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Friction measurements with yoghurt in a simulated tongue-palate contact

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ABSTRACT

The perception of many food attributes is related to mechanical stimulation and friction experienced in the tongue-palate contact during mastication. Friction in the tongue-palate is determined by the changing film properties (composition, component distribution, thickness) in the conjunction. We suggest this evolution is essentially determined by tongue-palate film loss rather than shear flow entrainment which predominates in conventional bearing lubrication. The paper reports friction measurements in a simulated tongue-palate contact for a range of high and low fat dairy foods. A reciprocating, sliding contact with restricted stroke length (<contact width) was used; under these conditions there is negligible shear-entrainment of fluid from outside the contact area. The tongue-palate contact was simulated by a PDMS ball and glass surface. The effect of hydrophobic and hydrophilic surfaces on friction was investigated for different fat contents (0, 4.2, 9.5% wt fat). Friction was measured over 60 s of rubbing. Significant differences were observed in the friction change with time for different fat contents ($\mu\,9.5 < \mu\,4.2 < \mu\,0$ wt%) and for different surface energy conditions (μ hydrophilic < μ hydrophobic). Post-test visualisation of the rubbed films showed that low friction coefficient was associated with the formation of a thin oil film on deposited particulate solids.

1. Introduction

Oral processing or mastication is a dynamic process whereby food structure is broken down and transported to the pharynx prior to swallowing. It is a complex series of processes which involve a number of surface interactions including tooth-tooth and tongue-palate mechanisms [1]. Sensory perception of food involves visual, physical and physiological elements in which the role of structure, rheology and the mechanisms of food breakdown are not fully understood. The perception of taste and texture which includes thickness, smoothness, slipperiness [1] and to some extent astringency are usually related to mechanical stimulation and hence friction experienced in the mouth.

Semi-solid food, which includes cream, yoghurt, custard and mayonnaise, are oil-in-water (O/W) emulsions which also contain proteins, emulsifiers, carbohydrates (including sugar) and other soluble components. Most formulation work has centred on research by food scientists [2,3] and the development of complex emulsions and micro-phase fluids. The focus has been on controlling the chemical and physical characteristics to improve the stability and storage properties [2]. However in recent years the role of food composition and structure in oral processing has received increasing attention. As Dalgleish [2] states "*These structures in turn give rise to the perception of texture as they are consumed*". The development of low and zero-fat food with the mouth-feel of high fat content analogues remains an important objective of the food industry [2,3]. The emphasis has been the role of fat in the original product structure [2] and how this evolves during mastication. The low/very low fat yoghurt market in the UK is currently worth over £500 million/year [4] and is growing rapidly. However dietary focus has recently switched to the reduction of sugar in foods and unfortunately many low-fat formulations contain higher levels of sugar (see Table 1). During mastication the structure of these foods change and the contribution of all components, not just fats, to perceived taste and texture must be understood if we are to effectively develop new products that satisfy consumer expectations.

The problem remains of how to quantify the mouth-feel of these products without excessive use of panel tests. Mouth-feel is the tactile sensation created when food is rubbed between the tongue and palate, up to the point of swallow. Many studies [5] have tried to link oral perception to bulk rheology of the foods however this method does not capture many important aspects of the problem. As Malone et al. [6] concluded "*thin film tribological properties correlated more closely with the composition and texture of the samples than the bulk rheological properties*". When food is masticated the material in the tongue-palate conjunction is sheared and reduces so that the surface and thin film properties and the structural evolution, rather than the bulk fluid, determine oral perception. Selway and Stokes [7] note "*The change in length-scale (film thickness between oral surfaces) is identified as a key feature driving the transition from a regime where the bulk fluid properties govern the sensory response, to one where surface interactions dominate.*"

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Table 1
Composition of test fluids.

Composition/100 g	0% wt fat	4.2% wt fat	9.5% wt fat
Total fat	0 g	4.2 g	9.5 g
of which saturates	0 g	2.5 g	5.9 g
Carbohydrates	8.5 g	4.2 g	6.4 g
Of which sugars	8.5 g	2.7 g	6.4 g
Protein	5.9 g	4.6 g	4.58 g

In recent years there has been a growing number of studies [6–18] reporting the tribological evaluation of semi-solid foods (e.g. yoghurt, salad dressings, milk, chocolate) with the intention of correlating measured friction with oral perception and to provide more relevant assessment of new products. The approach has been very successful as Chojnicka-Paszu et al. [9] concluded from their study of milk "*indicated a good correlation between creamy attributes and measured friction coefficient, a result that validates the use of tribology as an analytical technique to better programme specific sensory products in product development and reformulation*". Research has usually focussed on correlation of friction behaviour with fat content [6,9,18] of the sample however in future we must be able to relate measured friction to the wider chemical composition and component distribution properties of the lubricating film. A thorough review of the topic is provided by Stokes et al. [15] who consider more general aspects of the relationship between rheology, lubrication and oral processing. The focus of the current paper is to reexamine the tribology of the tongue-palate and development of improved test methodologies to better simulate oral processing.

