Effects of Cross-sectional Area on Human Bite Studied with Raw Carrot and Surimi Gel

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The effects of the cross-sectional area of food samples on bite force with molar teeth were investigated using raw carrots and surimi gels. We evaluated human bite force for food samples with different sizes between the upper and lower molars using a multiple-point sheet sensor and electromyography (EMG). The bite force curve and EMG clearly showed textural characteristics of the carrot and gel. In particular, the first peak in the bite curves corresponded to breaking point in the compression test. With increasing cross-sectional area of both foodstuffs, the bite force and contact area increased and the average stress to which the specimen was subjected (mean stress) tended to decrease, while the stress produced between the teeth and the specimen (active stress) did not change. Chewing rhythm and EMG activities were not greatly influenced by sample size. These findings suggest that higher bite force might cause difficulty in biting food with a larger cross-sectional area.

Key words: texture; bite force; multiple-point sheet sensor; electromyography

Food texture is mechanical, geometrical, and surface properties perceptible by means of mechanical and tactile receptors.1–3) Recently, the human mastication process has been studied using physiological techniques such as intra-oral force measurement, electromyography (EMG), and jaw kinematics.3–5) Masticatory variables can objectively display the perceived textural properties of food. These values sometimes differ from the results of instrumental mechanical tests because they are influenced not only by the mechanical properties of foods but also by size. Nakazawa and Togashi6) studied masticatory force parameters using an artificial molar tooth with a pressure sensor. The duration of the first chewing force, the number of chewing strokes, and mastication time were changed by both texture and size. The maximum force in the first chew and the maximum gradient of the force depended only on food texture. The chewing rhythm was influenced by neither food texture nor size. As we encounter more difficulty chewing food when the size of the food increases,7) the relationships between food size and masticatory variables has been studied by EMG and jaw-kinematics.8–10) Miyawaki et al. compared chewing behaviors for 10 g and 5 g gummy jelly samples and reported that the larger food sample evoked greater jaw movement and higher EMG activity, but did not change chewing rhythm.9,10) In such experiments using samples with a definite weight, the size effects involve both the cross-sectional area and the thickness of a specimen. The objective of this study was to investigate the influence of the cross-sectional area of food samples separately from that of thickness. Hence we tested food specimens with various cross-sectional areas and a constant thickness.

It is difficult to explain the effects of the cross-section of samples on the chewing force of humans using mechanical parameters obtained through instrumental tests. Normally we use much larger probes or much smaller probes for a given cross-section of food samples in an instrumental compression test to derive the stress value as the applied load divided by the contact area between probe and sample.3) However, when we chew food samples with the molars, the cross-sectional area of the sample and that of the molars are not very different. In addition, force sensors usable in intra-oral force measurement have a single sensing point and the sensitive area is similar to the food size. Besides chewing force, we need to measure the contact area between the teeth and the sample food.11) Agrawal and Lucas12) measured the contact area the same as the chewing pressure in a sample fracture by human teeth using a pressure-sensitive film (Prescale, Fujifilm, Tokyo). Their method is not dynamic: one can obtain only the maximum pressure and the maximum contact area after chewing a sample. The maximum pressure and maximum contact area do not always appear at the same time. Since the maximum bite force is often observed after fracture of the sample,13) this static method is useful for limited samples such as nuts which exhibit maximum stress during a chew at a fracture point.

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A multiple-point sheet sensing system (MSS) for dynamic measurement of bite force\textsuperscript{11,13–21} can conveniently be used for this purpose. The principle of the sensing device is similar to that of the T-scan sensor developed by Maness \textit{et al.}\textsuperscript{22} but our system can provide absolute pressure values in Pa applied to each sensing point after calibration with a known load. Since the sensor is a flexible plastic sheet thinner than 0.1 mm that possesses many pressure-sensing points, the total force and contact area were measured directly in real time using the sheet sensor. In this study, we used a sensor designed for detecting pressure distribution in the oral cavity around the incisors and molars on one side, and also providing the contact area between the food samples and the teeth, as in previous studies\textsuperscript{11,21}.

