Food breakdown during human mastication – Quantitative characterization

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ABSTRACT

Mastication, or chewing, is a complex process that occurs as food is crushed and ground by teeth and rendered safe for swallowing. This process is not only necessary for safe ingestion but also plays an important role in digestion and sensory perception (flavour, taste and texture). Understanding the way food is broken down can therefore help in the design of innovative, novel foods with controlled nutrient release and enhanced sensory appeal. For modelling, the food breakdown is ideally described using a simple breakage function that is valid throughout the whole chewing cycle. In this work, we studied the particle size distribution of broken food particles that forms during a single chewing stroke to find a simple breakage function. A half (or a quarter) peanut particle was used as a test food. Breakage of peanuts was also measured using uniaxial compression (by 3 different compression speeds) and a chewing robot that was designed to simulate the human jaw trajectory in 2D motion to assess how well breakage in the mouth can be simulated by a 1D or 2D motion. The results showed that the particle size distribution of peanuts after a single human chewing stroke exhibited a bimodal distribution, with a large fraction of fine fragments (<1 mm\textsuperscript{3}) and a small fraction of coarse fragments. It could be fitted well to a double Weibull or double Kumaraswamy distribution function ($R^2 > 0.99$). The 2D chewing robot result very closely mimicked the human chewing result, whereas the simple linear compression using a flat plate produced much bigger particles. This indicates that food breaks down in the mouth not only from the effects of compression but also from lateral jaw movement and tooth shape. The compression speed did not greatly affect the extent of particle fragmentation.

Keywords: mastication; breakage function; particle size distribution; chewing robot; uniaxial compression

INTRODUCTION

Mastication, or chewing, is a complex process that occurs as food is crushed and ground by teeth and rendered safe for swallowing. However, this also plays an important role in digestion and sensory perception (flavour, taste and texture). Recent studies report that the breakdown of food during mastication affects the bioaccessibility of nutrients [1-3], the release of flavours and the perception of taste [4,5]. Understanding the way food is broken down can therefore help in the design of innovative, novel foods with controlled nutrient release and enhanced sensory appeal.

As in industrial comminution processes [6], the breakdown of solid food can be considered as the composite result of two processes, selection and breakage [7,8]. During each chewing cycle, a food particle has the chance of being selected between the teeth (selection) and then being fractured into fragments of variable number and size (breakage). Due to repeated selection and breakage of particles in each chewing cycle, the size distribution of food particles will change. Relatively large particles gradually disappear while small particles become more abundant. Researchers have shown that the particle size distribution in a comminuted food can be quantitatively described using a Rosin-Rammler distribution function (2-parameter Weibull distribution function commonly used to describe the size distribution of particles generated by grinding, milling and crushing operations) [9,10]. In this way, the particle size distribution was characterized by the median particle size and a variable related to the variations in particle size. However, the Rosin-Rammler function failed to give a good description of the beginning of the chewing process as many unbroken food particles are still present in the mixture. Good fits were obtained with peanuts and Optosil (artificial food)
when the median particle size had dropped to about 70% of the original value (e.g. at least 5 chewing strokes for peanuts and 10 for Optosil) [10].

For modelling, the food breakdown is ideally described using a simple breakage function that is valid throughout the whole chewing cycle. In this paper, we studied the particle size distribution of broken food particles that formed during a single chewing stroke using peanuts as a test food to find a simple breakage function. Breakage of peanuts was also measured by uniaxial compression (set at 3 different compression speeds) and a chewing robot designed to simulate the human jaw trajectory in 2D motion to assess how well breakage in the mouth can be simulated using a 1D or 2D motion.

**MATERIALS & METHODS**

**Test food**

Roasted unsalted peanuts were used as a test food. Individual peanuts were split in half and some were further cut into quarters. Only halves (or quarters) thicker than 5.5 mm were used in this study.

**Breakage**

Breakage of single peanut particles was measured with a human subject, a 2D chewing robot and uniaxial compression. Experimental details of each method are described below. In order to obtain enough data to produce a representative particle size distribution, each experiment with a single chew/compression of a sample was repeated 20 times.

