

# The role of friction in perceived oral texture

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## Abstract

Instrumentally measured *in vitro* friction in semi-solid foods was related to oral texture sensations. Increased fat content resulted in lower sensations of roughness, higher sensations of creaminess, and lower friction, suggesting that lubrication is the mechanism by which fat affects oral texture in low fat foods. Starch breakdown by salivary amylase in low fat foods resulted in reduced friction, possibly through the release of fat from the starch food matrix, and the migration of fat to the surface of the bolus where it becomes available for lubrication. No evidence was found that salivary mucins or salivary viscosity play a role in lubrication. Astringent sensations may be related to reduced lubrication and increased friction caused by particles, either resulting from precipitation of salivary protein rich proteins or from flocculation of dead cells.

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## 1. Introduction

Friction has been implicated by some researchers as the mechanism underlying astringency (Green, 1993; Prinz & Lucas, 2000), although others have argued that astringency elicits a gustatory response (e.g., Schiffman, Suggs, Sostman, & Simon, 1992). Astringency is an attribute that is perceived in a wide variety of product groups, ranging from red wine to custard. It is defined as a drying or puckering sensation, typically evoked by tannin-rich foods (Green, 1993). Lawless, Corrigan, and Lee (1994) extended the definition of astringency, regarding it as a combination of three components: roughness, dryness, and puckering. More recently, Gawel, Iland, and Francis (2001) generated a set of over 30 descriptive terms relating to astringency. Green (1993), using psychophysical methods, suggested that friction is the physiological mechanism underlying the sensation of astringency. Further confirmation of this was provided

by Prinz and Lucas (2000), who demonstrated that tannic acid can decrease the viscosity of saliva and increase friction *in vitro*. Prinz and Lucas attributed this to the precipitation of proline rich salivary proteins (PRPs) by tannic acids, thinning the saliva and roughening the dental pellicle. The affinity of these proteins for tannins had already been demonstrated by others (Foley & MacArthur, 1994; Glendinning, 1994; Luck et al., 1994). Prinz and Lucas focused on the reduction of salivary viscosity while ignoring the role of the precipitate itself. However, the reverse position may also be valid, i.e., that it is the presence of the particulate precipitate that causes the sensation of roughness rather the reduction of salivary viscosity.

The presence of particles in a foodstuff is most easily sensed by the periodontal membrane of the teeth, which can detect particles down to 10 µm in diameter (Utz, 1986). At sufficiently high concentrations, particles of 5 µm in diameter can be detected as they give rise to sensations of roughness and dryness, while at low concentrations even large 2 mm diameter particles may be completely missed (Heath & Prinz, 1999; Kashket, Van Houte, Lopez, & Stocks, 1991). Obviously, detection of particles is not only determined by size and concentration but also by other properties such as hardness and shape (Tyle, 1993), where hard or sharp particles are

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more easily detected than softer or more rounded particles. We have previously demonstrated that two sensory dimensions, one running from perceived roughness to perceived creaminess and another from perceived melting to perceived thickness, can summarise the sensory space for vanilla custard desserts, explaining approximately 89% of the variance (de Wijk, van Gemert, Terpstra, & Wilkinson, 2003a). At one extreme, the rough-creamy axis had a group of attributes comprising roughness, astringency, dry/mealy mouth-feel and the flavours bitter/chemical and sickly. Opposite to this group of “rough” attributes was the “creamy” group comprising creamy and fatty mouth- and after-feels, and creamy, fatty, and vanilla flavours. Food samples were ordered along this dimension according to their fat content, with low-fat samples located near the rough end of the spectrum and high fat samples near the creamy end. Since fat has many functionalities including that of flavour carrier and lubricant, de Wijk et al. (2003a) and de Wijk, Rasing, and Wilkinson (2003b) suggested that the underlying physical mechanism of the rough-creamy axis could be friction related.

Conversely, pre-coating the mouth with oil has been shown to reduce the intensity of astringent sensations (Breslin, Gilmore, Beauchamp, & Green, 1993; Valentová & Pokorný, 1998). Here the oil may be acting either as a barrier protecting the epithelium or alternatively the surface layer of oil may act as a lubricating film. These effects may explain how the addition of milk to tea and coffee reduces astringency.

