Textural Properties of Food Used in Studies of Mastication

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Foods are known to influence jaw elevator muscle activity in chewing. With the long-range goal of gaining insight into force control and modeling muscle recruitment, these initial experiments were performed to determine the textural properties of commonly used test food.

Experiments were carried out by means of a standard Instron instrument, equipped with a compression cell. A stylus with 45-degree cuspal angulation and an opposing copper-plated lower arch was used for approximation of the natural situation. The breakage force characteristics of a single peanut, a carrot cube, beefstick, and monkey chow were determined.

The peanut demonstrated the steepest and beefstick the least steep force build-up, with breaking forces of 104 N (Newtons) for monkey chow, 66 N for the carrot, and 52 N for the peanut. No clear breakage point was found with beefstick; the force build-up showed an initial plateau at 25 N, which was followed by a significantly steeper force increase to peak.

We conclude that each of the test foods commonly used in studies of mastication had particular breakage characteristics in terms of its force-time curve.

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Introduction.

Black (1895) stated that "the only way to arrive at any satisfactory conclusion as to the force ordinarily employed, was to contrive means of weighing the stress necessary to crush the ordinary food." It has been reported that the myoelectric activity pattern of the jaw muscles differs among various types of foods (Ahlgren, 1966; Moller, 1966; Hiiemae, 1978; Haraldson and Ingerval, 1979; Hylander and Johnson, 1989). Harder food usually produces greater myoelectric amplitudes of the jaw-closing musculature. In addition, chewing rate, chewing cycle duration, and the amount of lateral mandibular excursion are influenced by the nature of the test food (Luschei and Goodwin, 1974; Bates *et al.*, 1975; Hiiemae, 1978). With the long-range goal of elucidation of mechanisms of force control and modeling of muscle recruitment, it is necessary that the textural properties of commonly used test foods be determined.

The purposes of this research were (1) to measure the breaking force of different foods of standardized size and shape, and (2) to record the force-time relationship during the initial bolus compression.

Materials and methods.

Experiments were performed by means of an Instron® Universal Testing Instrument (Instron Corp., Canton, MA 02021) equipped with a compression cell (Tension/Compression Cell, up to 4900 N, Instron Engineering Corp., Quincy, MA). A stainless-steel stylus with 45-degree cuspal angulation was used for simulation of the upper molar cusp. A model of the mandibular arch, consisting of an autopolymerized resin core with copper-plated surface, was secured firmly to the load table. The lower dentition included 14 intact, human teeth. A switching relay was connected between the stylus and the lower arch, so that whenever tooth contact was established, the Instron driving circuit was shut down (Fig. 1). For experiments with monkey chow, a model of the lower arch of an adult female *Macaca fascicularis* was used, in addition to the human dentition employed in the other tests.

The following test foods were included: (1) high-protein monkey chow (#5045, Purina Mills® Inc., St. Louis, MO) of cylindrical shape and 13 mm in diameter; (2) fresh carrot cubes of 2, 3, 5, and 10 mm thicknesses; (3) a half peanut (dry-roasted blanched peanut, Food Club®, Skokie, IL) with an approximate thickness of 5 mm; (4) beefstick (Bridgford®, Bridgford Foods Corp., Chicago, IL) without skin, and with an approximate thickness of 8 mm.

After the test food was placed on the occlusal table of the first lower molar, the stylus tip was positioned on the center of the test food. For recording of the subtle force changes in the compression cycle, cross-head speeds of 2 cm/min and 5 cm/min were selected. Although these speeds are slower than those found in mastication, only small differences have been found between series of measurements with different rates of