**Human mastication**

A half (or a quarter) peanut was sealed in a thin latex bag (a finger cot of a latex glove) to collect all fragments and to keep the particle free of saliva. A human subject, with complete dentition and no restoration work, was asked to place this bag (with the flat side of the peanut down) on the molars and to make a single chew as naturally as possible.

**2D Chewing robot**

A 2D chewing robot, developed to simulate the human chewing trajectory of the first molar in 2 dimensions, was used. The chewing robot is designed to simulate any trajectory between the lateral (grinding) and vertical (crunching) chewing. It is also equipped with anatomically correct teeth for reducing the food particle size. Full details of the design of the chewing robot can be found elsewhere [11,12]. A half peanut in a thin latex bag was placed in the chewing robot and “chewed” once under the condition of 70 N spring pre-tightening force. The output particle size distribution has been found to be very close to the effect of human chewing under this condition [13].

**Uniaxial compression**

An Instron Universal Testing Machine (Model 4444, Instron, High Wycombe, UK) fitted with a 500 N load cell was used. A half peanut with the flat side down was placed in a plastic cup (60 mm diameter) on the Instron base plate and then compressed once to 75% of their original thickness (i.e. 75% deformation) using a 50 mm diameter aluminium compression probe. Tests were conducted at three different crosshead speeds (120, 250 and 500 mm/min).

**Particle size distribution**

The broken particles produced after a single chew/compression were placed in a plastic test tube with 10 mL ethanol and left overnight. No changes in particle size take place during storage in ethanol [9]. The next day the mixture was vortexed for 5 s, poured on to a 312 µm sieve and further washed with 50 mL ethanol. This helped to remove peanut oil that might bridge broken particles and result in the overestimation of particle size. To determine the particle size distribution, the retained peanut particles were placed on a Petri dish (140 mm diameter) with 50 mL of ethanol and optically scanned in gray scale at 600 ppi. The images were processed using ImageJ (NIH, USA) and the area (in mm²) of each counted particles was measured.

The cumulative particle size distribution (area-based) of the peanut particles obtained from 20 single chews/compressions was fitted to a range of breakage distribution functions commonly used to describe industrial comminution processes. They were the Weibull [14], double Weibull [15], Kumaraswamy [16] and double Kumaraswamy distribution function (Table 1). The double Weibull (or double Kumaraswamy) is the sum of two Weibull (or Kumaraswamy) functions in different proportions defined by α. For the current work, the particle area x was normalised by
where $x_{\text{max}}$ is the maximum particle area measured. The value of the baseline constant, 0.0967, was chosen because all particles below 0.0967 mm$^2$ had been removed by washing the particles on a 312µm sieve.

### Table 1. Breakage distribution functions used in this study.

<table>
<thead>
<tr>
<th>Name</th>
<th>Cumulative distribution function</th>
<th>Parameters</th>
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<tbody>
<tr>
<td>Weibull</td>
<td>$F(X) = 1 - \exp[-(X/b)^\alpha]$</td>
<td>$a, b$</td>
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<tr>
<td>Double Weibull</td>
<td>$F(X) = \alpha[1 - \exp[-(X/b_1)^\alpha]] + (1 - \alpha)[1 - \exp[-(X/b_2)^\alpha]]$</td>
<td>$\alpha, a_1, b_1, a_2, b_2$</td>
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<tr>
<td>Kumaraswamy</td>
<td>$F(X) = 1 - (1 - X^m)^n$</td>
<td>$m, n$</td>
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<tr>
<td>Double Kumaraswamy</td>
<td>$F(X) = \alpha[1 - (1 - X^m)^n] + (1 - \alpha)[1 - (1 - X^m)^n]$</td>
<td>$\alpha, m_1, n_1, m_2, n_2$</td>
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* $X$ is the normalised particle size (area-based); $a$ and $b$ are the shape and scale parameter of Weibull distribution, respectively; $m$ and $n$ are the positive shape parameters of Kumaraswamy distribution; 1 and 2 denote the Type 1 and Type 2 breakage, respectively; $\alpha$ is the proportion of the breakage that can be described as Type 1 breakage (i.e. $0 \leq \alpha \leq 1$).