Although friction has been hypothesised as a mechanism underlying various texture sensations, surprisingly little research has been devoted to actually measuring friction in foods and relating the measured friction to sensations. Using a method similar to the one described by Prinz and Lucas (2000), measured friction was related to:

1. specific food properties such as viscosity and fat content known to affect specific texture sensations,
2. specific food modifications such as added particles of varying sizes, shapes, and concentration,
3. the role of saliva as a lubricant,
4. the functional properties of astringent substances.

## 2. Method

### 2.1. Friction tester

A friction tester (Halling, 1976; Fig. 1) was built for the investigation of the lubricating qualities of foods and saliva. This consisted simply of a rubber band (6 cm length  $\times$  1 mm diameter) attached to a load cell. One end of the rubber band was looped around the metal cylinder of an electric motor; the other was attached to the

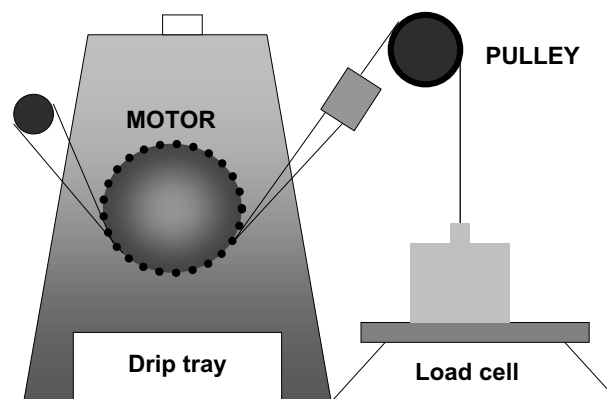


Fig. 1. Schematic representation of friction tester.

load cell. When the motor was switched on and rotated clockwise, friction between the cylinder and the rubber band produced a load,  $F_1$ , that could be detected at the load cell. When the direction of the cylinder was reversed, the load dropped to  $F_2$ . If loads  $F_1$  and  $F_2$  are both known, then it can be shown (Halling, 1976) that the coefficient of friction  $\mu$  equals:

$$\mu = 1/\pi \log_e(F_1/F_2).$$

Friction measurements were done in triplicate by coating the surface of the cylinder with a layer of the food product. A fresh rubber band was used for each measurement. Friction results were consistent within batches of rubber bands, and varied in absolute but not in relative values between batches. Typically, friction was measured on foods as is, with 15% w/w of stimulated saliva added, or with the same volume of water added. The friction of starch-containing custards mixed with saliva was measured when the custards had become fully liquefied, i.e., when the starch had been completely broken down by salivary amylase. With some gentle stirring, this took approximately 10 min. Friction was typically tested within a period of 1–2 h. During normal eating, complete liquefaction of the food bolus is probably not required before starch break down starts to affect friction. Since friction relates to force between surfaces, for example between food bolus and palate, it is probably sufficient to develop a thin layer of broken down starch at the surface of the bolus surface. Studies indicated that this happens very soon after the bolus contacts the saliva, i.e., within a single bite (de Wijk, Prinz, Engelen, & Weenen, 2003c).

### 2.2. Viscosity of saliva with added compounds

Possible effects of added compounds on salivary viscosity were investigated for a set of eight compounds. This set comprised of the four compounds selected previously by de Wijk et al. (2003b) to represent creamy (diacetyl, Merck Inc.), bitter (caffeine, Sigma–Aldrich

Inc.), vanilla (vanillin, Merck Inc.) and almond (benzaldehyde, Fluka Inc.) qualities. In addition, four more compounds were selected for their astringent (aluminum potassium sulfate dodecahydrate or alum and tannic acid, Sigma–Aldrich Inc.), bitter (quinine, Sigma–Aldrich Inc.), and sour (citric acid, Sigma–Aldrich Inc.) qualities. Fresh stimulated saliva (1 ml) was mixed with a vortex for 5 s with 1 ml of solution of the eight compounds at a concentration of 10 mmol. Salivary viscosities were measured using a Bohlin-VOR rheometer at 20 °C. A C14, or spindle and cup, configuration was used with a torsion element of 0.287 g cm, and an up-down shear-sweep was performed between 1.16 and 1160 1/sec. Salivary viscosity at 116 1/sec will be reported here but very similar results were obtained at lower and higher shear rates.

### 2.3. Fat droplet size measurements

For the fat droplet size measurements, 1.5 g of mayonnaise was diluted with 20 ml of 0.01 M SDS (sodium dodecyl sulfate 2.8838 g/l) and suspended for 2 h using a Variomag Multipoint type HP15 at 350 rpm. Next, the diluted mayonnaise was centrifuged for 15 min (CWS 4235) at 3000 rpm. Fat droplet size distribution in the fat containing top layer of the centrifuged sample was measured with a Coulter Laser.