Solid foods were categorized into four groups according to the pattern of masticatory curve between molars\textsuperscript{13}. These were (1) sponge-like foods such as bread crumbs, (2) gels, (3) raw fruits and vegetables, and (4) crispy and low-moisture foods such as crackers\textsuperscript{13}. We conducted a uniaxial compression test on each group of foods between two flat plates using the MSS system as detector.\textsuperscript{17} The contact area between flat probe and food surface varied with the variety of food even under a small strain, and increased as compression strain increased. We used flat probes to make the contact area maximum, but due to cellular structure, both sponges and dry-crisp foods showed smaller values for contact area than the calculated cross-sectional area based on initial diameter until very high compression strain was applied. Unlike the case of the mechanical test using a defined probe, the shape and size of the human tooth are very complex and individually different. As it is difficult to determine the effects of the cross-sectional area of samples in a human biting test, we avoided the two groups (sponges and dry-crisp types) to test the effects of cross section. Hence we chose \textit{surimi} gels from the second group and raw carrots as a representative of the third group.

The active stress was different from the stress calculated as the load divided by the initial cross-sectional area in instrumental compression tests\textsuperscript{17}. The value of active stress provided a better explanation of the textural characteristics of the food. We surmised that texture is often sensed under a large deformation where real contact area is difficult to measure and is a mixed assessment of mechanical and geometrical properties.

We examined the effects of hardness and thickness on bite force using silicone rubber samples as model food\textsuperscript{11,21} and also the effects of thickness in biting an apple specimen.\textsuperscript{18} The bite force increased with rubber hardness, while the contact area between the teeth and the sample did not change.\textsuperscript{21} The peak force in molar chewing was greatest for 2 mm-thick rubber, suggesting difficulty in biting thicker samples. A thick specimen of hard food is perhaps difficult to bite off between the molars. We found that 2 mm \textit{surimi} gels were rarely cut by instrumental compression tests (preliminary unpublished data), and that \textit{surimi} gels with a thickness of 10 mm could be cut by human molars without difficulty.\textsuperscript{16} In addition to bite force, the contact area between the teeth and samples with a constant cross-sectional area increased for thicker specimens.\textsuperscript{11,18} This suggests that thicker specimens may cause larger errors in contact area during biting. Hence we chose thin samples easy to cut off (2 mm for carrot and 4 mm for \textit{surimi} gel) to study the effects of cross-sectional area.

Previous studies using the sheet sensor have suggested that the physical properties of food changed greatly within the first chewing stroke.\textsuperscript{13,14,16} The carrot or gel of three different sizes on the sheet sensor was bitten between the molars to clarify the differences in bite force or active stress.

As well as the MSS measurement, we also recorded the EMG from the masseter muscles of the chewing side. EMG has often been used to evaluate food texture changes in the oral cavity during the mastication process\textsuperscript{3–5} but the effects of the cross-sectional area of the samples on EMG parameters have been never reported.

This is the first study to record synchronously intraoral force using the MSS and EMGs. We discuss the variables obtained in both measurements. Several dental researches have been carried out to study the relations between activity in surface EMGs and bite force measured by single-point sensors for clenching or biting without food.\textsuperscript{23–29} This relation has been used to estimate bite force on food from EMG activity, because previous sensors such as the bite fork were hard and large and difficult to use to measure with food, unlike the EMG technique. We also compared the bite force and EMG results with those of the previous methods.

\section*{Materials and Methods}

\textbf{Samples and subjects.} Carrots harvested in Ibaraki Prefecture, Japan, and fish \textit{surimi} gels (Yuzduki Kamaboro, Tokyo) were bought in a local supermarket. The carrots were sliced to 2 mm radially and the gel was cut to 4 mm thickness. This thickness (2 mm) was chosen as subjects could produce the maximum bite force for chewing silicone rubber samples.\textsuperscript{11} But since thin \textit{surimi} gels (2 mm) could not be broken under the condition of instrumental measurement described below, specimens of 4 mm thickness were used instead. The samples were then cut into rectangles of three sizes: 18 × 10, 22 × 14, and 24 × 16 mm. The cross-sectional areas were 180, 308, and 384 mm\textsuperscript{2} respectively.