### RESULTS & DISCUSSION

The cumulative particle area distribution obtained after a single human chewing stroke of a half peanut is shown in Figure 1. The particle size distribution exhibited a bimodal distribution, with a large fraction of fine fragments <1 mm$^2$ and a few coarse fragments. Thus, it could not be adequately described by a Weibull or Kumaraswamy distribution function, but was fitted successfully with a double Weibull or a double Kumaraswamy distribution function ($R^2 > 0.99$).

![Figure 1](image1.png)

**Figure 1.** Area-based cumulative particle size distribution of peanut fragments after a single human chewing stroke, with (A) Weibull and double Weibull distribution fits; (B) Kumaraswamy and double Kumaraswamy distribution fits. Lines are best fits through the data points (●). Data contains 20 single chews of a half peanut.

Bimodal distributions may be the norm for the chewed food particles. Peyron and co-workers [17,18] examined the particle size of six different foods (peanut, almond, pistachio, carrot, radish, cauliflower) at different stages of mastication. Although the particle size distribution differed between foods and the curves were shifted towards smaller particle sizes as chewing proceeded, for all foods the chewed particles had a bimodal or multimodal distribution during the mastication process. Chewed bread to the stage of swallowing was also found to have a bimodal distribution with two distinct peaks at mean diameters of 30 and 500 µm and chewed pasta contained a large fraction of particles of 0.5 to 30 mm$^2$ with a few bigger particles [1]. The double-form of breakage distribution function may therefore be more appropriate to describe the particle size distribution of a comminuted food than the single-form breakage distribution function such as a Rosin-Rammler distribution function.
The earlier study by van der Glas et al. [19] reported that food breakdown during mastication depends not only on the properties of the food, but also on particle size. They assumed that particles that are small with respect to the cusp size of molar teeth are not likely to be cleaved but, at most, will be squeezed between antagonistic tooth surfaces. Particles of medium size may frequently be cut by one or more cusps, resulting in many daughter particles. Large particles, which stick out when placed between the teeth, will cleave to produce a portion that falls free into the mouth cavity and another that is crushed and produces many fragments. In this study, the breakage of a quarter peanut was measured and compared with the half peanut result (Table 2). The breakage of quarter peanut resulted in more small daughter particles, and thus the particle size distribution curve shifted slightly toward smaller particle sizes. However, the output particle size distribution of a quarter peanut after a single chewing stroke was still fitted well with a double Weibull or double Kumaraswamy function ($R^2 > 0.99$).

<table>
<thead>
<tr>
<th>Table 2. Breakage of a half or a quarter peanut from a single human chewing stroke.</th>
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<td>Average number of fragments formed (n=20)</td>
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<td>Median particle size (mm$^2$)</td>
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<td>Maximum particle size, $x_{\text{max}}$ (mm$^2$)</td>
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<td>Best-fit value of breakage function parameters</td>
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<td>Double Weibull</td>
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The differences in the output particle size distribution of peanuts after a single chew/compression by human subject, chewing robot and uniaxial compression are presented in Figure 2.

**Figure 2.** Differences in the output particle size distribution of peanuts fragments after a single chew/compression by human subject, chewing robot and uniaxial compression (at 120 mm/min). Each data set contains 20 single chews/compressions of a half peanut.
The result generated by the 2D chewing robot was very close to the human mastication result, whereas the simple linear compression with a flat plate produced much bigger particles. This indicates that food breaks down in the mouth not only following its compression but also as the result of lateral jaw movement and tooth shape. Much smaller particles appear to form as a result of the combined action of lateral movement and tooth shape. The compression speed did not greatly affect the extent of particle fragmentation (Figure 3).

**Figure 3.** Effect of compression speed on the breakdown of a single peanut particle. Each data set contains 20 single compressions of a half peanut.

**CONCLUSION**

In this study, we investigated the size distribution of broken food particles formed during a single chewing stroke using peanuts as a test food to find a simple breakage function. It was found that food breaks down in the mouth as a combined result of compression, lateral jaw movement and tooth shape. The double-form of the breakage distribution function appeared to offer a more adequate description of the bimodal particle size distribution of broken food particles than single-form breakage distribution functions. However, this finding is based on a single human subject. Further investigation is needed to evaluate if the double-form of breakage distribution functions can accurately model the evolution of the particle size distribution during mastication, including a large number of human subjects.

**REFERENCES**