### 2.4. Stimuli: Vanilla custard desserts

Twenty three model vanilla custard desserts varying in milk fat content (0–15%), starch content (3.3–5.1%) and starch type (VA20, VA70, VA50T, VA85T, VM50, AVEBE Corp., The Netherlands) were manufactured at the ultra high temperature pilot plant of the Dutch Institute for Dairy Research (NIZO) in Ede, The Netherlands. A non-starch control custard dessert was based on sodium carboxy methylcellulose (or “CMC”) (Akuell AF 3295, Akzo Nobel Corp., Amersfoort, The Netherlands). This custard was manufactured using 0.85% of sodium CMC mixed with 6.25% of sugar and 0.33% of vanilla powder in full fat (3%) commercially available milk (Campina Corp., The Netherlands). Yellow colorant (Supercook, Leeds, United Kingdom) was added to match the color to that of the starch-based custards. For studies relating friction to viscosities, custards with various concentrations of CMC were manufactured resulting in viscosities ranging between 10 and 10,000 cP.

### 2.5. Stimuli: Vanilla custard dessert with particles

Silica dioxide (2.5 g cm<sup>-3</sup>; US Silica company, Ottawa, IL) particles were sieved into discrete classes; 20–50, 50–100, 100–150, and 200–250 µm. The median particle sizes of these classes were determined by Coulter laser

diffraction to be 40, 80, 135 and 230 µm, respectively. Spherical polystyrene particles (1.10 g cm<sup>-3</sup>; Dynoseeds®, Polymer-systems, USA) were used in the discrete sizes 40, 80, 140, and 230 µm. Particles were mixed into a commercially available full-fat vanilla custard dessert (Campina Boerenland custards, Campina Nederland, Woerden, The Netherlands) in concentrations equal to 5% weight (silica particles) and 2.3% weight (polystyrene particles) to assure equal numbers of particles of both types.

### 2.6. Stimuli: Mayonnaises

Oil-in-water mayonnaise emulsions were manufactured at TNO-Nutrition and Food Research in Zeist, The Netherlands. A mixture of oil (40%), water, and various concentrations of liquid egg yolk ranging between 0.8% and 5.6% w/w was homogenized by a Koruma homogenizer at 2900 rpm. Egg yolk content was varied in an attempt to systematically vary fat droplet size. The resulting homogenized oil was mixed in a Hobart mixer together with the water phase containing xanthan gum (1.3%), vinegar (3%), sugar (2%), and mustard powder (0.3%). Potassium sorbate (0.1%) and Na–EDTA (0.0087%) were used as preservatives. Finally, egg yolk was again added so that the total egg yolk content equaled 5.6% w/w.

### 2.7. Sensory tests

Eight subjects, aged 23–34 yr, participated in the sensory studies. Subjects were paid to participate. All had previously been screened for olfactory and taste disorders and received extensive training in assigning sensory mouth-feel and after-feel attributes for custard desserts and mayonnaises. Testing took place at the sensory facilities of TNO-Nutrition and Food Research in Zeist, The Netherlands.

### 2.8. Procedure

Subjects were seated in sensory booths with appropriate ventilation and lighting. During one 2 h session, they were presented with 24 transparent 50 ml cups partially filled with custard desserts or mayonnaises, at a rate of one sample every 4 min. Subjects took one dessert spoonful from each cup, smelled the content, rated the odor attributes, and put the content in their mouths. They then rated flavour and mouth-feel attributes (in the order in which they were perceived, this having been previously established by a Quantitative Descriptive Analyses (QDA) panel). Finally, the custard was swallowed and after-feel attributes were rated. Subject's responses were acquired by computer using FIZZ software (Biosystemes, 1998). The attributes appeared grouped by category on the monitor, with the attributes

on the left and a 100-point response scale on the right anchored at the extremes. Subjects mouse clicked to indicate the perceived strength of each attribute. Over three sessions, subjects were presented with three replicates of each custard, presented in a randomized order.