Ten healthy young women (mean age 24.5 years) who did not have any missing teeth in their molars on the chewing side except for the third molar, or any functional mastication problems, participated voluntarily in this experiment. They gave their informed consent prior to the recording session.
**Instrumental hardness measurement.** A mechanical compression test of each sample was carried out using a food rheometer (RE-33005, Yamaden, Tokyo, Japan) at room temperature. The center of the largest sample (24 × 16 mm) was compressed using a cylindrical probe with a diameter of 8 mm at a constant speed of 1 mm/s up to 97% strain. The sample rupture was determined at the point where the first reduction in stress was observed. Sample hardness was expressed as rupture stress, calculated as the detected load divided by the initial contact area of probe and sample. Strain was calculated as the ratio of sample deformation to initial height. The test was replicated more than 5 times for each food.

**Bite force measurement.** The bite force was measured with an I-SCAN system (Nitta Corporation, Osaka, Japan), as previously reported. A sensor sheet composed of 269 sensing points forming a grid with a 2-mm pitch on a flexible plastic film (<0.1-mm thick with a saturated pressure of 4 MPa) was used. The sensing area was 1,076 mm², and the shape was fit to the oral cavity to detect bite pressure using the molar teeth on one side and incisors. On the sensor sheet, there were 18 columns on the top side and 24 rows on the reverse side. The system unit scanned all the sensing points, digitized the output voltage, and calculated pressure values every 0.01 s. Each subject used an individual sensor sheet, and the sensor was calibrated with a fixed load before the experiment.

Chewing side was chosen by each subject. Subjects inserted the samples on the top surface of sensor sheet between their upper and lower molars without touching the sample with their fingers, and then chewed the sample twice with as normal chewing as possible. We analyzed the stress detected by the sensing cells just under the samples. The bite force was defined as the sum of forces detected by the sensing cells. Both foodstuffs exhibited two peaks in bite force versus time curves of the first chew, as reported previously. The following parameters were calculated from the time course of the bite force: (1) the first peak force, (2) the contact area at the first peak, (3) the mean stress (the force divided by the cross-sectional area of the sample), (4) active stress (the force divided by the contact area) at the first peak, (5) time to the first peak, (6) the second peak force, (7) the contact area at the second peak, (8) active stress at the second peak, (9) ascending time or time to the maximum bite force, (10) duration of force detected (from the onset to the end of one chewing stroke), and (11) cycle time, defined as the time from the beginning of the first chewing stroke to that of the second.

**Electromyography.** EMG activities were recorded from the masseter muscle of the chewing side using bipolar surface electrodes and an MEG-6108 amplifier with an AB-610J unit (Nihon Kohden, Tokyo, Japan), as previously reported. The data were stored in a Windows computer using an MP100 program (Biopac Systems, Goleta, California, U.S.A.), at 1000 Hz for further analysis. A synchronized time signal of the MSS sampling was added to the EMG records. From the EMG charts, (12) the amplitude or the maximum voltage in the first chew, (13) masticatory activity estimated as the time-integral of the EMG voltages, and (14) EMG burst duration were derived using wave-analysis software (AcqKnowledge ver. 3.5.7, Biopac). In addition, using both bite force and EMG, (15) the time difference between the beginning of the EMG burst and the onset in bite force, and (16) that between the end of the EMG burst and end of the bite force were also calculated.

**Statistics.** Statistical analyses were performed using an SPSS (ver. 11.0J for Windows) package (SPSS Inc., Chicago, Illinois, U.S.A.). Mean values of 2 replicates were subjected to a repeated-measure analysis of variance (ANOVA) to test the effects of sample size on the bite variables. When the differences were significant, a paired t-test with Holm’s correction was applied to all the combinations of two levels post-hoc. Statistical significance was set at \( p < 0.05 \).