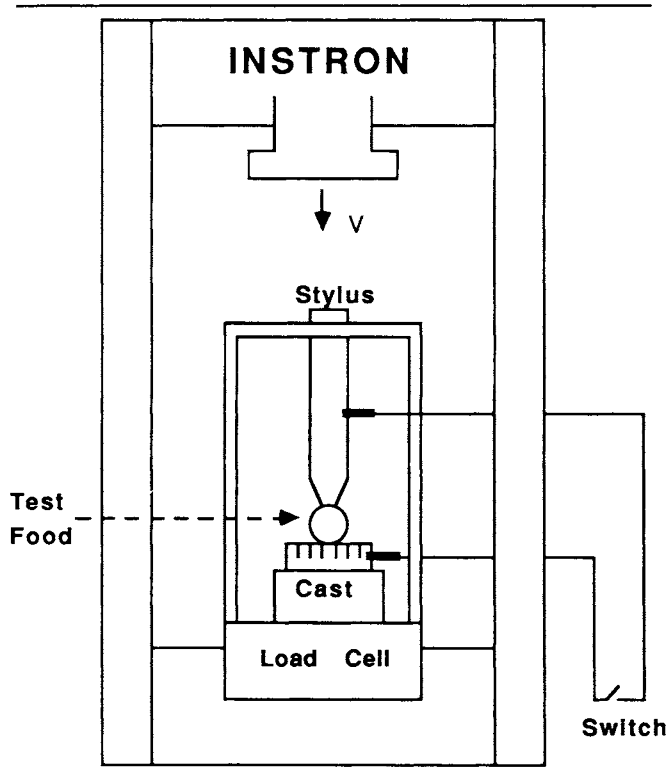

Fig. 1—Experimental instrumentation.

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loading in terms of the force-deformation curves (Olthoff, 1986). Stress, sensed by the load cell during food compression, was plotted on a polygraphic system with a paper speed of either 5 cm/min or 50 cm/min. The peanut, carrot, and monkey chow were tested with both cross-head speeds. For beefstick, however, only the larger cross-head speed was used. Twenty specimens were measured in each food and cross-head speed category. Experiments with monkey chow were performed with casts of both the human and monkey dentition. For the carrot, an additional five trials were performed with each of the 2^-, 3^-, 5^-, and 10-mm cubes.

Maximum breakage forces (MBF) of various test foods, compressed by different cross-head speeds, were analyzed by means of two-way analysis of variance for evaluation of the influence of cross-head speeds, test foods, and the interaction between them. The significance of the use of either the human or monkey dentition was statistically evaluated by means of the unpaired *t* test. The influence of food thickness was assessed by one-way analysis of variance.

The breakage patterns (force-time relationship) were further investigated by identification of parameters such as breakage point (BP), initial breakage force (IBF), initial force build-up (IFB), maximum breakage force (MBF), total compression time (TCT), and temporal location of MBF in the compression cycle (TL). These parameters are illustrated in Fig. 2. BP was defined by any increase in compression force that was followed by an immediate decrease of more than 4 N (Newtons). This facilitated distinction between stress relaxation and food deformation. The force magnitude of the first BP was regarded as IBF. IBF, divided by the time needed to arrive at IBF, was defined as IFB. TL was defined by the fraction of time needed to reach MBF within a total compression cycle. IBF in this study is equal to the definition of fracturability; MBF is equal to hardness (Brennan *et al.*, 1970; Bourne and Comstock, 1981).