### 2.9. Attributes

The attributes used in this study had previously been generated by the QDA panel during nine 2 h sessions. The full set of attributes with definitions has been reported elsewhere (de Wijk et al., 2003a), while the subset that is especially relevant for the present study is shown in Table 1. The attributes in the subset were those most likely to reflect different physical properties of the foods. Some mouth-feel attributes, such as perceived thickness, probably reflect a single physical property of the food such as its viscosity, whereas other mouth-feel attributes, such as perceived creaminess, may be combinations of several other attributes such as thickness, fatty after-feel, creamy flavour, and smoothness (de Wijk et al., 2003a). The attribute fatty after-feel probably results from residual food left in the mouth after swallowing, and astringency relates to changes in the lubricating properties of the residual food-saliva mixture.

## 3. Results

### 3.1. Friction versus texture sensations and ingredients

Fig. 2 summarises the effects on vanilla custard desserts of fat and starch content on oral texture attributes and friction. The interrelations among the texture

attributes can be summarised by two main “sensory” dimensions. The first dimension runs from rough to creamy and the second from melting to thick. The location of each custard sample relative to these two dimensions indicates that the melting/thickness dimension is related to starch content and probably reflects viscosity. The rough/creamy dimension is related to fat content and may also be related to the coefficient of friction, as has previously been hypothesised by de Wijk et al. (2003a). Inspection of the friction results indicates a reduction in friction of custard samples along the rough/creamy dimension, i.e., custards with higher fat contents cause lower friction and are perceived as less rough and more creamy. ANOVAs indicated a highly significant main effect of fat content on friction ( $F(3, 32) = 99.6$ ,  $p < 0.001$ ). Post-hoc tests indicated significant differences between friction for all fat contents, except 10% and 15% ( $p < 0.05$ ). A smaller but still significant main effect of starch content on friction was found ( $F(3, 32) = 6.0$ ,  $p = 0.002$ ) as well as an interaction effect between starch and fat content ( $F(9, 32) = 2.7$ ,  $p = 0.02$ ). Friction varied with starch content in a non-systematical way. No systematic change in friction was observed along the melting/thickness axis, and correlational analysis indicates no association between friction and perceived thickness ( $r = -0.24$ , n.s.) or between friction and perceived melting ( $r = 0.23$ , n.s.,  $n = 16$ ).

### 3.2. Friction versus fat content and fat droplet size

The friction of starch-based custards as well as non-starch CMC custard-like products decreases with in-

Table 1  
Panel definitions of relevant attributes related to mouth-feel and after-feel for vanilla custard desserts

Attribute	Definition
<i>Mouth-feel</i>	
Thick	Represents the thickness of the food in the mouth after the food is compressed via up-and-down motions of tongue against palate. For less viscous products such as dressings, information is also obtained from the rate of spreading of the product throughout the mouth
Melting (slow–quick)	The rate at which food becomes thin in the mouth and spreads throughout the mouth
Creamy mouth-feel	Range of sensations typically associated with fat content such as full and sweet taste, compact, smooth, not rough, not dry, with a velvety (not oily) coating. Food disintegrates at moderate rate
Dry/mealy	Degree to which food seems to absorb saliva, making it difficult to swallow while it is compressed between tongue and palate. Surface of mouth feels rough
Rough	Roughness sensed on teeth, palate and tongue, typically caused by products such as walnut, spinach, and wine
Prickling	A prickling, stinging, biting sensation that one wants to extinguish, typically perceived at the top and side surfaces of the tongue
<i>After-feel</i>	
Creamy after-feel	Degree to which the residual layer of food left after swallowing or expectoration produces a velvety sensation
Sticky	Degree to which food leaves a sticky feeling in the whole mouth, making it difficult to clear
Fat	Degree to which food leaves a fatty/oily feeling in mouth after swallowing
Astringent	Degree to which food leaves an astringent taste and feeling in the mouth, typically caused by products such as wine, nuts and spinach

The complete attribute set has been reported elsewhere (de Wijk et al., 2003a). Anchors unless indicated: very little–very much. Within each category, attributes are listed in the temporal order in which they are perceived during mastication.