**Results and Discussion**

**Mechanical test**

Figure 1 shows typical stress-strain curves for raw carrot and surimi gel measured using a cylindrical probe, which is often used as a model of the human molars. Rupture stress was one order higher in raw carrot, while rupture strain was higher in the surimi gel. The slope of the stress–strain curve before the rupture point was greater in raw carrot. The average data for sample ruptures are displayed in Table 1. These observations indicate that raw carrot is hard and brittle while the gel is soft and tough. The mechanical test did not provide a size effect for samples unless the size of the probe was unsuitable.

![Stress–strain Curves for Raw Carrot and Surimi Gel](image-url)
General findings for bite force and EMG measurements

Figure 2 shows an example of the stress distribution observed at the first peak of biting raw carrot and surimi gel. Since the distribution patterns accorded with the shape of the dental arch, a similar pattern appeared within a subject, but was highly dependent on subjects. The stress was detected by sensing cells placed just under the samples (either of 9/C2 5/rows or 12 columns). At the first peak, the stress values for carrot were higher than those for gels, corresponding to hardness.16) Although the gel was more homogeneous than raw carrot,17) it exhibited great spatial distribution of bite pressure like the carrot due to the irregular shape of the teeth. A similar observation was reported in previous studies using homogeneous samples.11,21)

Since the I-SCAN system provided a stress distribution map every 0.01 s, we can also draw the time course. In the upper graph of Fig. 3, examples of bite curves are shown. The bite force for surimi gel exhibited two peaks, resembling those for three surimi gels and agar gel.13,16) They were typical for gels and commonly observed in all subjects. The bite curves for raw carrot also exhibited two peaks, and they resembled previous observations that the first peak corresponding to a sample fracture was much steeper in raw carrot than in gels.13) As shown in the mechanical tests (Fig. 1 and Table 1), the force required to break raw carrot was much higher and the time to the first peak corresponded to the rupture deformation.13,16,18–21) The time to peak for the carrot was shorter than that for surimi gel. The slope of bite force–time curve before the rupture point was greater in raw carrot, as observed in the stress–strain curve (Fig. 1).

At the bottom of Fig. 3, EMG activities recorded from the masseter muscle of the chewing side during biting of the two samples are shown. EMG activity during biting of raw carrot was higher than that for surimi gel. Dependence on sample hardness was commonly observed in the mechanical test, bite force, and EMGs. It is known that the higher the clenching force or bite force, the larger the EMG amplitude or muscle activity from the jaw-closing muscle of the chewing side.23–29) A majority of subjects displayed a linear relationship between bite force and EMG amplitude.24–27)

Since the masseter muscle works to close the jaw,4) it activated when the mandible was elevated to the upper
teeth. Bite force and EMG activity began to appear at almost the same time. The first peak of the bite curve was accompanied by sample rupture,\(^{10}\) where the jaw-closing muscles worked continuously. The second peak appeared when the jaw began to open.\(^{13}\) From about this time the jaw-closing muscles finished acting and the jaw-opening muscles alternated with them. When the gap between the upper and lower teeth was greater than the thickness of the food bolus, the bite force was no longer observed. The duration between the beginning of the EMG burst and the onset of masticatory force, and that between the end of the EMG burst and that of the bite force are shown in Table 2. The former was almost zero, and the latter was about 0.14 s, not depending sample size or hardness. A similar relationship between bite force and masseter EMG activity measured on the chewing side has been reported.\(^{28,32}\)

Both carrots and gels displayed two peaks in the contact area curve as well as in bite force (Fig. 2). The ratio of bite force to contact area yields the active stress.\(^{11}\) For both samples, the active stress at the second peak was higher than that at the first peak, where the samples were fractured.\(^{16}\) This suggests that the maximal pressure during a bite may not provide the stress value for breaking the sample. Hence a dynamic time-course measurement is required.

