The role of saliva in oral processing: reconsidering the Breakdown Path paradigm

Michael W. Boehm[a*], Gleb E. Yakubov ORCID: 0000-0001-5420-9422[b,c], Jason R. Stokes ORCID: 0000-0001-7784-9297[b] and Stefan K. Baier ORCID: 0000-0003-4271-8624[a,b]

Highlights

- We consider approaches to experimentally quantifying the Hutchings and Lillford's conceptual food breakdown path
- New definitions of 'Structure'; and 'Lubrication' are proposed to obtain hypothetical 'breakdown' curves for a brittle snack food and an emulsion
- Strategies to incorporate the multiple influences of saliva on the underlying physics of oral processing are proposed

Abstract

We discuss food oral processing research over the last two decades and consider strategies for quantifying the food breakdown model, originally conceptualised by Hutchings and Lillford . The key innovation in their seminal 1988 paper was shifting the focus from intact food properties, measured in the lab, towards strategies to capture the dynamic nature of eating. This has stimulated great progress in the field, but a key aspect missing in oral processing research is the conversion of the Hutchings and Lillford breakdown path conceptual model into quantifiable parameters considered in the context of physiological factors such as saliva and oral movements. To address these short comings, we propose the following analysis: Hutchings's and Lillford's definitions of "Structure" and "Lubrication" are incomplete and they comprise many and varied physicochemical properties. We offer, here, a deeper analysis of each parameter, and propose strategies for researchers to consider in their quantification as an update of the Hutchings and Lillford Breakdown path.

Practical Applications

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The concept of a Breakdown Path for foods has been foundational to contemporary food oral processing research. However, the original idea described by Hutchings and Lillford was qualitative and therefore not easily applied to the analytical and sensory measurements commonly used. This manuscript presents a recrafting of the Hutchings and Lillford Breakdown Path in the context of analytical measurements. By being framed in terms of quantifiable properties, particularly time-dependent properties, our updated breakdown path can be considered alongside temporal-based sensory testing techniques.

Introduction

Several decades of research into food physical properties has led to good integration of texture measurements and sensory testing, integration that continues to provide insights about oral processing. For example, techniques like time-intensity and temporal dominance of sensations are moving our focus from measuring static properties—which texture measurements historically probed—to capturing dynamic behaviour. But texture is our brain's description of interactions between food and our physiology, as Hutchings and Lillford (1988) argued in their statement that texture exists in the brain. As such, using correlations of instrumental measurements performed *in vitro* with sensory data collected *in vivo* will not help us fully explicate the causality tying sensory percepts to physical properties. To complete the link, we hypothesise, requires *in vitro* experiments aimed at elucidating the physics underlying the processes occurring in-mouth. Liu *et al.* (2015), for example, present a highly integrated study into the structure and breakdown of emulsion-filled gels by using *in vitro* and *in vivo* techniques. Eating comprises mechanical & chemical actions, interactions between food and receptors, signal transfer to the brain, cognition and feedback. This complex system places rheology (i.e., flow), physiology and psychology as foundational disciplines in oral processing research. These disciplines therefore provide a framework for elucidating the following relationships: (1) the interplay between deformations (e.g., bending and puncture (Castro-Prada *et al.*, 2012) or dilution (Chen and Lolivret, 2011)), and food physical properties (e.g., shear viscosity, fracture behaviour, acoustic response), (2) how those properties are 'detected' by receptors in the oral cavity (e.g., mechanoreceptors and nociceptors) to create a sensory input (Engelen, 2012), (3) how the input is processed by our brain, including the input's cortical representation (Guest *et al.*, 2007; Eldeghaidy *et al.*, 2011) and (4) the sensory input's transformation into a perception (Rolls, 2011). Stieger and van de Velde (2013) highlight the presence of a feedback system linking perception and oral movements. We direct the reader elsewhere for a deeper review of the different receptors (Engelen, 2012) and brain activity (Rolls, 2011). Here, we will focus on the underlying physical processes linking deformations to changes in food physical properties (i.e., purely *in vitro* approaches). We will also highlight the role of saliva and the growing importance of and focus on capturing the transient behaviour of food.

With this article, we introduce an *in vitro* analytical-based research approach considered within the context of, but different to, the Hutchings and Lillford breakdown path (H&L BP). Our approach retains the "Structure" and "Lubrication" parameters and suggests quantifiable versions of both. The new model places the two parameters on separate two-dimensional graphs instead of the single three-dimensional graph proposed by Hutchings and Lillford.

Breakdown *during* oral processing

Hutchings and Lillford (1988) proposed that eating is dynamic and that food breaks down to a safe-for-swallow bolus following a unique path. Lillford (2011) followed up on the breakdown path conceptual model (H&L BP)by considering the experience of and the potential physical changes occurring during eating, using a few very different food systems as examples. The H&L BP, as a qualitative concept, has impacted the field of oral processing research. However, loose and abstract definitions of "structure" and "lubrication" restricted the adoption of the H&L BP as a tool for quantifying texture attributes in terms of physical measures. These two terms encompassed a range of size scales and processes thereby rendering them a bridge from texture to physical properties, not absolute quantities. Whilst Hutchings and

Lillford focused on presenting a conceptual model of "in-mouth perceived texture" by framing the psychophysics in terms of intuitive food physical properties, it also encouraged exploration of quantifiable relationships between the physics of food breakdown and perceived texture and highlighted the need to consider in more detail the influence of saliva.

The H&L BP in brief. The Hutchings and Lillford breakdown path conceptual model sought to combine in-mouth perceived properties as bulk mechanical/rheology properties (e.g., toughness, thickness), particulate properties (e.g., meat fibres, lumps in custard) and transport properties (e.g., flavour, juiciness, sensation of fat) into three axes: "degree of structure", "degree of lubrication" and time. Structure was considered in terms of mechanics, of both the bulk product and individual particles within the sample or formed during comminution (chewing). Lubrication was considered in terms of the presence of liquids, e.g., moisture level or amount of fat, and incorporates the effect of saliva to hydrate, lubricate and assist in breaking down the food. Time was considered according to the number of chews or temperature.

