.56×10^{7}* (1.36×10^{7})	0.85* (0.48)	0.44 (0.08)	2.85×10^{3} (1.66×10^{3})
Middle	Average (SD)	9.78×10^{3} (6.52×10^{3})	3.74×10^{4} (4.61×10^{4})	9.30×10^{6} (8.26×10^{6})	0.61 (0.40)	0.45 (0.10)	2.23×10^{3} (1.37×10^{3})
Last	Average (SD)	7.08×10^{3} (5.01×10^{3})	1.08×10^{4}* (1.07×10^{4})	3.30×10^{6}* (2.40×10^{6})	0.39* (0.24)	0.53* (0.08)	2.00×10^{3} (1.54×10^{3})

Table 3 CV value

Food samples	Point	Rupture energy	Elasticity	Viscosity	Hardness	Cohesiveness	Adhesiveness
Rice cracker	First	0.69	0.77	0.72	0.69	0.16	0.57
	Middle	0.73	0.71	0.68	0.85	0.13	0.65
	Last	0.86	0.48	0.56	0.63	0.10	0.74
Cheese	First	0.24	0.29	0.64	0.22	0.14	0.43
	Middle	0.44	0.56	0.74	0.44	0.13	0.45
	Last	0.71	1.10	1.10	0.56	0.13	0.56
Peanuts	First	0.49	0.99	0.87	0.56	0.18	0.58
	Middle	0.67	1.23	0.89	0.66	0.22	0.62
	Last	0.71	0.99	0.73	0.62	0.15	0.77

Table 4 (a) PCA on six parameters

component	Rice cracker		Cheese		Peanuts	
	Eigenvalue	Contributing ratio % (cumulative)	Eigenvalue	Contributing ratio % (cumulative)	Eigenvalue	Contributing ratio % (cumulative)
1st	3.97	66.2(66.2)	3.95	65.8(65.8)	3.79	63.2(63.2)
2nd	0.85	14.2(80.4)	1.02	16.9(82.7)	0.90	15.1(78.3)
3rd	0.46	7.7(88.1)	0.40	6.7(89.3)	0.61	10.1(88.4)
4th	0.34	5.6(93.7)	0.33	5.4(94.7)	0.35	5.8(94.2)
5th	0.22	3.6(97.3)	0.21	3.6(98.3)	0.22	3.7(97.9)
6th	0.16	2.7(100.0)	0.09	1.7(100.0)	0.13	2.1(100.0)

The factor structure was determined by factor analysis of two factors (Table 4 (b); Factor 2 negatively correlated with cohesiveness, and factor 1 positively correlated with the remaining five parameters).

Table 4 (b) Factor loadings by factor analysis on six parameters

Parameters	Rice cracker		Cheese		Peanuts	
	Factor1	Factor2	Factor1	Factor2	Factor1	Factor2
Rupture energy	0.74	0.42	0.88	0.19	0.81	0.32
Elasticity	0.74	0.46	0.88	0.05	0.47	0.56
Viscosity	0.85	0.32	0.83	0.13	0.71	0.56
Hardness	0.78	0.39	0.94	0.18	0.69	0.58
Cohesiveness	-0.14	-0.96	-0.08	-0.99	-0.07	-0.94
Adhesiveness	0.91	-0.06	0.86	-0.15	0.93	-0.01

Table 5 (a) PCA on five parameters at the first point

component	Rice cracker		Cheese		Peanuts	
	Eigenvalue	Contributing ratio % (cumulative)	Eigenvalue	Contributing ratio % (cumulative)	Eigenvalue	Contributing ratio % (cumulative)
1st	3.4	68.6(68.6)	2.3	45.3(45.3)	3.4	68.1(68.1)
2nd	0.6	12.7(81.3)	1.1	22.0(67.3)	0.5	11.0(79.1)
3rd	0.4	8.7(90.0)	0.7	13.8(81.1)	0.5	10.2(89.3)
4th	0.3	6.0(96.0)	0.5	10.2(91.3)	0.4	7.8(97.1)
5th	0.2	4.0(100.0)	0.4	8.7(100.0)	0.1	2.9(100.0)

PCA of five parameters

The cumulative contribution ratio of the first two principal components accounted for 65% of the variance in the three food samples at all points (Table 5 (a) (b) (c)).