### Effects of cross-sectional area

Table 2 describes the effect of sample size on human biting. With increasing cross-sectional area, the bite force and contact area at both peaks increased. Mean stress calculated as the force divided by the cross-sectional area of the samples gradually decreased, though this was statistically insignificant. But active

<table>
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<tr>
<th>Food sample</th>
<th>Parameter</th>
<th>F-ratio</th>
<th>180</th>
<th>308</th>
<th>384</th>
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<tbody>
<tr>
<td>Raw carrot</td>
<td>First peak force (N)</td>
<td>3.35</td>
<td>28.2</td>
<td>18.9</td>
<td>38.2</td>
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<td>Contact area at first peak (mm(^2))</td>
<td>8.80*</td>
<td>83</td>
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<td>Mean stress at first peak (MPa)</td>
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<td>0.146</td>
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<td>0.079</td>
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<td>3.78</td>
<td>30.8</td>
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<td>14.01***</td>
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<td>0.135</td>
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<td>0.191</td>
<td>0.790</td>
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<td>Surimi gel</td>
<td>First peak force (N)</td>
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<td>17.3</td>
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<td>25.96***</td>
<td>107</td>
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<td>Mean stress at first peak (MPa)</td>
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<td>0.113</td>
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<td>0.238</td>
<td>0.102</td>
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<td>0.008</td>
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<td>Burst duration (s)</td>
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<td>0.332</td>
<td>0.102</td>
<td>0.353</td>
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</tbody>
</table>

Mean and standard deviation of 8 subjects. *, \(p < 0.05\); **, \(p < 0.01\); ***, \(p < 0.001\).

Mean values with different alphabetical letters in a row differ significantly (\(p < 0.05\)).
stress derived as the ratio of force to contact area was almost constant. Time to the first peak, ascending time, duration, cycle time, and EMG activities were not much influenced by sample size.

The contact area increased with increases in sample size. The maximum contact area was 80 to 160 mm$^2$, as shown in Table 2. This was much smaller than the original cross-sectional area (180, 308, or 384 mm$^2$). This means that the samples were subjected to force by the teeth partly on the cross-sectional area. But the contact area depending on the sample size, area of human teeth, and that of one moulthful food were close. Application of the MSS is useful for investigation of the effects of sample size.

With increases in the cross-sectional area of samples, the bite force and contact area increased slightly. When humans encounter difficulty in chewing large food, bite force and contact area likely work. The EMG activity and time related parameters (force duration, EMG duration, and cycle) were basically unchanged for different samples in cross-section. This suggests that humans do not change chewing in biting different samples. Since mastication is programmed in the pattern generator in the brain stem, the muscle power and chewing rhythm are likely unchanged by the cross-sectional area of the food specimen. Our findings were consistent with previous reports that neither food texture nor size influenced chewing rhythm, unlike another mastication parameters. Active stress remained almost constant for different cross-sectional areas, but was definitely different between the two foodstuffs. Food hardness is perhaps sensed by the magnitude of sensation from periodontal ligaments corresponding to active stress as well as by muscle spindles. The extent of active stress or the area detecting the stress is important for perceiving differences in cross-sectional size of food. The differences can be detected by multiple sensors but not by a single sensor or the EMG technique.

The observed size effects were more significant in surimi gels than in raw carrots. This is probably due to a smaller special distribution in mechanical properties for the gels as has been reported in an instrumental compression test. Highly heterogeneous carrots may break at a point where the structure is the weakest and is less dependent to the sample size, while more homogeneous gels resist bite force with a wider contact area.

**Conclusion**

Our conclusion is that bite force is more sensitive to express size effects on biting between the molars. When a hard food was bitten, humans produced greater bite force, stress, and EMG activity. With increasing cross-sectional area of food, both bite force and contact area between the teeth and food increased, but active stress and EMG activity did not change significantly. Though humans do not change muscle activity and active stress, greater force and contact area may influence perceived texture. Multiple-point sensing displayed differences in contact area according to the sample size and similar active stress nevertheless the cross-sectional area.

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