Additionally, Hutchings and Lillford provided the following insightful statements: (1) texture exists in the brain, and (2) eating is a dynamic process thus no single physical/physiological/neural property measurement can capture the entirety of eating. The second statement underlies recent advances, including: time-intensity (TI), temporal dominance of sensations (TDS) (Lenfant *et al.*, 2009; Foster *et al.*, 2011; Koç *et al.*, 2013; Young *et al.*, 2013). Additionally, methods such as acoustic signal capture (Saeleaw and Schleining, 2011) and jaw activity measurements (Koc *et al.*, 2014) nicely supplement mechanical testing and sensory trials. There have also been advancements to *in vitro* approaches that capture the transient behaviour of some important physical properties, e.g., bulk elastic modulus (Boehm *et al.*, 2013; Boehm *et al.*, 2014) and friction (Selway and Stokes, 2013). Recently, Mohammed *et al.* (2014) used Scanning Electron Microscopy, X-ray Micro Tomography and Finite Element modelling to probe microstructural changes *during* compression while simultaneously collecting stress-strain responses; this approach combines several techniques to investigate potential changes occurring during first bite and comminution.

Developments on the H&L BP and the role of saliva in oral processing. A key aspect in the H&L BP that is challenging to incorporate is the multiple facets and complexity arising from the influence of saliva on the modification of structure and lubrication parameters with time. Rosenthal and Share (2014) propose a shift in the way we think about the H&L BP: taking peanut paste as an example, the authors suggest that upon addition of small amounts of saliva the paste "structure" actually increases, then decreases with increased saliva incorporation. Contrary to the historical idea of a pure "breakdown path", Rosenthal and Share suggest a more complicated physical pathway, at least for the structure component. The behaviour seen by Rosenthal and Share was most likely due to small amounts of saliva, i.e., a water-rich proteinaceous secretion, binding particles and resulting in an increase in the phase volume due to aggregation; this process is called granulation (Stokes *et al.*, 2013). Other researchers (Lucas *et al.*, 2002; Rodrigues *et al.*, 2014) have also made steps towards integrating granulation into oral processing.

Research into the astringency of polyphenol-rich foods, e.g., tea and certain fruits and vegetables, as well as wine, led to a shift in how we evaluate saliva's role in mediating oral processing (de Freitas and Mateus, 2001; Jobstl *et al.*, 2004; Bajec and Pickering, 2008; Rossetti *et al.*, 2008; Rossetti *et al.*, 2009). Astringency was thought to be a tactile percept driven by aggregation of astringent compounds with salivary-proteins, which caused a loss of the lubricating salivary film from the oral surfaces (Green *et al.*, 1993), but it is now clear that this is a contributing factor rather than a defining one (Gibbins and Carpenter, 2013; Ma *et al.*, 2014). Rossetti et al (2009) certainly found that highly astringent compound aggregated with salivary proteins and caused their depletion from substrates (pre-adsorbed, *in vitro*) and led to an increase in friction; however, in some formulations, astringency was still observed without this occurring, whilst in others, there was a significant loss of saliva-lubrication yet astringency was only weakly perceived if at all.

Another influencing factor is that some astringent compounds are found to directly interact with oral tissues and epithelial cells (Gibbins and Carpenter, 2013). In addition, recent work identified a trigeminal G protein–coupled receptor pathway for astringent compounds, which suggests direct involvement of specific astringent molecules (e.g. galloylated polyphenols) in the stimulation of trigeminal nerve fibres (Vogt-Eisele *et al.*, 2014).

Also influential is the realisation of how a saliva deficiency affects swallowing (Engelen *et al.*, 2005; Chen, 2009) and contributes to the mechanisms implicated in dysphagia (Cichero and Halley, 2006). Another important factor was an attempt to understand the underlying physical mechanisms of "creaminess" perception, which is a highly complex and culturally subjective consumer attribute that is nonetheless widely used in consumer need-driven industrial product design (Janssen *et al.*, 2007; Dresselhuis *et al.*, 2008; Vingerhoeds *et al.*, 2009; van Aken *et al.*, 2011).

First, saliva is a key factor in mastication of solid foods as they undergo comminution into sub-millimetre particles that reform into a cohesive bolus for swallowing. Within this process, saliva plays multiple roles that depends on the food material and can include actions such as wetting, hydration, emulsification and flocculation (see review by Witt & Stokes 2015), and it lubricates to enable swallowing and prevent friction from the rubbing of hard particles at oral surfaces (Bongaerts *et al.*, 2007b). Hydration can soften and swell solid-food particles, and for starch-containing foods, this is a rate-limiting step for the enzymatic digestion of starch (Boehm *et al.*, 2013). Saliva can thus modulate the food chemically via the action of such enzymes as salivary α-amylase (Janssen *et al.*, 2007; Janssen *et al.*, 2009). Saliva modulates particle/bolus adhesion to oral surfaces as well as cohesion between particles, and can thus determine the progression of oral processing and swallowing (Prinz and Lucas, 1995). In addition, the thin salivary film that coats oral surfaces, a so-called salivary pellicle (Gibbins *et al.*, 2014a; Yakubov, 2014), impacts such perceptions as astringency and stickiness, and may mediate such after-feel attributes as drying or roughness (Prinz and Lucas, 2000; Lucas *et al.*, 2002). All these factors are important to texture, mouthfeel and taste perception (Dresselhuis *et al.*, 2008;

Vingerhoeds *et al.*, 2009l; van Aken *et al.*, 2011). With regards to the taste perception, it is mediated by the ability of tastant molecules to transfer (either via diffusion or through other mass transfer mechanisms such as mechanical and osmotic mixing and convection) through the salivary film to the underlying taste receptors (Salles *et al.*, 2011). This can be evidenced in patients with xerostomia (dry mouth syndrome) who have been found to have a diminished sense of taste (Christensen *et al.*, 1981).

The key colloidal factors that influence saliva's ability to break down foods, modulate bolus rheology, lubricate and mediate post-swallowing oral friction are the presence of salts and a cocktail of proteins, including a set of highly specialised enzymes (Yakubov *et al.*; Gibbins *et al.*, 2014a) that contribute to saliva's capacity to transform food via enzymatic reactions. This multicomponent system has four key unique physical properties, listed below:

(A) saliva is a highly viscoelastic fluid—as illustrated by its stringiness upon extension—with a surprisingly water-like shear viscosity (Stokes and Davies, 2007; Davies *et al.*, 2009).