PCA on the correlation matrix of five parameters revealed two factors (Table 6 (a) (b) (c)). Correlation

Table 5 (b) PCA on five parameters at the middle point

component	Rice cracker		Cheese		Peanuts	
	Eigenvalue	Contributing ratio % (cumulative)	Eigenvalue	Contributing ratio % (cumulative)	Eigenvalue	Contributing ratio % (cumulative)
1st	3.8	77.0(77.0)	3.4	68.5(68.5)	3.1	61.9(61.9)
2nd	0.6	11.0(88.0)	0.7	14.9(83.4)	0.9	18.7(80.6)
3rd	0.3	5.5(93.5)	0.5	10.7(94.1)	0.4	8.0(88.6)
4th	0.2	4.0(97.5)	0.2	3.6(97.7)	0.3	6.2(94.8)
5th	0.1	2.5(100.0)	0.1	2.3(100.0)	0.3	5.2(100.0)

Table 5 (c) PCA on five parameters at the last point

component	Rice cracker		Cheese		Peanuts	
	Eigenvalue	Contributing ratio % (cumulative)	Eigenvalue	Contributing ratio % (cumulative)	Eigenvalue	Contributing ratio % (cumulative)
1st	3.35	67.0(67.0)	3.16	63.3(63.3)	3.44	68.7(68.7)
2nd	1.01	20.2(87.2)	1.04	20.8(84.1)	1.09	21.9(90.6)
3rd	0.37	7.4(94.6)	0.41	8.1(92.2)	0.18	3.7(94.3)
4th	0.18	3.6(98.2)	0.28	5.6(97.8)	0.16	3.3(97.6)
5th	0.10	1.8(100.0)	0.11	2.2(100.0)	0.12	2.4(100.0)

Table 6 (a) Factor loadings by factor analysis on five parameters at the first point

Parameters	Rice cracker		Cheese		Peanuts	
	Factor 1	Factor 2	Factor 1	Factor 2	Factor 1	Factor 2
Rupture energy	0.81	0.28	0.29	0.70	0.84	0.20
Elasticity	0.89	0.23	0.00	0.88	0.26	0.96
Viscosity	0.82	0.42	0.85	-0.07	0.83	0.42
Hardness	0.22	0.92	0.74	0.36	0.76	0.37
Adhesiveness	0.52	0.68	0.77	0.14	0.72	0.37

Table 6 (b) Factor loadings by factor analysis on five parameters at the middle point

Parameters	Rice cracker		Cheese		Peanuts	
	Factor 1	Factor 2	Factor 1	Factor 2	Factor 1	Factor 2
Rupture energy	0.33	0.89	0.87	0.00	0.89	0.03
Elasticity	0.42	0.83	0.77	0.45	0.08	0.96
Viscosity	0.85	0.37	0.80	0.41	0.64	0.62
Hardness	0.78	0.51	0.74	0.61	0.84	0.24
Adhesiveness	0.90	0.32	0.16	0.95	0.83	0.24

Table 6 (c) Factor loadings by factor analysis on five parameters at the last point

Parameters	Rice cracker		Cheese		Peanuts	
	Factor 1	Factor 2	Factor 1	Factor 2	Factor 1	Factor 2
Rupture energy	0.92	0.08	0.81	0.23	0.85	0.39
Elasticity	0.14	0.92	0.38	0.84	0.07	0.98
Viscosity	0.35	0.87	0.11	0.94	0.79	0.50
Hardness	0.92	0.31	0.91	0.23	0.93	0.16
Adhesiveness	0.80	0.44	0.91	0.20	0.95	-0.15

rates larger than 0.2 were not recorded in the residual error matrix. The data structure could be explained by two factors.

The factor structures of the five parameters at the last point differed slightly between the three food samples. Factor 1 positively correlated with rupture energy, but Factor 2 positively correlated with elasticity and viscosity.

Discussion

Masticatory behavior

It became easier to swallow the bolus of the rice cracker after crushing or absorbing saliva during mastication. The cheese bolus emulsified without absorbing saliva, and its adhesiveness decreased. A unique characteristic behavior was that the cohesiveness remained unchanged at 0.5 even during mastication. The bolus of peanuts neither absorbed saliva nor did its essential properties change during mastication.