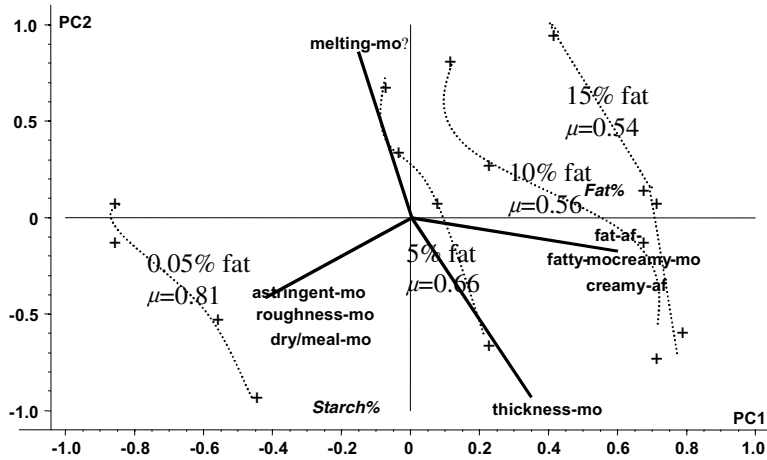


Fig. 2. Bi-plot of principal components analysis depicting selected mouth (-mo) and after feel (-af) texture attributes, and vanilla custard desserts (+) with varying fat (indicated by *fat%* in the graph) and starch levels (*Starch%*). Custards with similar fat levels but different starch levels are connected with dashed lines. Averaged coefficients of friction for each fat level are also shown ( $\mu$ ). Solid lines reflect the sensory dimension running from melting to thick and from rough to creamy. The first two principal components explain 51% and 24% of the variance, respectively.

creased fat content up to 5–20%. A similar reduction is seen for milk fat (as shown in Fig. 3) and canola oil. The reduction in friction was especially large for low fat products. Foods with higher fat contents, such as dressings and mayonnaises, failed to show any reduction in friction with increasing fat content above approximately 10%. However, in these foods friction was affected by fat droplet size as was demonstrated in model mayonnaises with varying levels of emulsifier (egg yolk). Friction increased with fat droplet size, especially for

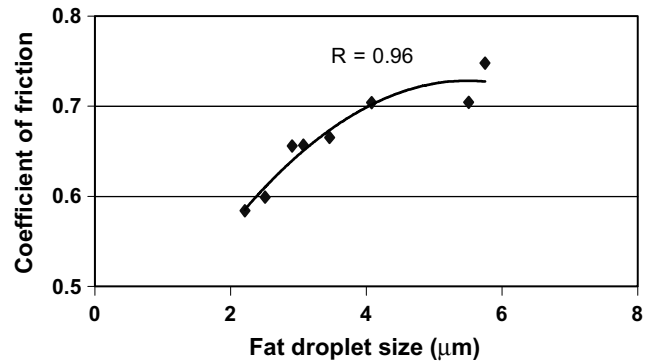


Fig. 4. Effect on the coefficient of friction of fat droplet size, measured by CSLM image analysis in mayonnaises.

droplet sizes above 4  $\mu\text{m}$   $r = 0.96$ ,  $p < 0.01$ ,  $n = 8$  (Fig. 4).

### 3.3. Friction versus viscosity

Increasing viscosity typically resulted in reduced friction, but only when greater than 100 cP (see Table 2).

### 3.4. Friction versus structure breakdown

Starch-containing products, such as the custard desserts used here, became less viscous as their structure

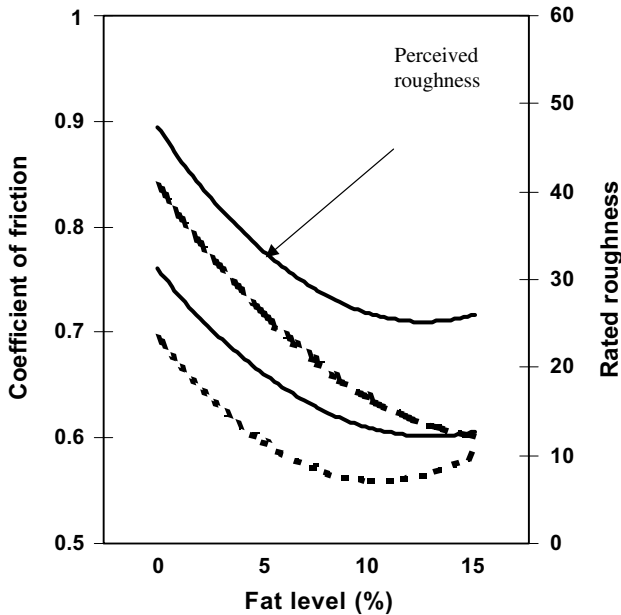


Fig. 3. Fat level of vanilla custard desserts versus perceived roughness (solid grey line), friction of vanilla custard as is (solid black line), diluted by 15% w.w. of water (dashed black line), or broken-down by 15% w.w. of stimulated saliva (dotted black line).