(B) saliva has the unique ability to absorb onto substrates of different chemical nature, including air-liquid interfaces, and form multi-component protein-rich films that facilitate lubrication, wetting, changes in the surface tension and surface elasticity (Rossetti *et al.*, 2008; Macakova *et al.*, 2010, 2011; Harvey *et al.*, 2012; Gibbins *et al.*, 2014b; Yakubov *et al.*, 2015).

(C) salivary α-amylase contributes to the starch hydrolysis and associated transformation of starch-rich foods. Carbonic anhydrase IV catalyses the hydration of carbon dioxide and is crucial to the buffering capacity of saliva and the balance of salivary bicarbonate (Ash *et al.*, 2013; Ash *et al.*, 2016).

(D) The oral microflora, which comprises more than 1000 identified species (Marsh *et al.*, 2016), has a diverse impact on such aspects as flavour perception (e.g., though the formation of cysteine-conjugates (Starkenmann and Niclass, 2011)).

The key physiological factor contributing to saliva's role in oral processing is that saliva is primarily produced by three types of paired glands: parotid, sub-mandibular and sub-lingual. As a note, soft tissues of the oral mucosa host small (1–2 mm) secretory apparatuses, called minor salivary glands. These are distributed throughout the oral cavity, with some notable locations in the tissues of the buccal, labial and lingual mucosa. Although minor salivary glands contribute only about 10% to the total volume of human saliva, they produce mucin- and immunoglobulin-rich saliva. In addition, the von Ebner's glands (also called gustatory glands), which are located proximally to the circumvallate and foliate papillae in the tongue, produce secretions that contain several enzymes such as lingual lipase.

The salivary glands are stimulated by neural reflexes, and at rest, the salivary flow rate is relatively low, on the order of 0.1-0.5 ml/min; the resting saliva along with the oral microbiome are important factors in generating a "neutral" oral perception baseline. Upon stimulation, such as mechanical chewing action or presence of acids (Stokes and Davies, 2007; Davies *et al.*, 2009), the salivary flow rate increases to 1-5 ml/min. The type of stimulation dictates variations in salivary composition (Stokes and Davies, 2007). Chewing actions stimulate parotid glands that produce watery secretions. Acid stimulates sub-lingual and sub-mandibular (SLSM) gland secretions, which are rich in mucins, a specialised class of high molecular weight glycoproteins that confer SLSM saliva its highly elastic rheological properties and ability to lubricate above that of parotid secretions. The salivary flow rate from all glands vary between individuals and time-of-day within individuals, which is anticipated to alter how products behave and are perceived during oral processing. A key challenge in oral processing research is accounting for inter and intra-individual differences in oral physiological parameter that includes saliva flow rate and composition.

Next-generation H&L

In considering the H&L BP, we propose a two-fold means in which to take it from a qualitative framework for oral processing research to a quantitative model capable of representing the dynamics of *in vitro* changes in physical properties and guiding measurements of *in vivo* physical properties. First, for ease of presentation and interpretation, we recommend that the original three-dimensional graph of the H&L BP is replaced by two two-dimensional graphs: one displaying the structure parameter versus time, the other displaying the lubrication parameter versus time. Second, we suggest the structure and lubrication parameters be defined with relevant measurable parameters: we use a dimensionless particle area for the structural parameter and a dimensionless friction parameter for the lubrication parameter. This interpretation aims to provide a numerical frame of reference for structure and lubrication.

[figure 1 here]

<u>Structure.</u> We consider this in the context of solid foods, whereby Witt & Stokes (2015) provide a schematic of the oral processing that shows breakdown with time due to comminution (chewing), but then comminuted particles agglomerate, hydrate and form a suspension upon incorporation of saliva. As an example of this process, we consider the structure parameter as applied to brittle snack foods, e.g., potato chips. We illustrate in figure 1 the hypothetical response of a potato chip to the different stages of oral processing and highlight the important physical properties underlying the different physical processes that occur.

During the stages of first bite and comminution, breakdown will depend on properties like size, shape and modulus and/or hardness of the chip. Research has found that the critical stress intensity factor to be a useful tool when comparing different foods (Vincent *et al.*, 2002), whilst fracture strain is also useful when examining the breakdown of gels (Rodrigues *et al.*, 2014; Mosca *et al.*, 2015). In general, the fracture behaviour of a food is critical, but our ability to determine, *a priori*, the resulting particle size distribution is still under investigation. One approach involves developing mechanical mouth models to controllably investigate breakdown (Sun *et al.*, 2014). As the food is broken down into particles, oil or associated water can be released from as well as saliva incorporated into the particles; this liquid, i.e., binder, can drive aggregation of the particles. This process of binder-mediated aggregation is called granulation, which is dependent upon particle kinetic energy and binder viscosity. Mosca et al. (2015) investigated sweetness perception as a function of gel mechanical properties: using agar and gelatin, they independently adjusted the fracture stress and fracture strain of their gel samples; these gels were layered to create a bulk sample with a heterogeneous distribution of sucrose. Sucrose release was measured *in vitro* and sweetness intensity was measured *in vivo*. Images were taken of expectorated boluses at different chew points, which show, for this soft-solid food, that comminution and granulation likely proceed in tandem. For these high water-content samples, one might expect water release throughout oral processing thereby leading to a cohesive, capillary force-driven bridging between newly created particles.

As bolus formation proceeds, the particles hydrate and soften, aggregate and form the soft mass that is eventually swallowed. We have focused extensively on the rheological properties of that soft mass in relation to potato chips (Boehm *et al.*, 2013; Boehm *et al.*, 2014), and we have analyzed the transient and pseudo-steady state behaviour of the bolus. We found that the bolus elasticity, G', can be modelled in terms of a square-root-of-time dependence and a power law dependence on solids concentration (figure 1).

