Perspective

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Enabling the rational design of low fat snack foods: Insights from *in vitro* oral processing

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Abstract

Texture perception is conceptualized as an emergent cognitive response to food characteristics that comprise several physical and chemical properties. Contemporary oral processing research focuses on revealing the relationship between the sensory perceptions and food properties, with the goal of enabling rational product design. One major challenge is associated with revealing the complex molecular and biocolloidal interactions underpinning even simple texture percepts. Here, we introduce *in vitro* oral processing, which considers oral processing in terms of discrete units of operation (first bite, comminution, granulation, bolus formation, and tribology). Within this framework, we systematically investigate the material properties that govern each *specific* oral processing unit operation without being impacted by the biological complexity of the oral environment. We describe how this framework was used to rationally design a low fat potato chip with improved sensory properties by investigating the impact from adding back, to a low fat potato chip, a small amount of oil mixed with the surface active agent polyglycerol polyricinoleate (PGPR). The relevance of instrumental measures is validated by sensory assessment whereby panelists ranked the perceived oiliness of three different types of potato chips. The sensory results indicate that perceived oiliness was higher when a low fat potato chip was supplemented with an additional 0.5% w/w topical coating (the coating comprised 15% w/w PGPR in oil) compared to the unaltered low fat potato chip. The perceived difference in oiliness is hypothesized to correspond to the dynamic friction measured *in-vitro* with a saliva-coated substrate in the presence and absence of PGPR. The study

illustrates how dividing oral processing into distinct units provides a rational approach to food product design focused on controlling key sensory attributes.

Introduction

Consumers are increasingly interested in healthier and sustainable food options and that necessitates a health conscious approach from manufacturers. Unfortunately, the inclination towards a clean label that offers an enjoyable eating experience and a strong following from consumers presents a dilemma: oil, for instance, is often a main contributor to a pleasurable eating experience for something like a potato chip. Therefore, the process of building strategies to overcome the negative sensory attributes resulting from the elimination of fat starts with determining its associated structure-function relationships for the food of interest. This knowledge then underlies the design and manufacture of healthier consumer acceptable foods.

The typical research approach in the food sciences involves elucidating the functionality of specific food ingredients, like fat, at a specific point in time during consumption: the initial breakage of foods has been studied and related to the mechanical properties¹; the comminution of model foods has been investigated *in vivo*², in the absence of saliva³ and in mechanical mouths⁴; the rheological and tribological properties of various foods and food additives have been measured in the presence of saliva⁵⁻⁷ and in the absence of saliva⁸⁻¹⁰ then analyzed in the context of the microstructure and other physical properties. The next step is to investigate the texture and sensory properties.

When consumers talk about “liking” or “disliking” the texture of a food, they are referring to an automatic cognitive response to the sensory perception of food properties. We know that textural properties are dependent on the physical properties of the food. Researchers, e.g., Szczesniak¹¹, proposed and developed the idea of instrumental texture analysis as an “objective” measure of intact food properties and also proposed that it was relatable to sensory perception. Instrumental texture profile analysis was designed to capture the initial unit operations of oral processing, associated with first bite impression and the initial stages of comminution. More recently, researchers have focused on capturing interactions between the food and the eater’s physiology^{12, 13}, e.g., saliva flow rate and composition. Similarly, sensory scientists now more often use tools that capture the dynamic nature of eating¹⁴ (e.g., Time

Intensity (TI), Temporal Dominance of Sensations (TDS)). The difficulty that arises with these recent approaches is that this dynamism and the variability between humans complicate the elucidation of structure-function relationships, which are needed to rationally design new foods and novel ingredients.

To augment advancements in sensory and texture analysis research and to aid in the rational design of foods, the *in vitro* oral processing framework was developed¹⁵⁻¹⁷. This is founded on the philosophy that using controlled, *in vitro* techniques to investigate individual unit operations based on the underlying physics of eating offers a systematic means of elucidating structure-function relationships. A researcher can then “build in” complexity to their model by incorporating digestive enzymes¹⁷ or expectorated saliva as a way to bridge the purely *in vitro* technique with sensory measurements. Ultimately, rational design of next generation foods will be best served by developing this bridge.