Table 2  
Coefficient of friction ( $\mu$ ) versus viscosity ( $\eta$ ) of non-starch CMC custard-like foods

$\eta$	10 cP	100 cP	1000 cP	10,000 cP
$\mu$	0.60 (0.03)	0.62 (0.01)	0.45 (0.04)	0.40 (0.03)

Standard errors are shown in brackets.

was broken down chemically by salivary amylase. Broken-down custard with low viscosity was expected to result in increased friction (see Table 2). However, friction in a starch-custard broken down by amylase is reduced compared to a similar custard mixed with the same volume of water (see Fig. 3). As a control, friction of a non-starch custard was not reduced when saliva was added. In fact, friction increased somewhat compared to the water control. Similarly, non-starch mayonnaises with xanthan instead of starch as a thickener showed increased friction when mixed with saliva.

### 3.5. Friction versus particles

Starch-containing custard desserts with either added silica (sharp–Sil) or dynaseed (rounded–Dyn) particles showed significant differences in friction with particle size irrespective of type of particle (main effect of size:  $F(4, 20) = 3.2$ ,  $p = 0.04$ ). Post-hoc tests indicated that friction for the largest particle size was higher than that for the smaller sizes ( $p < 0.05$ ). Sharp particles resulted in higher friction than rounded particles ( $F(1, 20) = 11.0$ ,  $p = 0.003$ ). Sharp particles continued to result in higher friction when the starch matrix was broken down by amylase from added saliva ( $F(1, 20) = 10.2$ ,  $p = 0.005$ ), but particle size affected friction differently for the two types of particles. For the sharp particles, friction for the two smallest sizes was significant *higher* than that for the larger sizes ( $p < 0.05$ ). In contrast, for the rounded particles, friction for the smallest particle was significantly *lower* than that for the largest particle ( $p < 0.05$ ). Similar to friction for custard as is, sensory ratings of astringency lip feel and rough after feel increase with particle size ( $F(3, 48) = 5.2$ ,  $p = 0.009$  and  $F(3, 48) = 6.5$ ,  $p = 0.004$ , respectively). In contrast to friction results, astringency lip feel ratings were highest for the rounded particles ( $F(1, 16) = 9.8$ ,  $p = 0.006$ ). Rough after feel ratings were unaffected by particle type (see Table 3).

### 3.6. Friction of saliva

Friction of natural saliva containing mucins and amylase, was compared to that of artificial saliva containing mucins, probably related to lubrication (Van

Table 4

Coefficient of friction ( $\mu$ ) of mucins (artificial saliva) and mucins plus amylase (natural saliva) on their own and when added to starch custard

	$\mu$	SE
Artificial saliva	0.81	0.01
Natural saliva	0.71	0.02
Custard	0.79	0.04
Custard + artificial saliva	0.80	0.02
Custard + natural saliva	0.61	0.02

Nieuw Amerongen, 1994) and astringency (Noble, 1994), but without amylase. Artificial saliva caused more friction than natural saliva, even though it was more viscous and could have been expected to reduce friction. Artificial saliva did not affect the friction of custard. In contrast, natural saliva greatly reduced friction of starch-based custard (see Table 4).

### 3.7. Friction of saliva with added compounds

The addition of some well-known astringent compounds, tannic acid and alum, as well as another compounds, showed differential effects on salivary friction. Friction increased after addition of alum, citric acid and quinine, and decreased after addition of tannic acid, diacetyl and benzaldehyde. No effects were found for vanilla and caffeine (Fig. 5). One of the assumed mechanisms by which astringent compounds reduce the lubricative properties of saliva is via a reduction in its viscosity (similar to our earlier finding that a less viscous

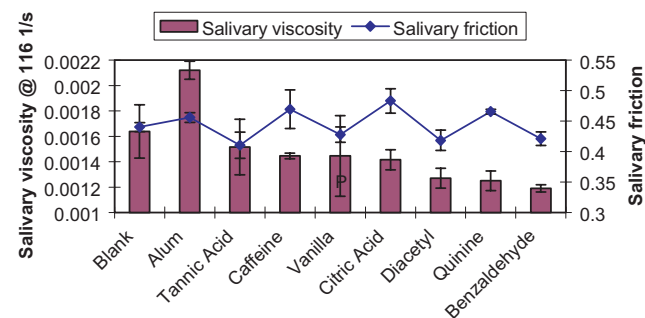


Fig. 5. Effects of added compounds on salivary viscosity and friction. Error bars indicate standard errors.