[figure 2 here]

Given the evolution of the food into a bolus, in the H&L approach we propose that the structure parameter be a function of some dimensionless area: at any time, the average area of a 'particle' (a_p) (or some characteristic particle area) is compared to the initial, i.e., intact, food area ($a_{initial}$). The so-called 'particle' is initially the particles generated from comminution but is then the agglomerated mass as the bolus forms. For instance, figure 2a shows a hypothetical breakdown curve for potato chips where the structure parameter, $S = a_p/a_{initial}$. From literature (Prinz and Lucas, 2001), we know that first bite results in large pieces, and comminution further breaks those large pieces; granulation and bolus formation, however, involve aggregation and thus a build-up in the characteristic bolus 'particle' area. The scenario presented assumes that the large comminuted particles are perceived in the initial stages of consumption, but the bolus size is dominant at the later stages. While this scenario may capture the evolution of some characteristic structural parameter as solid food is transformed to a swallowable bolus, it does not incorporate the bulk or particulate mechanical properties nor changes in the physical properties of the bolus; we suggest this is the role of the lubrication parameter.

For soft foods and fluids, it is less clear as to the defining structural parameter, and we suggest that the largest structural element within the system is most relevant. Figure 2b considers this approach for a food emulsion, where the initial area is the average area of oil droplets before first bite. In this case, past research (Dresselhuis *et al.*, 2008; Vingerhoeds *et al.*, 2009; van Aken *et al.*, 2011) has shown that initially stabilized oil droplets may aggregate in-mouth, which would lead to a build-up in the area of the oil (*as well as coating of oral surfaces*). Another novel aspect of our proposed approach is to also attempt to incorporate the structure parameter after swallow: coating of oral surfaces by oil or tooth packing by solids are known to impact the sensory experience, yet these attributes have not been captured in past models.

[figure 3 here]

<u>Lubrication</u>. Oral lubrication is essentially the degree by which there is a smooth process of operation between interacting oral surfaces. The main contribution to lubrication is the rheology (viscosity) of the fluid confined between oral surfaces in relative motion, but lubrication (i.e., tribology) is a systems property that depends on many factors (figure 3). To adequately describe the properties of a rubbing contact we should consider the following points: (1) properties of the rubbing surfaces, including their surface roughness and viscoelasticity (Bongaerts *et al.*, 2007a; Selway *et al.*, 2017); (2) confined fluid films that can be characterised by viscosity and, for multi-phase fluids, the properties of constituent phases such as particle modulus; (3), the fluid-solid interfaces, which include properties such as wetting characteristics and polymer/surfactant adsorption. These nuances have been deeply explored using model lubrication studies involving soft substrates such as elastomeric balls and plates, i.e., soft-tribology (Bongaerts *et al.*, 2007a). With the work of Stokes (Stokes, 2012c, d; Stokes *et al.*, 2013; Witt and Stokes, 2015), van Aken (Dresselhuis *et al.*, 2008; van Aken, 2013), Prinz (de Hoog *et al.*, 2006; De Wijk and Prinz, 2006; Prinz *et al.*, 2007), Norton (Gabriele *et al.*, 2010) and many others, soft-contact tribology has, over the past decade, become a pivotal tool for gaining insights into the

lubricating properties of liquids and macromolecules relevant to oral processing (the reader is guided elsewhere (Stokes, 2012b) for background on soft-contact tribology).

[figure 4 here]

For our purposes, we state that the commonly measured parameter is a friction coefficient, which is essentially the inverse of how we define lubrication. We highlight, in figure 4, the importance of identifying the underlying physical processes contributing to the measured friction. Due to the shape of the Stribeck curve, similar friction coefficients are attainable in the approach to the boundary regime and the hydrodynamic regime. In considering just the influence of viscosity on lubrication and friction, both a low viscosity and high viscosity fluid can exhibit a low degree of lubrication (high friction); a high viscosity may prevent surface contact but causes high resistance to motion, while a low viscosity has little resistance to motion but is unable to prevent contact between surfaces. Another key factor is that foods are typically heterogeneous, whereby the lubrication is dependent on the presence and properties of large particles or droplets in the mouth in addition to the properties of the fluid present in the mouth.

In considering quantification of the lubrication parameter, we suggest here that the best reference state is the friction coefficient for unstimulated, resting saliva expectorated and adsorbed on soft substrates. This is chosen as an *in vitro* equivalent to the *in vivo* condition of saliva-coated oral surfaces. We emphasize the importance of using appropriate and controlled protocols for saliva collection, with recommended methodologies detailed in Stokes et al. (2012a, b) that seek to limit saliva variability by having a consistent source of saliva for any given set of work.

We show hypothetical curves for the lubrication during oral processing of hypothetical brittle snack food (e.g., oily potato chips), in figure 5a, and an emulsion, in figure 5b. In the case of oily potato chips, the friction would be initially high because the chip particles are hard and un-hydrated. During further comminution, oil can be released that may coat the particles and/or surface to enhance lubrication. As oral processing proceeds, the particles may also hydrate and become softer as the bolus is formed. The rheology or viscosity of the bolus may then dominate the lubrication and this may lead to a drop in the friction. Oil from the potato chip is likely to coat oral surfaces, and thus after swallowing, an oily residue may exist and thereby impact mouthfeel.

[figure 5 here]

For an emulsion, the salivary film coating may dominate the initial stage of oral processing, but the salivary proteins can wear from the surfaces due to associations with components in the food, or due to favourable wetting of the underlying surface by oil, both of which will likely increase the friction coefficient. This is a nuanced topic, however. Some surfactants do provide a friction coefficient lower than saliva, and whether or not the system is in the boundary or mixed regime influences, e.g., oil's impact on the friction coefficient.

In the case of a food emulsion, the sample may be lubricating (low friction coefficient) initially due to the high-viscosity (although shear-thinning rheology) of the emulsion, which is anticipated to drive the lubrication into the elastohydrodynamic regime. However, as the food emulsion structure evolves with time due to shear and upon interacting with saliva, the rheology will alter and there may be an increase in friction associated with oil flocculation by salivary proteins (Silletti *et al.*, 2007; Vingerhoeds *et al.*, 2009). This could potentially arise from the flocculates impairing lubrication due to an increase of effective roughness or due to depletion of proteins from the salivary pellicles that get adsorbed to the floc (and thus a loss of the lubricating salivary film coating). In addition, one should consider oil emulsification by salivary proteins, where oil added directly to the mouth has been shown to break up into droplets during *in vivo* oral processing (Adams *et al.*, 2007). The exact mechanism will depend on the stability of the emulsion, and type/quantity of emulsifier (protein, surfactant, particle). Unstable emulsions with large oil droplet size may be perceived as lubricating, because oral de-stabilisation and droplet coalescence lead to an oily coating of the mouth.