The scientific literature has not historically placed much emphasis on probing the dynamic changes in food during eating; it is much simpler to characterize intact food when comparing physical characteristics and sensory perception. A dynamic approach was alluded to in 1988 by Hutchings & Lillford¹³ (in their Breakdown Path, or H&L, model), but the execution of their approach has been limited^{18, 19} (*see^{16, 19, 20} for extensive reviews*). Their paper was visionary, yet the definition of “structure” and “lubrication” were ambiguous; thus, we have taken a slightly different approach (described herein and in a recent publication on rethinking the Breakdown Path paradigm²¹).

We built upon the H&L model by considering the act of eating in the context of sequential unit operations, the full set of which we call “oral processing.” By creating this framework, we have a way in which to systematically investigate the different steps of eating and how each step can be characterized by the relevant set of physical interactions and length scales. By probing the physical and biophysical mechanisms of each unit operation separately and systematically, we are able to more clearly define the parameters of “structure” and “lubrication”.

To illustrate, let us consider the act of eating a potato chip (see figure 1b). The chip is taken from the package and broken by the teeth into a distribution of particle sizes; we call this

phase “First Bite.” The particles are further broken down and begin to mix with and be hydrated by saliva; we call this phase “Comminution.” The small, softened particles then begin to agglomerate into a single mass as enzymes in saliva begin to digest the starches; we call this “Bolus formation.” The agglomerated mass (*called the bolus*) is then moved to the rear of the oral cavity and finally swallowed; we call this phase “Swallow.” Any remaining particles, residual oil etc. interact with the tongue and other oral surfaces (e.g., palate); we call this phase “After-feel.”

[Figure 1 here]

Figure 1 illustrates *in vitro* oral processing and hypothetical trajectories for potato chips, drawn in the context of the H&L model and covering the stages up to the point of swallow. In figure 1.a, we show *in vitro* oral processing in terms of the unit operations described above. In figure 1.b, we drew one hypothetical curve for the breakdown of full fat potato chips (PC) as well as the curve’s profiles on the Structure-Time plane and the Lubrication-Time plane; we represent the transition between unit operations as circles on the hypothetical curve. Finally, we drew additional profiles for the oral processing of low fat potato chips, highlighting how we hypothesize that structure and lubrication are impacted by the removal of oil.

We used several techniques to investigate the above processes. For First Bite, we used mechanical testing, such as three-point bend and puncture tests, to measure the force to break and the elastic modulus of potato chips. For Comminution, we used grinding combined with image analysis to measure the size and number of agglomerates formed as potato chips broke down under mechanical action. We adapted the principles of granulation science (granulation being a field of science concerned with the way in which particles agglomerate in the presence of a viscous binder) to observe aggregation of solid particles, following comminution, due to the presence of oil in the sample. For Bolus formation, we used rheology to measure the hydration rate of the particles in aqueous fluid (using a physiological buffer) as the system underwent a transition from that of a dispersion of un-hydrated particles to a soft solid. For the Swallow phase, we used a rheometer-based technique, but in this case, we measured the pseudo-steady state (i.e., fully hydrated) oscillatory and yielding properties, as well as the narrow gap shear

behavior. For the final After-feel phase, we measured the friction between particles and oral surfaces using a combination of tribology and granulation.

We used the *in vitro* oral processing framework to probe how a sample changed after its removal from the package up to a simulated swallow point and measured how changes in formulation manifested as measurable differences during the various phases within *in vitro* oral processing. A key strength of this *in vitro* framework is that it provides context for *in vivo* investigations and sensory studies: with this we can separate effects due to changes in formulation from changes due to inherent biological variability (e.g., saliva flow rate, composition). An additional strength is that comminution and bolus formation occur simultaneously *in vivo*, but we can separate the two *in vitro*. By exploiting these strengths, we are thus able to more rationally approach food product development.