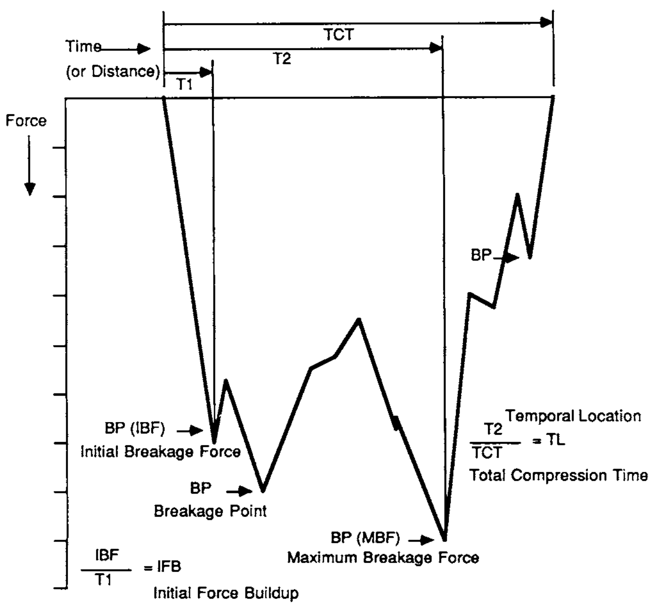

Fig. 2—Diagramatic representation of the definitions. Horizontal arrows indicate the positions of breakage points (BP), which were defined by any increase and then a decrease of more than 4 N. Force magnitude of the first BP was initial breakage force (IBF) which, when divided by the time needed (T1), was regarded as initial force build-up (IFB). Maximum force found in all BPs was maximum breakage force (MBF). The time needed to reach MBF was T2, which, divided by total compression time (TCT), was the temporal location of MBF (TL).

Results.

Force-time relationship. —Force-time curves of the different test foods, with a cross-head speed of 5 cm/min, are presented in Fig. 3. The mean and standard deviations of various force categories and breakage patterns are summarized in Tables 1 and 2.

(A) *Beefstick.* —The force-time curve of beefstick showed the lowest initial force build-up (IFB) (3.1 N/s, with a cross-head speed of 5 cm/min), which can be explained by the tenderness of beefstick. Beefstick tended to flow rather than break, exhibiting a defined breakage point (BP) of less than 1 *per* compression cycle, on average. At 60% of total compression time (TCT), the force reached its maximum of about 25.4 N, then decreased slightly to form a force plateau that was maintained until late in the compression cycle. Because of the specific property of beefstick, food residuals were usually trapped between tooth antagonists, producing an end force of more than 400 N at the final compression stage.

(B) *Peanut.*—The peanut showed the highest IFB (53.8 N/s, with a cross-head speed of 5 cm/min), representing the rigidity of the food. At about 20% of TCT, the force had already reached 50 N on average. Because maximum breakage force (MBF) was the first BP in six of nine tests of the peanut, the initial breakage force (IBF) of the peanut (49.4 N) was close to MBF. Following the point of breakage, the compression curve was quite irregular. Due to the brittleness of the peanut, the average number of BPs was found to be 3.2 *per* cycle. Finally, and similarly to beefstick, an end force of more than 400 N was always observed.

(C) *Monkey chow.* —Due to the rigidity of monkey chow, the initial slope of the force-time curve showed a rapid increase. IFB (46 N/s at a cross-head speed of 5 cm/min) was only a little less than that of the peanut. Monkey chow was further characterized by its brittleness, which was reflected by the highest number of BPs (4.8/cycle) among all the test foods. Interestingly, in six of nine trials, MBF was the last BP in

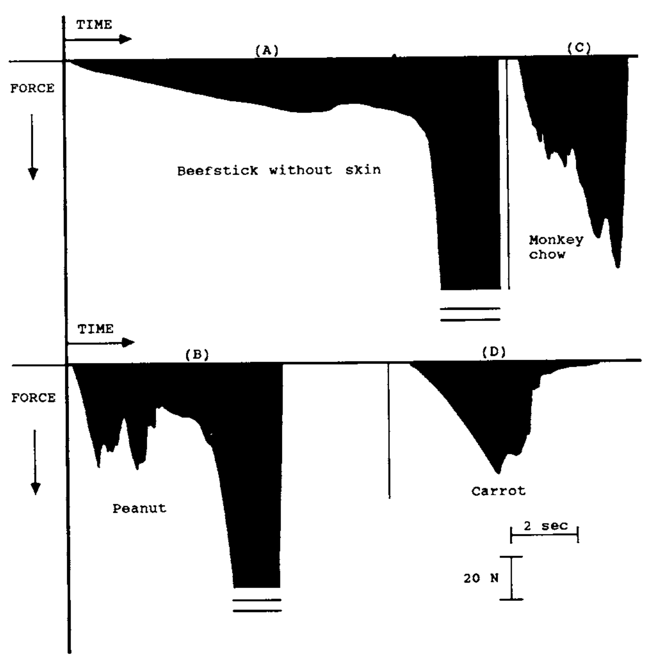

Fig. 3—Force-time curves of various test foods (cross-head speed, 5 cm/min; paper speed, 50 cm/min). (A) Beefstick without skin, (B) peanut, (C) monkey chow, (D) carrot. End forces of beefstick and the peanut are not displayed fully (see text).