One should consider the choice of the surfactant used to stabilise emulsions—some surfactants can enhance lubrication (Bellamy *et al.*, 2009) while others may compete with salivary proteins for the surface area, and, by replacing salivary proteins on oral surfaces, lead to an astringent sensation (e.g., SDS (Bongaerts *et al.*, 2007b; Rossetti *et al.*, 2008)

Saliva and Lubrication. We highlight saliva's role in the Lubrication parameter by dividing the friction coefficient at any given time by the friction coefficient of saliva at rest (*see figure 5*). This relates friction during oral processing to the inherent friction we experience when not eating, a so called neutral friction or resting friction. Given the diversity of food structures and the frequency with which we experience saliva's inherent frictional properties, we believe using a lubrication parameter normalized to saliva's resting friction is the most relevant approach. That is, it is deviations from saliva's "normal" lubricating function that is likely to be perceived, as can be expected upon interactions with foods and beverages. We suggest that a relevant baseline, one tethered to a measurable physiological property (i.e., resting saliva friction), is needed in order to consider the frictional properties of disparate foods.

Recent research highlights ways in which saliva's interactions—and importance—with foods can be measured and used to inform on *in vivo* oral processing. Stokes et al. (2013) discusses how soft tribology is being used to investigate the *in vitro* transient behaviour of liquid and soft-solid systems confined to narrow gaps between moving surfaces and to gain insights into *in vivo* percepts like mouthfeel and afterfeel. Recently, Selway and Stokes (2013) used smooth poly(dimethyl siloxane) (PDMS) surfaces (root mean squared roughness of approximately 10 nm) to capture the change in friction due to interactions between different soft-solid foods (i.e., yoghurt, thickened cream and custard) and a saliva layer adsorbed to the PDMS disk. Their data are represented in figure 6. They concluded that interactions between saliva and the food system lead to breakdown of the salivary film (or at least part of the absorbed salivary proteins); they also discussed the possibility of several other chemical and physical causes underlying the increased friction.

[figure 6 here]

We highlight that lubrication prior to oral processing is dominated by adsorbed salivary proteins (anchored and weakly associated). Saliva is accepted to play a role in oral processing, and recent studies have focused on capturing the impacts on food physical properties when adding saliva. Joyner *et al.* (2014) used sensory and *in vitro* techniques to probe the impact saliva has on the frictional properties of various model milk-based gels. The authors added expectorated saliva and measured the frictional properties once the milks attained a pseudo steady state, i.e., they did not capture the transient response upon saliva addition; polypropylene balls and whey protein isolate gel disks were used for the tribological tests. We would like to stress that, in addition to pseudo steady state tests like those of Joyner *et al.* (2014), experiments need to capture transient behaviour as in Selway and Stokes (2013).

Conclusions

Oral processing research comprises sensory studies, [imitative] instrumental texture measurements and *in vitro* investigations of the underlying physics. Traditionally, a concomitance has existed between the two former approaches, whereas the latter approach has found great utility by those scientists engineering food physical properties based on a pre-oral processing context, e.g., shelf stability, manufacturing. The original conceptual breakdown path of Hutchings and Lillford seems to be an early attempt at bridging the three approaches. To move forward, greater effort needs to aim to provide quantifiable attributes on the transformation of food during oral process that can be incorporated into the H&L approach. This is a non-trivial exercise but with the integration of *in vitro* measurement techniques and approaches (e.g., tribology, rheology), and consideration on the influence of saliva, together with an understanding of the temporal sensations, it may be possible.

Author Information

[a]PepsiCo. R&D, 3 Skyline Drive, Hawthorne, NY, 10532, USA

[b]School of Chemical Engineering, The University of Queensland, Brisbane 4072, Queensland, Australia.

[c] the current address for G. Yakubov is as follows: Division of Food Sciences, School of Biosciences, University of Nottingham, Sutton Bonington Campus, Loughborough LE12 5RD, UK

*Authors to whom correspondence should be sent:

Dr. Michael W. Boehm

PepsiCo. R&D, 3 Skyline Drive, Hawthorne, NY, 10532, USA

Tel: +1 914 608 9327

Email: michael.boehm@pepsico.com

Email: s.baier@uq.edu.au

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Ethical Statements

The authors declare that there are no conflicts of interest, and this study did not involve human or animal testing.