In this paper, we discuss each part of the *in vitro* oral processing framework by providing a short description of the underlying physics and offering examples of a real product and product enhancement, specifically how we can build back texture attributes lost when reformulating reduced oil starch-based snack foods. By probing for the pertinent material properties at relevant length scales, based on the unit operations we introduced in 2013¹⁶, we determine the role of oil during each stage of oral processing. This insight was used to tailor the wetting and lubrication properties of a seasoning oil, which is a topical coating applied to a low fat potato chip at an amount of 0.5% w/w seasoning oil. The success of this tailored solution was assessed in a blind taste test that compared the low fat chip with the topical coating against both a negative control (unaltered low fat potato chip) and a positive control (full fat potato chip). The samples were ranked for oiliness perception.

First Bite

For semisolid and solid snack foods at first bite, we expect a minimal effect on the food from physiological factors, and the sensory experience of the food together with associated sensory processing are closely related to the food's intact properties.

Macroscale deformation techniques that probe aggregate responses (e.g., compression/shear testing) are used to measure forces²² and auditory signals²³. The more foundational mechanical testing methods (e.g., three-point bend²⁴) are predicated on analyzing

data in the context of fundamental physics principles. In this way, force-strain measurements provide details about the elastic modulus at a low degree of deformation, which can then be related to the physical structure, and how that structure fractures and fails at high deformation. The process of rational design then turns to identifying the molecules or manufacturing processes that provide those important physical structures, finding suitable materials or processes to replace the original ones and finally testing the fracture and failure behavior. Sensory testing can then be performed to determine if the sensory experience has also been retained or is acceptable.

Though more development is needed, researchers have made progress measuring relevant mechanical properties and relating those to sensory properties^{24, 25}. We would like to stress, however, the limitations. Vincent and co-workers have made use of Weibull's statistical approach²⁶, a *phenomenological* model that does more to alleviate our inability to manufacture and measure without replication errors. In one respect, the method of Weibull, as applied by Vincent, does provide [mathematical] parameters that are, in a sense, indicative of the underlying physical properties. These parameters can then be compared to sensory texture terms. However, the rational design of new foods requires that we know the food property origin of the relevant sensory responses that we can then influence, either by adding structuring agents like fillers or otherwise altering the mechanical properties. For example, knowing the fracture response of potato cells in a fried chip is useful, but when we make the move to baked chips we are better served by controlling the microstructure rather than simply knowing the calculated statistical parameters. In other words, by determining which changes in food properties impact the sensory characteristics allows us to extrapolate our model further than is possible with a statistical model.

[Figure 2 here]

In figure 2, we show mechanical property data for several different potato chip types. Figure 2.a shows the maximum force at break for thin-cut potato chips with systematic changes in oil content, measured using a puncture probe. The lowest fat and highest fat PC have significantly different maximum force at break values, though we cannot clearly attribute this difference to any particular physical structure. Figure 2.b shows the Elastic Modulus and the

maximum force at break for several commercial PC samples as well as the low fat and full fat PC samples from figure 2.a.

Comminution

The purpose of the initial sequence of chewing solid foods (e.g., potato chips, cookies, crackers) is to reduce the resulting particles to a size (comminution) suitable for swallowing. In addition and during comminution, saliva responds to the food: its flow rate and composition alter with mechanical action, taste and aroma, and the salivary film coating that lubricates and protects oral surfaces may interact with the solid food components. Despite the strong foundation in relating mechanical properties and “first bite” behaviors, there are many opportunities in relating the breakdown of, particularly, solid foods to the mechanical properties and microstructure. Researchers such as Ashby and Gibson^{27, 28}, Vickers²⁹, Vincent³⁰ and Peleg^{31, 32} have measured an assortment of mechanical properties that are relevant to comminution. The literature highlights active development in simulated chewing techniques and advances in our understanding of the physical processes and sensory perceptions associated with this phase of oral processing³³.