The general characteristics of data

In this study, the larger cohesiveness became, the larger wateriness became. The minimal cohesiveness possible for swallowing was constant in all the food samples. Every food sample should be masticated toward the constant cohesiveness.

Small SD of cohesiveness indicates variability of normal subjects was small. It is strongly suggested that mastication goes toward the point of cohesiveness.

It is quite natural that other five parameters (rupture energy, elasticity, viscosity, hardness and adhesiveness) decrease with mastication progress. Past reports estimated an attenuation rate of one of these parameters for ability of mastication function,[32] but in this study, because each SD of these parameters was very large, it would be difficult to calculate the accurate attenuation rate with only one parameter of one test food sample.

Therefore, the analysis of factor structure of the six mechanical parameters was performed.

Multivariate analysis

PCA and factor analysis of six parameters

The factor structure was determined by factor analysis of two factors. Examination of the residual correlation matrix indicated a close fit between the observed and reproduced correlation matrices. This is thought to be an appropriate method to determine the two factors.

In all three food samples, raw data showed that cohesiveness had different behavior from other five parameters, and it was confirmed by PCA of six parameters.

PCA and factor analysis of five parameters without cohesiveness

Cohesiveness was separately investigated because it was independent of the remaining five parameters. Factor analysis of the correlation matrix of five parameters at each point yielded additional two factors. The factor loading of each of the three food samples showed a characteristic structure for a set of five parameters at the first and the middle point. It indicates the changing of mechanical properties of bolus was depended on the texture of test food. There was no difference between the three food samples regarding the factor structure of five parameters immediately before swallowing despite the variations in the raw data at the last point, therefore, it should be a key component during examination on masticatory performance. It is clarified that the correlation of parameters became constant as mastication progressed toward the end point in all three food samples.

The influence of saliva to the mechanical properties of food samples may become important for more detailed study. The viscosity of saliva and powder-water ratio of bolus would be measured to investigate their influence on the mechanical properties of food samples.

Conclusion

The standard deviations of rupture energy, elasticity, viscosity, hardness and adhesiveness vary considerably, and it is difficult to outline the changes in the mechanical properties of a food bolus during mastication. The results of PCA indicate that five parameters of the bolus during mastication can be summarized by two factors (factors 1 and 2), and masticatory performance can be represented by the plane of these two factors.

Cohesiveness immediately before swallowing was constant in all three food samples. Factor analysis showed that despite the variations in the raw data at the last point, there was no difference between the three food samples regarding the factor structure of five parameters immediately before swallowing.

In all food samples, the endpoint of mastication was clarified in this study.