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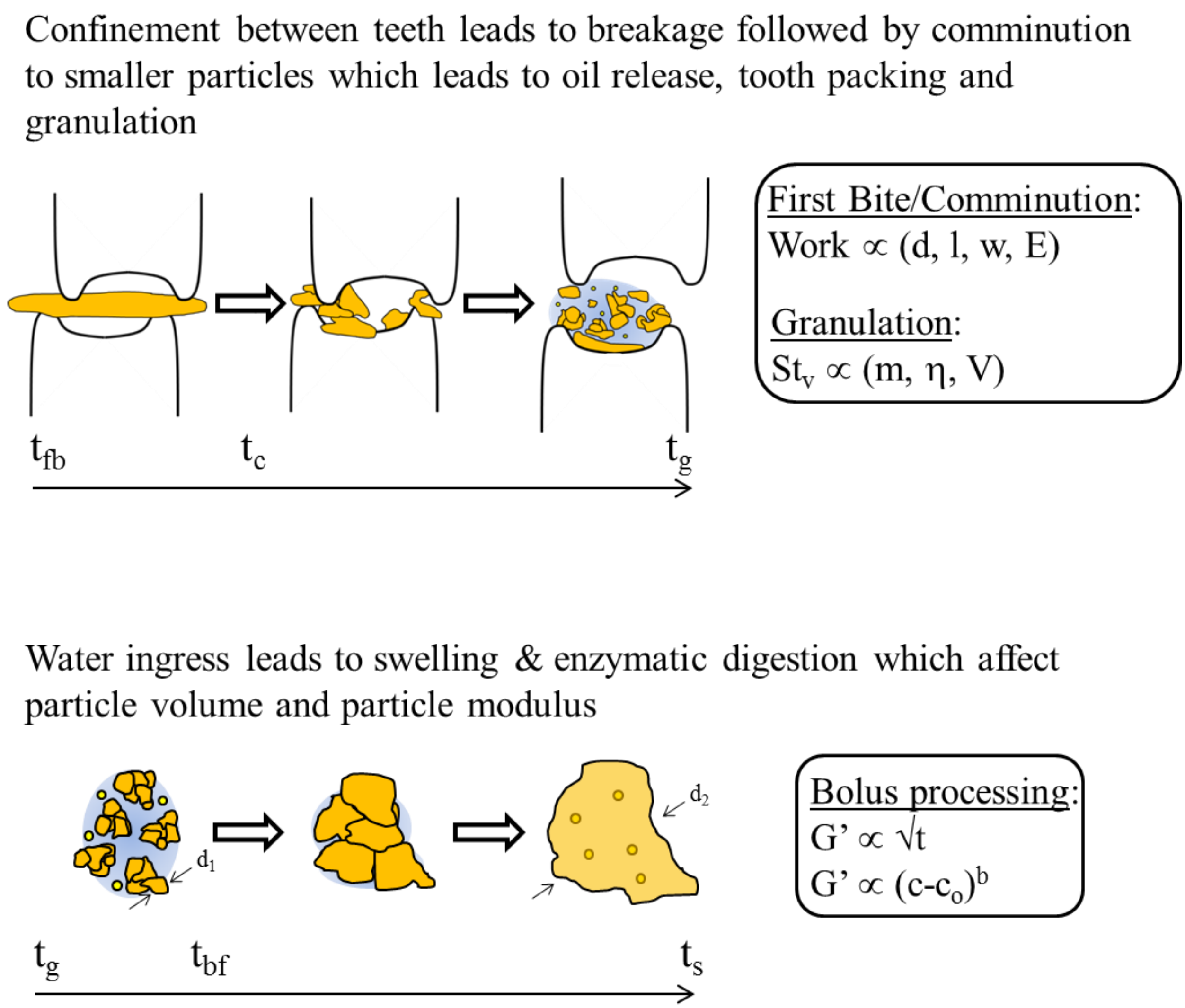

Figure 1. Cartoons depicting how the stages of oral processing of a brittle potato chip impact the Structure of the bolus and a list of the physical properties impacting those processes. For instance, the work to break and comminute chips depends on the diameter, d, length, l, and width, w, of the chip (which are geometrical properties of the chip) as well as the elastic modulus, E (which is a material property that will be altered by saliva). The viscous Stokes number, St_v, depends on particle properties like particle velocity, V, and particle mass, m, as well as the binder liquid viscosity, (which is another property effected by saliva and is time dependent). As the soft bolus forms, the bolus elastic modulus, G', will depend on parameters such as time of hydration, t, and solids concentration, c. See (Boehm

et al., 2013; Boehm *et al.*, 2014) for more details about the rheological response of the bolus.

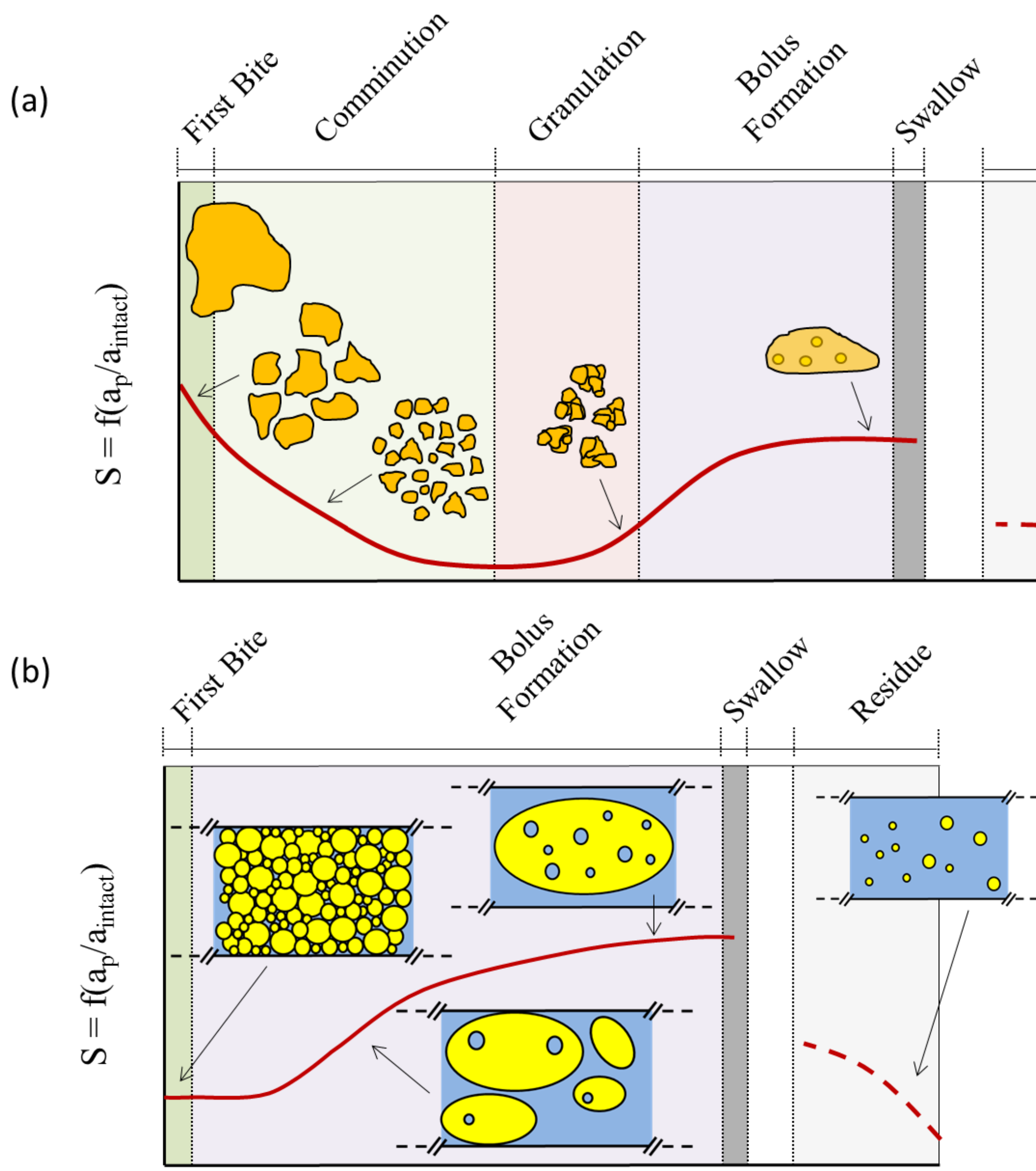

Figure 2. Hypothetical curves for the structure parameter, S, graphed versus oral processing time for (a) an oily potato chip and (b) an oil-water emulsion. The parameter $S=a_p/a_{initial}$ is related to the characteristic area of a particle (a_p) normalised over the initial area of the food piece (a_{intact}). We note that the commonly used