Granulation

As solid foods break down in the mouth, we hypothesize that saliva (or released oils or water when those liquids are present in the sample) may induce aggregation amongst the particles. The clustering process of particles binding together under the action of some liquid is called Granulation³⁴, which is well known by engineers in the powder and pharmaceutical industries. One approach (figure 3) we have used is to investigate the granulation process of comminuted foods in dry (i.e., no added water) conditions using a sieve shaker to promote aggregation, a standard digital scanner to collect images and a custom image analysis program written in MATLAB (an example of the output is shown in figure 3.a.). Figure 3.a. shows the particle size distribution measured using this technique for low fat (22.9% w/w oil), low fat with added polyglycerol polyricinoleate (PGPR) in oil (3 grams and 6 grams added PGPR/oil with varying PGPR weight fraction) and full fat (34% w/w oil) comminuted potato chips. The oil dissipates energy via internal friction, so we hypothesized that potato chips coated with more

oil would result in larger particle agglomerates compared to chips coated with less oil. The mean particle size was larger for the higher fat content chips, which confirmed our hypothesis.

[Figure 3 here]

Another hypothesis we examined was if by reducing the fat content on potato chips and incorporating a minimal amount of a surface active component (e.g., PGPR), we could mimic a full fat potato chip³⁵. The main theory underlying this hypothesis was that a surface-active component could influence friction between particles and oral surfaces by adsorbing to oral surfaces or particle surfaces, which could compensate for the role oil plays (wherein it acts as a viscous lubricant between the chip particles and oral surface). However, a separate hypothesis was that a surface active component might also influence the granulation process. Thus, we also used our granulation experiment to investigate how the fraction of PGPR in oil affected the mean particle size. Figure 3.e. shows the results of that investigation. We did not see a clear additional effect on the particle agglomeration by adding increasing amounts of PGPR in place of oil. Granulation science shows substantial promise for *in vitro* oral processing research, though further development is needed.

We used the Ring Shear Tester (RST)³⁶⁻³⁸ to measure the internal friction of dry (i.e., without added water) potato chips under an applied load and shear stress. The RST's versatility is due to its control of the normal load applied prior to and during shear testing, which should be particularly useful for investigating compaction and tooth packing. We also envision using the RST to test particle-particle friction under controlled moisture conditions. The RST has found limited use in similar oral processing focused research^{38, 39}, and we recently showed that measurements can be directly related to sensory texture/mouthfeel attributes that arise during mastication³⁸. We performed experiments, detailed here, to examine the impact of oil content on the friction between dry potato chip particles: an increased oil content corresponded to decreased cohesion between particles and thus an increased flowability. The flowability factor, ff_c ,—which provides a measure of how easily a compacted solid will flow and is defined as the ratio of consolidation stress and unconfined yield strength—was measured using a 2000Pa consolidation stress with three repeats for each oil content: $ff_c=1.5$ for 22.9% w/w oil, $ff_c=1.7$ for 29% w/w oil and $ff_c=2.4$ for 34% w/w oil.

When two surfaces are sliding against each other, the presence of a fluid film enables lubrication. As the surface film thickness decreases, the friction force can increase due to asperities from the rough particle surface penetrating the surface film. We suspect that for full fat PCs, there is a thick oil coating on the PC particles that enables lubrication between the particles and oral surface. However for the low fat PC, the oil layer is below the roughness scale of the particles and increased friction occurs as a result. This may explain why in sensory testing low fat PCs generally feel less oily in the mouth than full fat PCs. We now have the means in which to investigate the lubrication between PC particles and a basis for comparison when developing ways to mitigate the negative mouth feeling associated with low fat PCs.

In our potato chip example, sensory testing was performed and the participants were asked to rank three chips from the least oily to the oiliest, where the chips ranked were a low fat negative control (22.9% w/w oil | mean rank of oiliness $\approx$ 1.6), a full fat positive control (34% w/w oil | mean rank of oiliness $\approx$ 2.5), and a modified low fat chip (the negative control chip pan coated with 0.5% w/w topical oil comprising 15% w/w PGPR in oil | mean rank of oiliness $\approx$ 2.0). The coated low fat chip was demonstrated to have an intermediate level of perceived oiliness.