Table 3

Effects of rounded (Dyn) and sharp (Sil) particles with varying size (in  $\mu\text{m}$ ) added to starch-based custard, on perceived roughness, astringency, and the coefficient of friction ( $\mu$ )

Type of particle	None	Sil5	Sil	Sil	Sil	Dyn	Dyn	Dyn	Dyn
Size of particle ( $\mu\text{m}$ )			20–50	50–100	100–50	40	80	140	230
Perceived astringent lip feel	28	28	44	37	40	42	43	42	39
Perceived rough after feel	27	33	48	48	47	39	44	48	39
$\mu$ (Custards as is)	0.53	0.55	0.54	0.57	0.60	0.45	0.51	0.47	0.57
$\mu$ (Broken-down custards)	0.53	0.58	0.61	0.49	0.50	0.44	0.49	0.50	0.53

The latter was measured on custards as is and on those broken down by salivary amylase.

food results in increased friction). Salivary viscosity was increased by alum and decreased by diacetyl, quinine, and benzaldehyde. Salivary friction was unrelated to salivary viscosity ( $r = 0.17$ , n.s.).

#### 4. Discussion

Objective measurements of the coefficient of friction in starch-based custard desserts indicated that friction is closely associated with fat-related texture attributes ranging from roughness to creaminess. Custards with zero or low fat content have high ratings of roughness, low ratings of creaminess, and high friction. Conversely, custards with high fat content have low ratings of roughness, higher ratings of creaminess, and low friction. The present results support the hypothesis that at least one of the mechanisms affecting fat-related texture attributes is lubrication by fat (de Wijk et al., 2003a). The role of fat in lowering intra-oral friction is further illustrated by the finding that friction is affected by both the number of droplets and the size of the fat droplets. Smaller droplets may be less deformable than larger ones, which results in a smaller contact area and consequently in reduced friction. Friction increased with increasing fat droplet size, decreasing fat content, increasing particle sizes, and sharper particle shapes. Increased friction typically resulted in significantly increased sensations of roughness, prickling, dry-mealiness, and heterogeneity, and significantly decreased

sensations of creaminess, fattiness, stickiness, slipperiness, and smoothness. The only inconsistency in the sensory–friction relationships involved sharp particles that resulted in increased friction but reduced astringency (Fig. 6).

Fat is especially effective for the reduction of friction at relatively low levels (between 0% and 5%), but this effect continues to grow up to fat contents as high as 10%. Other friction results from the same laboratory indicated that friction for other foods continues to decrease for fat levels up to 20% (de Wijk, Weenen, & Prinz, 2004). At even higher fat contents, as typically found in high fat products such as dressings and mayonnaises, friction seems no longer related to perceived roughness but may still relate to certain fat-based attributes such as fatty after-feel (although these are preliminary results).

Friction is not only inversely related to fat content but also to the viscosity of foodstuffs, i.e., foods with relatively high viscosities (above about 100 cP) result in less friction than do those with lower viscosities. This supports findings by others who have reported less astringency for products with high viscosities (Breslin et al., 1993; Lyman & Green, 1990; Smith, June, & Noble, 1996). In contrast, when viscosities of starch-containing custards are reduced by amylase-induced starch breakdown, friction will decrease rather than increase. A possible explanation for this involves the mucins in saliva that are thought to affect lubrication. This, however, seems unlikely given our results that