parameter of total surface area (A) in our notation can be expressed as $= \sum_{i=1}^{N_p} a_{p_i}$, where N_p is the number of particles. When broad distributions are considered, the advantage of using the parameter S is that the characteristic size a_p may represent a subset of particles rather than their entire ensemble, e.g., $a_p = {}^{1}\!/_{(n-m)} \sum_{i=m\geq 1}^{n\leq N_p} a_{p_i}$. The inset cartoons depict the potential physical changes occurring during each step of oral processing of (a) an oily potato chip and (b) oil-water emulsion. *The six-step breakdown of oral processing is based on Stokes et al. (Stokes et al., 2013).*

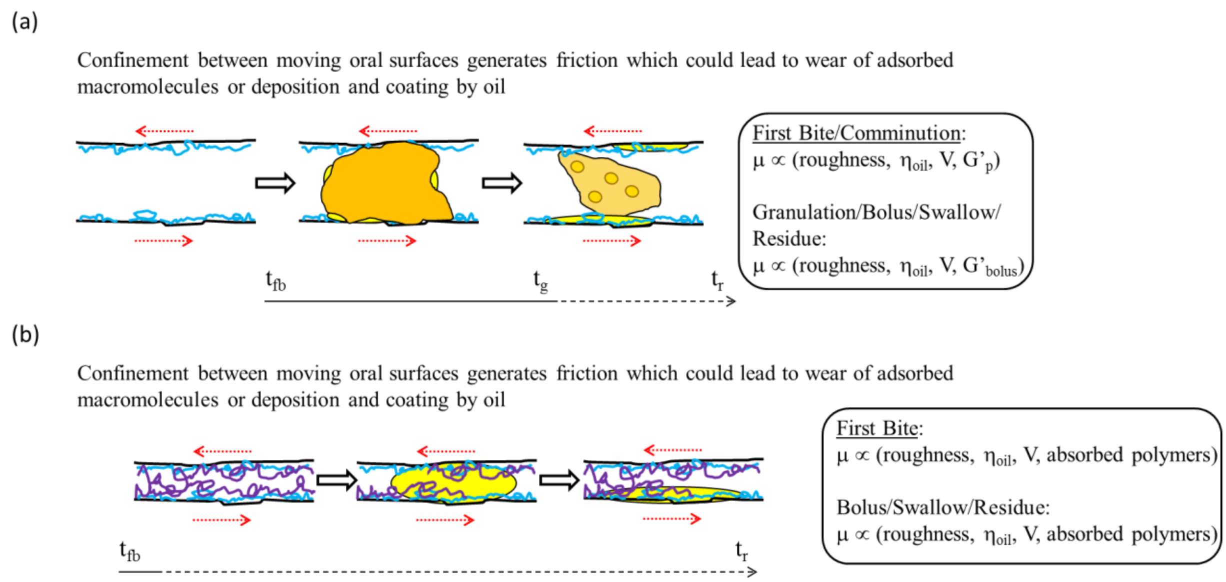

Figure 3. Cartoons depicting how the stages of oral processing of (a) an oily potato chip and (b) an oil-water emulsion impact the Lubrication of and friction between oral surfaces and a list of the physical properties impacting those processes. The friction is dependent on parameters such as surface roughness, the presence of adsorbed polymers, the viscosity of any oil, η_{oil}, and the velocity of the moving surfaces, V.

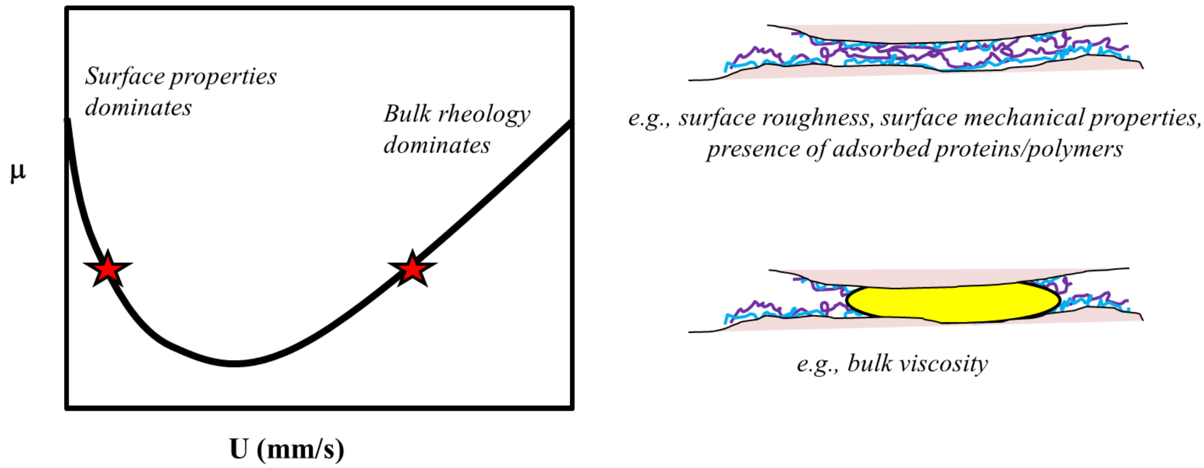

Figure 4. "U" shape in the friction-speed curve. We would like to stress that due to the nature of lubrication, one can measure two equal friction coefficients even though the system dynamics may be in either the mixed regime or the hydrodynamic regime. This occurs because increases in lubricant viscosity decrease the friction coefficient in the mixed regime but increase the friction coefficient in the hydrodynamic regime. The inset cartoons depict two different physical mechanisms leading to a similar friction coefficient.