Bolus formation

Comminution and hydration may lead to agglomeration of food particles for most foods. Eventually, a soft bolus is formed and the food swallowed. Rheology has been the preferred method to probe properties of the bolus both *in vitro*^{15, 17} and *ex vivo*⁴⁰, and texture analysis has been used on expectorated samples⁴¹. We argue that contemporary research—and future directions—should focus on capturing dynamic rheological properties (e.g., hydration and enzymatic degradation) as these properties should be relatable to temporal sensory measurements, such as Temporal Dominance Sensation (TDS) and Time-intensity (TI) studies. TDS focuses on the dominant sensation arising during oral processing, while TI can be used to track the evolution of certain attributes with time. We further suggest that in addition to simply measuring rheological properties, researchers should elucidate the structure-function relationships^{15, 17} to allow for more rational product development.

Traditional rheological measurements focus on bulk properties (e.g., viscosity, elastic and loss moduli) which have been shown to correlate well with certain sensory assessments. Moving forward, we believe that any experimental toolbox should comprise techniques that probe properties from the macroscale to the nanoscale. Along these lines, we have developed techniques based on gap dependent rheology and tribology¹⁶.

[Figure 4 here]

Gap-dependent Rheology: Upon swallowing, the bolus is sheared between two surfaces that quickly probe the entrained bolus at the length-scale of the largest particle. Studies have focused on perceiving particles of different sizes, hardness etc. but neglect that macromolecules can adsorb to oral surfaces or that a liquid phase can preferentially coat a surface thereby forming a slip layer. As a consequence, squeeze and shear between oral surfaces is not only affected by particle modulus—film formation by adsorbed macromolecules, oil release, hydration of starch by water can all additionally effect the rheological response under confined conditions for similarly oily starch-based foods.

To bridge the gap between rheology and tribology, several researchers have begun to explore how changes in gap size affect the rheological properties of fluids and soft solids. Rheological measurements at narrow gaps (100 nm to 100 micrometers) reveal two key system attributes: the rheology at narrow gaps is strongly dependent on the local mechanics of the dispersed phase (e.g., particle modulus, interfacial tension of droplets) and the interaction between these and the surface⁴². This is potentially important for certain sensory attributes like grittiness. Grittiness is a common mouthfeel perception when hard particulates are present in a food, while in contrast soft particles of the same size may not be noticeable. From a rheological point of view, the rheology of hard and soft non-interacting particles are the same for low phase volumes (< 40%)⁴³. The perception of grittiness implies that the relevant in-mouth gap between oral surfaces is on the order of the hard particle diameter. Burbidge et al⁴⁴ discussed the perception of smoothness and grittiness in the human mouth and drew some conclusions about the likely interactions between in-mouth hydrodynamics and stimulation of biological mechanoreceptors.

We feel that gap-dependent rheology is a novel tool for studying interactions between a food bolus and shearing surfaces without the inherent difficulties of making tribological measurements in the presence of particles. Therefore, future work should focus on developing gap-dependent rheology, namely building capabilities, and then investigating things like slip of multi-phased soft materials, phase separation, homogenization and how these dynamics potentially influence sensory perception.

We have begun work along these lines and offer here preliminary data for a simulated PC bolus confined to narrow gaps. Figure 4.a. shows transient data for an *in vitro* simulated potato chip bolus measured with a vane tool and confined between two parallel plates. Using a controlled stress, the normal force response was recorded. What we found is that once the material yields, the stress homogenizes the bolus and begins to shear apart the larger particles. This in turn results in a noticeable increase in the measured normal force (when using parallel plates). We also observed migration of the oil phase to the shearing surfaces. These findings motivate future measurements at large deformations, in contrast to more traditional highly controlled, small deformation, oscillatory shear rheological techniques. While those small shear techniques reveal insights about structure-function relationships, they do not inform on how a sample will breakdown, mix, homogenize or destabilize under the conditions most likely to exist between oral surfaces during the latter stages of oral processing.

We would like to note that method development was necessary because, at the gaps used, the errors from edge fracture and slip become noticeable⁴⁵. To serve as a more common point of reference, we also sheared a simulated PC bolus using the vane tool (shown in figure 4.a.). In this latter case, the shear viscosity curve exhibits a typical yield point.