TABLE 1
INITIAL FORCE BUILD-UP, INITIAL BREAKAGE FORCE, AND MAXIMUM BREAKAGE FORCE (MEAN ± S.D.) FOR VARIOUS TEST FOODS (CROSS-HEAD SPEED, 5 cm/min)

Test Food	Initial Force Build-up (IFB)	Initial Breakage Force (IBF)	Maximum Breakage Force (MBF)
Beefstick (n = 9)	3.1 ± 0.2	25.4 ± 3.8	25.4 ± 3.8*
Peanut (n = 9)	53.8 ± 17.2	49.4 ± 11.6	51.7 ± 10.1*
Mon. chow (n = 10)	46.0 ± 9.7	34.3 ± 20.1	103.9 ± 24.4
Carrot (n = 9)	17.5 ± 3.4	66.3 ± 9.2	66.3 ± 9.2

*Because of a specific property of beefstick and the peanut, food residuals were usually trapped between tooth antagonists, causing an end force of more than 400 N at the final compression stage. However, end force was not included in the consideration of MBF, because it is unlikely to occur in natural mastication.

TABLE 2
BREAKAGE PATTERNS OF DIFFERENT TEST FOODS (CROSS-HEAD SPEED, 5 cm/min)

Test Food	No. of Breakage Point* (BP) (unit/cycle)	Total Compression Time (TCT) (s)	Temporal Location of MBF (TL) (% from the start point)
Beefstick (n = 9)	0.7 ± 0.5	13.6 ± 0.2	59.3 ± 11.0
Peanut (n = 9)	3.2 ± 0.4	7.0 ± 0.5	20.4 ± 10.7
Mon. chow (n = 10)	4.8 ± 2.6	4.6 ± 1.6	72.1 ± 16.0
Carrot (n = 9)	1.3 ± 0.5	5.9 ± 2.0	54.5 ± 10.5

*Any increase and then a decrease of more than 4 N was counted as a breakage point; end force was not included in the counting. In beefstick, almost no clear breakage was found, only flow. In the peanut, MBF was the first BP in six of nine trials; on the contrary, in six of nine trials, MBF was the last BP in monkey chow. All of the MBF were the first BP in the carrot.

monkey chow, which was temporally located at 72% of the full compression cycle. This feature was quite different from the peanut's. Monkey chow also showed the highest hardness (MBF = 103.9 N). Following the point of fracture, force

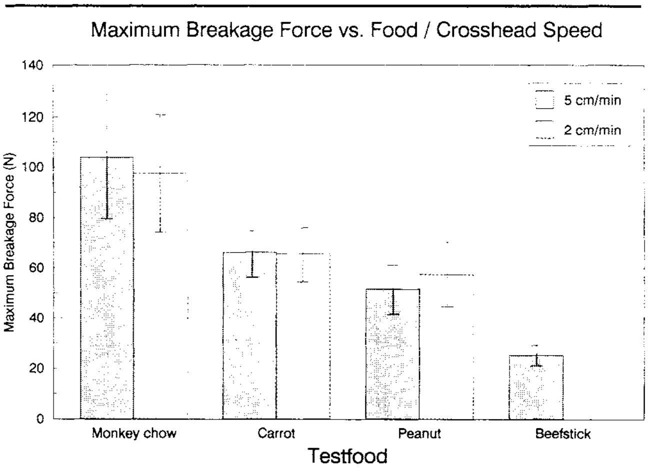

Fig. 4—Maximum breakage force *vs.* test food / cross-head speed.