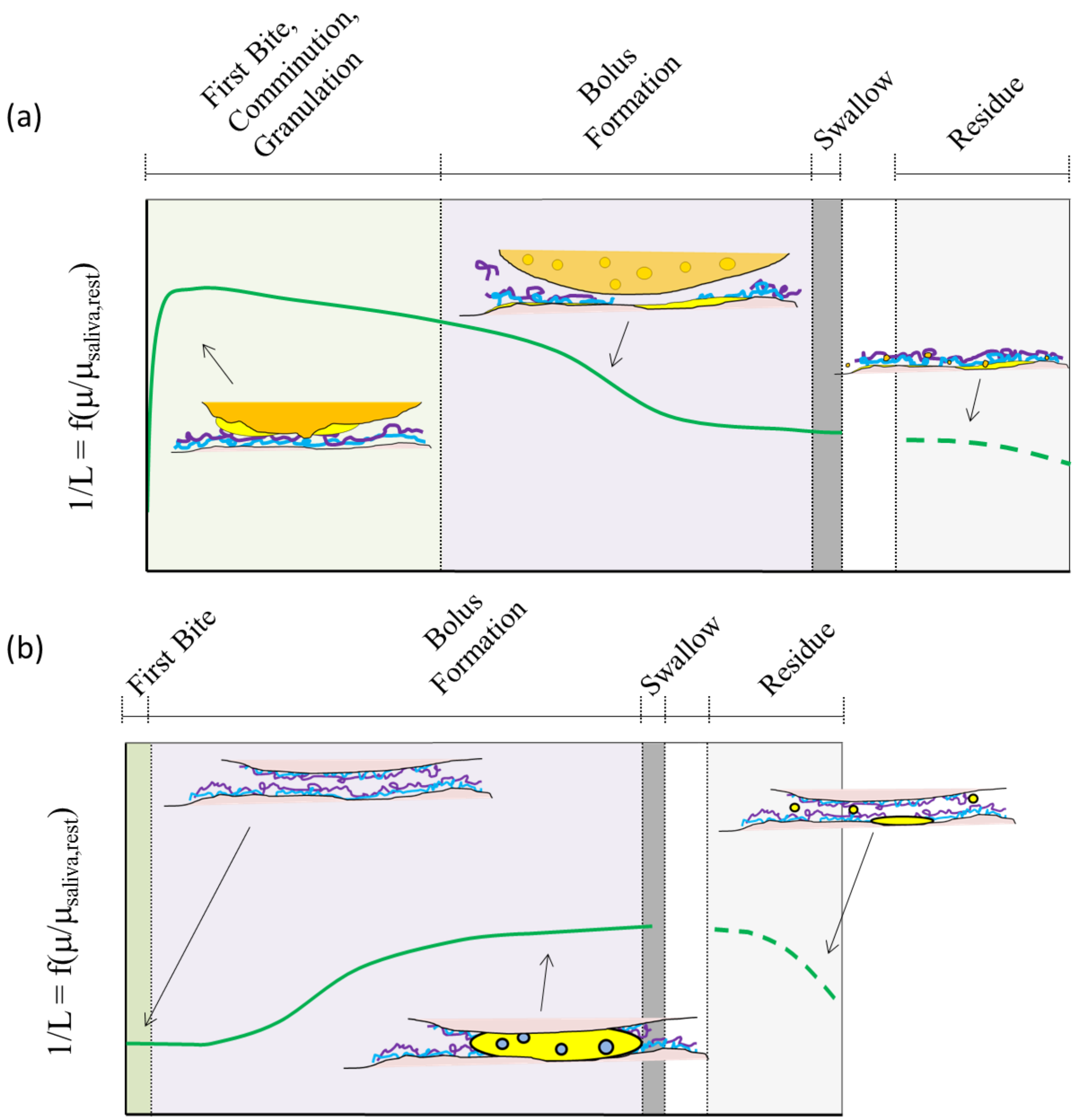

Figure 5. Hypothetical curves for the lubrication parameter, 1/L, graphed versus oral processing time for (a) an oily potato chip and (b) an oil-water emulsion. The inset cartoons depict the potential physical changes occurring during each step of oral processing. *The four-step breakdown of oral processing is based on Stokes et al. (Stokes et al., 2013).*

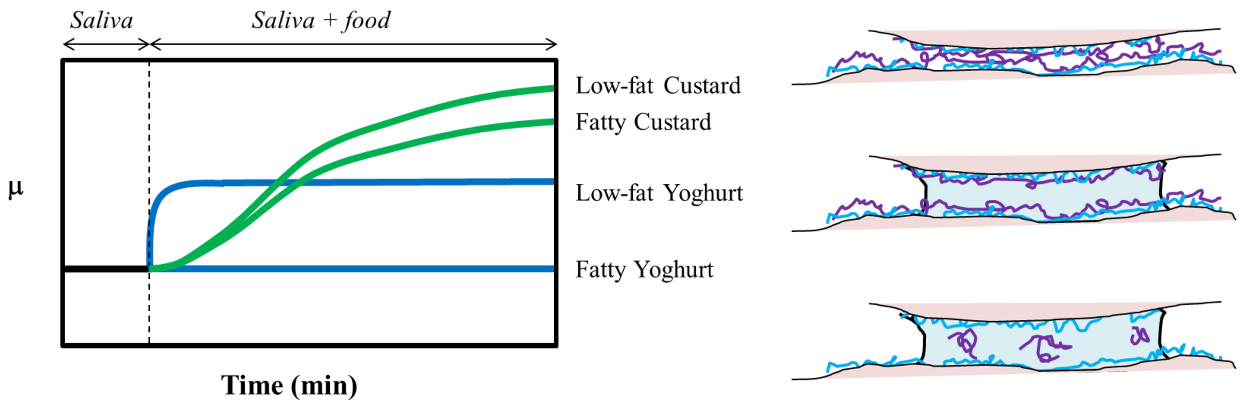

Figure 6. Depiction of transient friction as measured with saliva pre-adsorbed to PDMS soft contacts and after *in situ* introduction of different foods (adapted from Selway and Stokes (Selway and Stokes, 2013)). Cartoons represent the wearing off of adsorbed macromolecules from oral surfaces.