Tribology

Tribology is the study of friction and lubrication between contacting surfaces in relative motion. It is established that friction and lubrication play an important role during food oral processing²⁰, and their study captures the surface related physics contributing to a number of mouthfeel-related sensory percepts⁴⁶, such as astringency⁶. Extensive detail on tribology fundamentals and food lubrication can be found in a review on 'oral tribology'⁴⁷ while a

discussion on the emergence of tribology as a contributing discipline for understanding oral processing, texture and mouthfeel is presented in a paper by Chen and Stokes⁴⁸.

The fundamental approach to study the oral tribology of foods is to use well-defined substrates and configurations and model fluids that provide insights into consumer product formulations⁴⁹. The ball-on-disk in a mixed rolling and sliding contact using at least one PDMS (polydimethylsiloxane) substrate is the most widely used set up for such studies. The PDMS is used because it has a low modulus (ca. 2.5 MPa), can be modified chemically to be hydrophobic or hydrophilic and offers a simple platform to control surface roughness⁵⁰. In more advanced bio-mimetic applications, PDMS surfaces can be micro-engineered to have a specific topology⁵¹ to emulate the tongue surface. Finally, PDMS's surface functionality can be modified by adsorbing macromolecules such as salivary proteins including mucin and whole mouth saliva⁶,⁵²⁻⁵⁴. It is also relatively easy to create films of PDMS that can be used in complimentary techniques such as QCM-D (Quartz Crystal Microbalance with Dissipation monitoring), ellipsometry and AFM (Atomic Force Microscopy) to study adsorption and interactions with food components⁵⁵⁻⁵⁷. Film thickness measurements are possible for a soft ball and disk configuration^{58, 59}, Raman spectroscopy⁶⁰ can be used, and the film thickness can be predicted numerically for Newtonian fluids in the hydrodynamic regime⁶¹.

There is a substantial body of literature focused on the driving mechanisms of the lubrication properties of food and beverage formulations and in particular identifying the role of various food ingredients. By using the tribometer as a controlled environment, guidelines can be formulated with respect to tribological contacts in the mouth. The dynamic nature of a tribological contact enables accessing fluid rheological behavior at high shear rates (10^5 s^{-1} and above) due to the small gaps between rubbing surfaces (typically on the order of a few micrometers). Complex fluids, such as emulsions, can undergo a transformation due to the high shear/high pressure nature of the rubbing contact⁶². Large particles ($D \gg$ contact roughness) may build up around the inlet zone and thus be excluded from being entrained into the contact. This leads to dynamic separation of a complex fluid into particle-rich and particle-depleted phases, with the latter dominating lubrication behavior due to its preferential entrainment into a soft tribological contact⁶³. Larger fluid droplets have the tendency of coalescing within the

contact and promoting the coating of rubbing surfaces. De Vicente et al.⁶⁴ have shown that the viscosity ratio between oil and aqueous phases determines which phase ends up dominating the tribological contact. At high values of the viscosity ratio (>5.8 , i.e., the dispersed oil is at least 5.8 times more viscous than aqueous phase) the oil phase controls the lubricant film formation and friction. Accordingly, at lower values of the viscosity ratio lubricating film formation is dominated by the aqueous phase.

In addition, tribological behavior will depend on wetting properties of the lubricant fluids and its constituents, as well as on adsorption of surfactants and polymers on the PDMS surface. The presence of adsorbed moieties can determine the transition from the elastohydrodynamic regime (viscosity dominated) to the mixed regime (asperity contact dominated). These moieties may also have a profound effect on the friction coefficient in the boundary regime^{10, 65}.

A MTM2 tribometer (Mini-traction Machine 2 (MTM2), PCS Instruments) was used to measure the friction between two soft solid surfaces (a disk and a ball, referred to as a tribopair and manufactured using a silicone elastomer kit (Sylgard 184, Dow Corning)) moving relative to each other. Between these two solid surfaces is the lubricating liquid (e.g., sunflower oil). Friction can also be measured with saliva pre-adsorbed to the PDMS disk. The technique detailed here was similar to that used by Bongaerts et al⁶⁵.