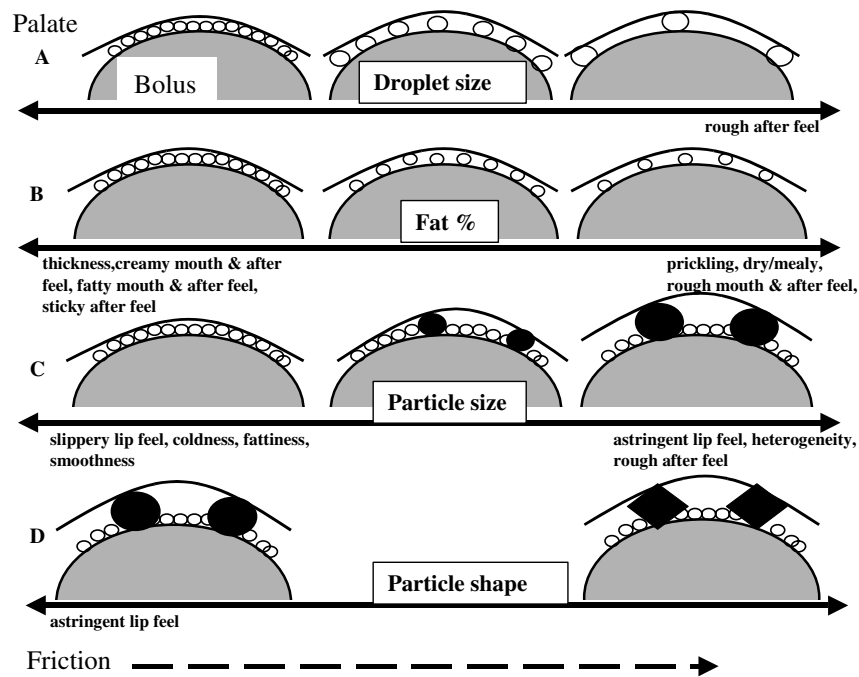


Fig. 6. Schematic representation of the effect of fat droplet size (a), fat content (b), particle size (c), and particle shape on friction. Grey color indicates the food bolus, white the fat droplets, and black the particles. The effects are ordered with respect to friction, with low friction on the left and high friction on the right. Significantly affected attributes are placed on the left (associated to low friction) and right (associated to high friction).

friction of custards with added artificial saliva, containing only mucins and no amylase, failed to show any notable reduction in friction. In contrast, custards broken down by added artificial amylase without mucins did result in a considerable reduction in friction. An alternative explanation involves the liberation of fat from the starch matrix when it is broken down by salivary amylase. The liberated fat may migrate via convection currents to the surface of the food bolus where it becomes available for lubrication between the bolus and the oral tissue. In the product as is, only part of the fat present is located at or near the surface where it is available for lubrication. In higher fat content products, more fat is located at or near the surface where it can reduce friction. After breakdown with amylase, even more fat becomes available for the reduction of friction. Breakdown should be especially effective at lower fat levels in reducing friction since any increase in available fat has a relatively large effect (see Fig. 3). Indeed, the influence of breakdown on friction gradually decreases with fat content up to 15%, i.e., the coefficient of friction functions of custards without saliva, with saliva, and with water converge at higher fat levels.

Friction has been implicated as the mechanism behind the astringent sensations caused by substances such as alum and tannic acids. Possible mechanisms underlying astringent sensations include precipitation of salivary proline rich proteins (PRPs) by astringent substances, resulting in a loss of salivary viscosity. Reduced salivary viscosity would reduce the lubricative properties of saliva (resulting in increased friction). The precipitated PRPs themselves may also be sensed as particles, reinforcing astringent sensations. Our results indicated a loss of salivary viscosity, but only for certain astringent substances. Salivary viscosities were reduced when tannic acid was added, but was increased when alum was added. Salivary friction was not related to salivary viscosity. Hence, our results do not support the hypothesis that astringency is caused by reduced salivary viscosity resulting in increased friction.

Pilot studies in our laboratory suggest that alum, in contrast to tannic acid, does not precipitate salivary PRPs, which would explain why alum does not reduce salivary viscosity. The fact that alum still causes astringency may be related to flocculation by alum of dead cells and other debris, resulting in the formation of particles clearly visible using light microscopy. Our studies have indicated that silica and dynaseed particles added to custards affect friction and sensations of roughness and astringency. The specific effects of particles depended on their sizes and shapes. Our particle results confirm a possible mechanism for astringency based on reduced lubrication and increased friction caused by particles, either resulting from precipitation of PRPs or from flocculation of dead cells. Research in our laboratory will continue to focus on the proposed

mechanisms underlying astringency, as well as other mechanisms. For example, tannins also affect the stiffness of oral tissue directly via interactions between tannins and the cell walls (a mechanism well known in the leather industry). Possibly, this may elicit the sensations of puckering that have also been associated with astringency.

In summary: the effect of fat on textural attributes for (low-fat) custards (up to 15–20%) was related to its lubricating properties and the resulting effects on friction. Breakdown of starch by salivary amylase and the resulting loss of viscosity reduced friction, possibly as a result of fat migrating from within the food bolus to its surface where fat can facilitate lubrication. Astringent sensations may be related to reduced lubrication and increased friction caused by particles, either resulting from precipitation of salivary protein rich proteins or from flocculation of dead cells. No evidence was found for reduced lubrication as a result of reduced salivary viscosity.

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