TABLE 3
ANOVA TABLE FOR A TWO-FACTOR ANALYSIS OF VARIANCE ON MAXIMUM BREAKAGE FORCE

Source	df	Sum of Squares	Mean Square	F-test	p value
Food (A)	2	426.499	213.249	81.861	0.0001*
Cross-head speed (B)	1	0.901	0.901	0.346	0.5576
AB	2	4.515	2.257	0.867	0.4232
Error	114	296.972	2.605		

*Statistical significance.

TABLE 4
THE EFFECT OF THE OCCLUSAL TABLE ON MAXIMUM BREAKAGE FORCE (MBF) DURING COMPRESSION OF MONKEY CHOW WITH A CROSS-HEAD SPEED OF 5 cm/min

Dentition	Test Number	MBF (N)*
Human	20	101.04 ± 20.87
Macaca fascicularis	12	91.34 ± 15.58

*The results are expressed as mean ± S.D.
t test: p = 0.32; no statistical significance.

decayed rapidly because the fractured pieces fell off the occlusal table, and the stylus established contact with its counterpart. Although monkey chow was clearly thicker than the peanut, TCT of monkey chow was less than that of the peanut.

(D) *Carrot.*—The initial slope increased moderately; IFB was about 17.5 N/s when a cross-head speed of 5 cm/min was used. The first breakage point was MBF, which was located at 55% of the full duration of the compression cycle. MBF was 66 N, on average. The number of BPs was 1.3 *per* cycle, indicating that following fracturing, the force declined in steps and was rarely associated with a rapid increase of force. This represents the low cohesiveness of the xylem tissue. The broken pieces also fell off the occlusal table. The average duration of TCT was only 5.9 s, which was shorter than the corresponding values for the peanut and beefstick.

Statistical analysis.—By means of multivariate analysis of variance (Wilks' Lambda F statistics), the force-time curves of different test foods were shown to be significantly different from each other ($p<0.001$, s). Parameters of the force-time curve were also found to be significantly different between test foods by one-way analysis of variance ($p<0.001$, s).

Based upon 20 trials with the 5 cm/min cross-head speed, MBF was 103.9 ± 24.4 for monkey chow, 66.3 ± 9.2 N for the carrot, and 51.7 ± 10.1 N for the peanut. Skinned beefstick did not exhibit a breaking point, as observed with the other test foods; in fact, an initial force plateau was recorded which was related to the force needed for the beefstick to be punctured. The average force of this initial plateau was 25.4 ± 3.8 N. Results are summarized in Fig. 4. At final compression stage, the carrot and the monkey chow fell off the occlusal table; however, beefstick and the peanut showed an end force because food residuals were trapped between tooth antagonists.

Two-way analysis of variance showed that there was no interaction between cross-head speed and test food in the measurement of MBF (p = 0.42, n.s.). Different cross-head speeds had no statistically significant influence on the results (p = 0.56, n.s.). However, the type of food was significant in the determination of MBF (p = 0.0001, s.). Statistical results are summarized in Table 3. Multiple comparison (Fisher test and Scheffé's F test) showed that the MBFs of different types of

TABLE 5
THE EFFECT OF BOLUS (CARROT) SIZE ON MAXIMUM BREAKAGE FORCE (MBF) WITH A CROSS-HEAD SPEED OF 5 cm/min

Thickness	Test Number	MBF (N)*
10 mm	5	65.9 ± 9.6
5 mm	5	63.3 ± 4.4
3 mm	5	58.6 ± 12.3
2 mm	5	50.8 ± 4.9

*The results are expressed as mean ± S.D.
One-way analysis of variance: p = 0.1; no statistical significance.

food were significantly different from each other. Although the human and monkey occlusal morphology are quite different, the effect of the type of occlusion was of no significance with monkey chow (p = 0.32, n.s.) (Table 4). No statistically significant influence was found when carrots of variable thickness were used (p = 0.1, n.s.). However, there was a tendency for thicker food to require a slightly higher MBF; these data are summarized in Table 5.