[Figure 5 here]

A tribological study was performed on the lubrication properties of PGPR in oil as well as PGPR/oil with saliva in a soft contact. Figure 5.a. shows the friction coefficient for sunflower oil and a 1% w/w solution of PGPR in high oleic sunflower oil between PDMS-PDMS contacts. At the concentration tested, PGPR has no significant effect on the lubrication properties of the oil in the mixed to elastohydrodynamic regime; this is in contrast to water-soluble non-ionic surfactants (e.g., Graca et al⁶⁶) that enhance the lubrication properties of water and allow a significantly lower friction coefficient to be achieved at the junction between the mixed and hydrodynamic regimes due to adsorption of surfactant molecules onto hydrophobic surfaces. The study results suggest that PGPR is not associating with the hydrophobic surface, which we hypothesize is due to a strong affinity of oil to the hydrophobic PDMS surfaces.

For PC, the key hypothesis is that the oil phase separates and preferentially migrates towards the hydrophobic surfaces, thus providing a lubricating layer at the oral interface. Essentially, oil is squeezed out of the food material and forms a film over (or in place of) the saliva coating on oral surfaces. This hypothesis is consistent with full fat foods—which have a greater volume of oil—providing greater surface coverage and hence being more effective at dominating lubrication between oral surfaces. By adding a surface active agent, like PGPR or lecithin, we can improve the wetting characteristics of the oil phase to promote wetting and spreading on the saliva-coated oral surfaces. This has been achieved by modulating the friction coefficient in the boundary regime of a model seasoning oil and investigating the lubricating properties of oil between PDMS surfaces³ in conjunction with adsorbed saliva films (figure 5). The oil's lubricating properties were significantly reduced in the boundary regime through incorporation of food emulsifiers, i.e., PGPR (figure 5) and lecithins³⁵.

To better model in-mouth lubrication, a film of saliva was pre-adsorbed to the PDMS disk. The friction was then measured over time by holding the ball speed and disk speed constant following exposure to either oil or a 15% w/w PGPR/oil solution. The results (figure 5.b.) show that upon addition of the oil or PGPR/oil, the friction coefficient decreases with time until a minimum is reached, at which point there is a steady increase over time. Based on the results, we conclude that the oil or PGPR/oil pushes the system out of the boundary regime (which occurs when only saliva is present) and into the mixed regime due to the increase in viscosity of the lubricant system (i.e., oil or PGPR/oil viscosity). However, by adding PGPR to the seasoning oil, intended to be applied to a low fat PC at a 0.5% w/w level of PGPR/oil, we were able to modulate the friction coefficient in the boundary regime to a greater extent, as can be seen from the lower value of steady-state friction coefficient for the PGPR/oil system compared to pure oil³⁵. This behavior may suggest that PGPR interacts with saliva, but extensive testing is needed to validate the result.

Sensory

Due to the multimodal nature of sensory, it is challenging to correlate single texture attributes against individual analytical methods for heterogeneous samples or after first bite.

Therefore, new sensory techniques need to be investigated, like Temporal Dominance of Sensations (TDS)¹². We can also start with a negative control (like low fat PC), compare that to a positive control (like full fat PC) and determine at what length scales these are different. We then modulate the response at a specific length scale, in our case using tribology (lubrication properties) to capture the response. For potato chips, we made a low fat PC pan coated with a 0.5% w/w PGPR seasoning oil, based on our observations that PGPR impacted the boundary friction between PDMS contacts with adsorbed saliva.

In order to validate the improved mouthfeel attributes for low fat PC, we recruited 10 panelists that were able to accurately discriminate low fat and full fat PC. We then asked the panelists to rank the PC samples (low fat, PGPR modified seasoning oil PC, and full fat PC) for oiliness perception. The panelist were able to accurately discriminate PC samples for oil content and the PGPR modified PC sample moved towards the positive control, building back 50% of the oiliness perception, even though only 0.5% w/w of the modified oil was added.

Sensory trials have long been used to identify apparent or subtly different percepts for different foods and food formulations as part of an effort to ultimately determine consumer “liking.” Whereas the *in vitro* unit operations framework highlighted above is useful for explaining why changes in food formulation lead to changes in static and dynamic physical properties, sensory trials are used to identify when changes to formulation result in changes to sensory perception. The “rational design” methodology emerges from the coupling of these two approaches.