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References

1. Manly RS, Braley LC. Masticatory performance and efficiency. J Dent Res 1950;29:448-462.
2. Ishihara T. Masticatory efficiency and particle size distribution of masticated raw rice. (in Japanese, English abstract) Stomatological soci 1955;22:207-255.
3. Agrawal KR, Lucas PW, Prinz JF, et al. Mechanical properties of foods responsible for resisting food breakdown in the human mouth. Arch Oral Biol 1977;42:1-9.
4. Ono T, Hori K, Nokubi T, et al. Evaluation of mastication and swallowing of gummy jelly using digital subtraction angiography. J Jpn Prosthodont Soc 2003;47:107-116.
5. Tanaka A, Shiga H, Kobayashi Y, et al. Quantitative evaluation of mandibular movements and masticatory muscular activities by analyzing the amount of glucose discharge during gumi-jelly chewing. J Jpn Prosthodont Soc 1994;38:1281-1294.
6. Shiga H, Kogayashi Y, Unno M, et al. Chewing time for evaluating the masticatory efficiency of gumi-jelly chewing. (in Japanese, English abstract) J Jpn Soc Stomatognath Funct 2004;11:21-25.
7. Farrell JH. The effect of mastication on the digestion of food. Br Dent J 1956;100:149-155.
8. Honma W, Kohno S, Mukawa Y, et al. Evaluation of masticatory function focusing bolus formation by the number of chewing strokes until swallowing of water absorbing rice crackers. (in Japanese, English abstract) J Jpn Soc Stomatognath Funct 2004;10:151-160.
9. Edlund J, Lamm CJ. Masticatory efficiency. J Oral Rehabil 1980;7:123-130.
10. Yomoda S, Hisano M, Amemiya K, et al. The interrelationship between bolus breakdown, mandibular first molar displacement and jaw movement during mastication. J Oral Rehabil 2004;31:99-109.
11. Ogawa T, Ogawa M, Koyano K. Different responses of masticatory movements after alteration of occlusal guidance related to individual movement pattern. J Oral Rehabil 2001;28:830-841.
12. Kido T, Watabe A, Kohno S, et al. Relationship between behavior of food and occlusal configuration on masticatory function. J Jpn Soc Stomatognath Funct 1995;2:27-31.
13. Shiozawa K, Kohyama K, Yanagisawa K. Influence of ingested food texture on jaw muscle and tongue activity during mastication in humans. Jpn J oral biol 1999;41:27-34.
14. Shiozawa K, Kohyama K, Yanagisawa K. Food Bolus Texture and tongue activity just before swallowing in human mastication. Jpn J oral biol 1999;41:297-302.
15. Yanagisawa Y, Tamura A, Teramoto Y. Correlation between masticatory muscular activity and texturometric parameter. (in Japanese, English abstract) J home economics Jpn 1989;40:1011-1016.
16. Prinz JF, Lucas PW. 'The first bite of the cherry' intra-oral manipulation prior to the first bite in humans. J Oral Rehabil 2001;28:614-617.
17. Blissett A, Prinz JF, Wulfert FA. Effect of bolus size on chewing, swallowing, oral soft tissue and tongue movement. J Oral Rehabil 2007;34:572-582.
18. Jack FR, Gibbon F. Electropalatography in the study of tongue movement during eating and swallowing (a novel procedure for measuring texture-related behaviour). Int J Food Sci Technol 1995;30:415-423.
19. Hori K, Ono T, Nokubi T. Coordination of tongue pressure and jaw movement in mastication. J Dent Res 2006;85:187–191.
20. Kodaira Y, Ishizaki K, Sakurai K. Effect of palate covering on bolus-propulsion time and its contributory factors. J Oral Rehabil 2006;33:8-16.
21. Ertekin C, Kiylioglu N, Tarlaci S, et al. Effect of mucosal anaesthesia on oropharyngeal swallowing. Neurogastroenterol Motil 2000;12:567-572.
22. Szczesniak AS. Classification of textural characteristics. J Food Sci 1963;28:385-389.
23. Szczesniak, AS. Objective measurements of food texture. J Food Technol 1963;28:410-420.
24. Szczesniak AS, Brandt MA, Friedman HH. Development of standard rating scales for mechanical parameters of texture and correlation between the objective and the sensory methods of texture evaluation. J Food Sci 1963;28:397-403.
25. Liedberg B, Stoltze K, Öwall B. The masticatory handicap of wearing removable dentures in elderly men. Gerodontology 2005;22:10-16.
26. Alexander R. News of chews: the optimization of mastication. Nature 1998;391:329.
27. Luschei ES, Goodwin GM. Patterns of mandibular movement and jaw muscle activity during mastication in the monkey. J Neurophysiol 1974;37:954-966.
28. Lucas PW, Ow RKK, Ritchie GM, et al. Relationship between jaw movement and food breakdown in human mastication. J Dent Res 1986;65:400-404.
29. Yanagisawa Y, Tamura A, Akasaka M, et al. Physical properties of food and eating functions. 1, An objective method for the measurement of the physical properties of foods, and classification of foods. (in Japanese) Shoni Shikagaku Zasshi 1985;23:962-983.
30. Ministry of Health and Welfare Japan. Management about foods for elderly. Shokuhin Eisei Kenkyu 1994;44:90-104.
31. Shiozawa K, Kohyama K, Yanagisawa K. Relationshipi between physical properties of a food bolus and initiation of swallowing. Jpn J oral biol 2003;45:59-63.
32. Olthoff LW, Van der bilt A, De boer A, et al. Comparison of force-deformation characteristics of artificial and several natural foods for chewing experiments. J Texture Studies 1986;17:275-289.