Discussion.

Food properties have been studied extensively in the field of food science. The test food is usually prepared in bite-sized pieces that are studied by means of compression instruments. Based on the force-time curves obtained, the mechanical properties are described by parameters such as hardness, cohesiveness, adhesiveness, viscosity, elasticity, brittleness (fracturability), "chewiness", and "gumminess" (Szczesniak, 1963, 1975). Commonly used instruments for assessment of these properties include the General Foods Texturometer (Friedman *et al.*, 1963; Brennan *et al.*, 1970) and the Instron Universal Testing Machine (Bourne *et al.*, 1966; Shama and Sherman, 1973). In this experiment, the Instron Instrument was used for simulation of the food compression process. A stainless-steel stylus with a 45-degree angulation tip was constructed to model the upper molar cusp, a lower dental cast was attached to the load cell, and a relay was interfaced in the power line to the device that sensed the existence of contact between stylus and teeth. Experiments focused on the initial compression, which is representative of the first chewing cycle in a masticatory sequence. Due to the intrinsically changing nature of the bolus, however, subsequent cycles *in vivo* may show quite different textural properties of the bolus.

We found that each test food possessed specific properties, as seen by significantly different force-time curves. It was also noticed that the force-time curve of soft food was more reproducible than that of hard or brittle food. This is in agreement with Brennan *et al.* (1970), who reported that reproducibility decreases with increasing hardness of the material under test.

At the final compression stage, the peanut and beefstick showed a higher end force than had been reported in the literature. This was because the stylus was driven to establish occlusal contact rather than being stopped in the vicinity of maximum intercuspation. Instruments used in food science leave a distance of 1 mm or so open between stylus and occlusion. This higher end force was associated with residuals of food being squeezed between antagonists in the final stage of bolus crushing. Such great end forces are unlikely to occur in natural mastication, since tooth contact is most likely not established in the first chewing stroke, particularly with foods such as the peanut and beefstick. This has been confirmed by Hylander and Crompton (1986), who reported the absence of tooth contact during the initial compression of monkey chow in *Macaca fascicularis*. In human subjects, Atkinson and Shepherd (1967) observed that during the first two or three chewing cycles; the teeth approached one another but did not make contact; however, in succeeding chewing strokes, as the bolus was softened, tooth contact was found highly likely to occur.

In terms of hardness, referred to as maximum breakage force (MBF) in our study, results are in agreement with the standard hardness rating scale used in food science (Szczesniak *et al.*, 1963). Fresh carrot was found to be harder than the cocktail peanut, and the peanut harder than beefstick. Food properties are known to influence masticatory behavior (Bates *et al.*, 1975; Hiiemae, 1978). Harder food is associated with greater muscle activity. In fact, it has been reported that the chewing of a peanut is associated with greater masseteric mean peak electromyographic activity than with gum, an apple, or bread (Ahlgren, 1966; Haraldson and Ingerval, 1979). Higher mean peak chewing forces have also been reported for the peanut than for cheese or gum (Gibbs *et al.*, 1981; DeBoever *et al.*, 1978). On the other hand, Howell and Brudevold (1950) reported that raisins resulted in a greater peak chewing force than the peanut. Clearly, hardness is not the only mechanical food property shaping masticatory behavior. Foods are complex mechanical systems, frequently inhomogeneous. In addition, different food preparations may lead to diverse results.

The morphology of the occlusal table was not of significance for maximum breakage force (MBF), and inherent food properties were more important than cross-head speed in terms of MBF. Although food thickness was not found to affect MBF significantly, there was a tendency for thicker food to induce higher MBF.

From this study, we conclude that each test food has particular textural properties reflected in characteristic details of its force-time curves. It is generally assumed that each foodstuff shapes the masticatory behavior in terms of force generation and jaw movement. So that insight into masticatory force and mandibular movement control may be gained, knowledge of the food in terms of its textural properties is essential.

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