2. Research into food tribology

2.1. Conventional tribology test methods

A variety of test devices have been used to study friction properties of foods, Prakash et al. [8] provide a recent review. Most studies of fluid or semi-solid food tribology [6,7,9,12,13,14] have used the Mini Traction Machine (MTM) or Optical Tribological Configuration (OTC) [11,17]. The MTM uses a ball-on-disc contact immersed in excess of fluid and measures friction coefficient as a function of different test conditions including entrainment speed, slide-roll ratio and temperature. The OTC uses a pin (PDMS or other soft surface) reciprocating against a glass counterface [11,17]. Lee et al. [10] also used a pin-on-disc (unidirectional sliding) device (CSM Instruments) to study the tribology properties of molten chocolate.

In tribology terms the tongue-palate contact is characterised as a soft, rough, viscoelastic specimen (tongue) rubbing against a harder, smooth counterface (palate). The contact pressure is generally low (~MPa) and the sliding speeds in the range 10–30 mm/s to match tongue movement in eating [19]. The various test methods described in the literature use a wide range of materials (polymer, zirconia, glass, steel, porcine tongue), specimen surface properties (smooth/textured, hydrophobic/hydrophilic) contact conditions (pressures, temperature, speed range) and kinematics (sliding/rolling/reciprocation). The test specimen materials are chosen to simulate the tongue-palate contact and include "soft/soft" (polymer/polymer) [7] and "soft/hard" (polymer/steel or glass, porcine tongue/glass) [11,12,13,14,17] combinations. The kinematic condition is particularly important as this plays a significant role in determining lubricant film properties. The MTM test has usually been used in a rolling-sliding configuration (50% SRR) where both the ball and disc are driven at different speeds [6,12–15]. Other studies have used simple sliding [10] or reciprocating sliding [11,16,17]. In some cases very high speeds (~500 mm/s [12]) were used, however the usual range is 5–80 mm/s [10,11,17]. This is supported Hiiemae and Palmer [19] who quote an average measured speed range of 10–32 mm/s for tongue movement during eating

Food tribology tests are usually run as "Stribeck" curves [6,7,12–14,] with average friction measured over a range of speeds. The technique has been successfully used to distinguish between different fat contents in semi-solid foods including yoghurt [7], milk [9] and O/W emulsion [6, 11]. Typical examples of MTM speed-sweep curves carried out in our laboratory are shown in Fig. 1a. The friction coefficient in the low-speed region (usually <50 mm/s) decreases with increasing fat content as has been reported in other studies [6,7,9]. For the speed-sweep results friction coefficient at 20 mm/s is ranked 9.5% fat ($\mu = 0.025$) $<$4.2% fat ($\mu = 0.04$) $<$0% fat ($\mu = 0.15$). However measurements at constant speed (20 mm/s) gave different results for the 9.5% fat yoghurt (average $\mu = 0.09$) as shown in Fig. 1b. This result was unexpected and possibly indicates that the shear history experienced by the food is important in determining friction response.

The friction/speeds curves are usually interpreted in terms of classical fully-flooded lubrication regimes (boundary, mixed, full film) denoted by changes in friction coefficient [6,7,8,11–15]. For the O/W emulsions the reduction in friction at slow speeds is attributed to the preferential entrainment of oil [4,7] and the formation of an oil "boundary" film [8] on the contacting surfaces. For example Selway and Stokes [7] concluded "*The medium- and high-fat products both generate friction curves identical to that of the pure oil phase over the entire range of speeds measured, indicating preferential entrainment of oil and exclusion of the thickened aqueous phase from the contact zone*." Thus in these tests the conditions experienced by the fluid as it is *entrained* through the inlet into the contact are critical in determining both the composition of the film formed ("*preferential entrainment of oil*") and the resulting friction behaviour. Thus the film in the contact zone is not representative of multiphase composition of the food.

2.2. Tribology analysis of oral processing

The preceding discussion has emphasised the role of the inlet in determining the film formation and friction response of two-phase (emulsions) fluids. Lubricant is entrained into the contact region by the relative motion of the surfaces and thus forms a film which supports the load and separates the surfaces. A fundamental principle of tribology is that under normally lubricated conditions i.e. where there is continued supply of lubricant it is the properties (viscosity, composition) of the fluid in the inlet region that determine the lubricating film properties (chemistry, thickness) in the contact region. The shear conditions in the inlet (due to narrowing gap height) are severe and even for modest speeds (mm/s) can reach $10^5\ \mathrm{s}^{-1}$ for the classical ball/disc arrangement. This can lead to shear thinning or degradation, phase and compositional changes, particularly for emulsions, prior to the contact (Fig. 2a left image) and is clearly not representative of the eating process. Semi-solid foods are placed in the oral cavity and broken down either in the tooth-tooth or tongue-palate rubbing contacts. There is no continued flow of fresh material into the contact and a representative distribution of components is present at the start of mastication.

The role of the inlet in determining film properties in the contact has been extensively studied in classical (oil-based) lubrication [20–22]. O/W fluids are used as metal-working lubricants where shear degradation and coalescence of oil droplets in the inlet occurs to provide an oil-rich reservoir which supplies the lubricating film in the contact zone [20,21]. At low speeds the film in the contact is predominately composed of oil giving a thicker film and lower friction than the continuous water phase [20]. At higher speeds replenishment of the oil reservoir is not maintained and entrainment of the bulk fluid, which is predominately water, occurs [20,21]. The film thickness of industrial O/W emulsions often drop with increasing speed because of this effect [20]. Thus the oil/water composition in the contact will change depending on the properties of the fluid and the ability of the contact to generate and retain the oil reservoir (materials, surface energy, entrainment speed, chemical composition) [20,21].

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