The unit operation framework combined with a set of multi-scale physical techniques was utilized to disentangle processes occurring during oral processing of potato chips. We illustrate its utility by designing a lower fat potato chip with improved sensory score for oiliness by focusing on the role of oil and using technologies to enhance that role at lower amounts.

The innovative approach includes the utilization of measurement techniques as a complimentary—and in some instances the only—tool to evaluate the different stages of oral processing from the first bite to bolus formation and swallowing. In particular, we show that comminution and granulation can be evaluated as separate processes. We argue that insights

generated from these measurements provide guidance when crafting hypotheses for material response under conditions of oral processing.

To rationally design next generation ingredients and foods, we argue that research should focus more on the underlying physics as manufacturers are in need of design rules to assist in rational development approaches for next generation processed foods, such as low fat snack foods. To this end, we developed an *in vitro* oral processing framework, and we have used insights gleaned to guide product development of a reformulated low fat potato chip with enhanced mouthfeel. Finally, we validated the importance of the manipulated variables to the sensory perception using an experimental design containing both positive and negative controls.

In this way, we move beyond mere correlations to a more rational approach whereby links between sensory percepts and physical measurements are based on gaining structural insights that define the physical behaviour of a potato chip with a range of different oil contents.

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Figure 1. (a) Cartoon listing the unit operations that make up *in vitro* oral processing, up to the point of swallow, and some of the experimental techniques used to investigate each operation.

(b) A hypothetical curve for oral processing of full fat potato chips in the context of the Hutchings & Lillford model, with profile curves shown for the Structure-Time plane and the Lubrication-Time plane as well as one profile curve for a low fat potato chip. The beginning of each phase (e.g., “First Bite”, Comminution) is represented by ● and the process is represented by —. The — represent the projection of the curve onto the Structure-Time or Lubrication-Time planes. Hypothetical projections for a low fat chip are shown as dotted lines ----.

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Figure 2. (a) Maximum force, $F_{\max}$, graphed versus oil content on thin-cut PC, as measured via the puncture test. The oil content was systematically altered by starting with full fat PC then removing oil. There is a statistical difference between the lowest fat and highest fat PC; the other pairings are not statistically different. (b) Elastic modulus, E , and maximum force, $F_{\max}$, graphed versus potato chip type, as measured via the three-point bend test. The Thins, Kettle and Full fat PC were all commercially available; the low fat and full fat samples are the same as the samples shown in (a). The Elastic Moduli are not statistically different.

Figure 3. (a) Percent of total granules graphed versus granule area for comminuted low fat (no additional coating, an additional oil coating and an additional PGPR/oil coating) and full fat PC. The additional oil and PGPR/oil coatings were added to bring the low fat chip (22.9% w/w oil) to a fat content similar to the full fat chip (i.e., near 34% w/w oil). (b) Image of granulated comminuted low fat PC. (c) Processed image of granulated comminuted PC, colored by granule area. (e) Mean of log(Area) graphed versus weight fraction of oil coating added to low fat PC.

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Figure 4. (a) Shear viscosity, η , and normal force, F_N , graphed versus time for an *in vitro* simulated PC bolus probed at narrow gap between parallel plates with attached emory paper and sheared by a vane tool. (b/c) Images of the *in vitro* simulated PC bolus after shearing between parallel plates with attached emory paper.

Figure 5. Soft contact, i.e., PDMS-PDMS contacts, tribology. (a) Sunflower oil and a 1% w/w PGPR in sunflower oil solution. The friction coefficient is graphed versus the entrainment speed. Both liquids were in the hydrodynamic and mixed regimes, for the conditions tested, and the PGPR does not make a significant impact on the friction coefficient. (b) Sunflower oil and a 15% w/w PGPR in sunflower oil solution in the presence of an adsorbed layer of saliva ($n=1$, and zero time corresponds to the friction of an adsorbed saliva film). The friction coefficient is graphed against time showing the transient friction and, potentially, interactions between PGPR and saliva (further testing is required). A velocity of 9 mm/s was used for the transient tests. A 1N normal load and SRR of 50% were used for all tests.

660 TOC Graphic

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