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A new biomimetic set-up to understand the role of the kinematic, mechanical, and surface characteristics of the tongue in food oral tribological studies

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Abstract

A biomimetic tribological set-up was developed to better integrate physiological characteristics in oral friction studies. Polyvinyl alcohol was used to design tongue-mimicking samples (TMSs) with controlled bulk rigidity and surface roughness. The set-up allowed normal stresses and sequences of shearing motion to be applied between a TMS and a rectangular aluminum plate mimicking the hard palate. Cottage cheese with and without suspended microcrystalline cellulose particles of two sizes (small: 15 μm and large: 250 μm) was used as the model food in the experiments, making it possible to introduce heterogeneities well above the perception threshold, which often get excluded in conventional tribology studies.

The feasibility of the set-up was tested by measuring how friction coefficient values were affected by food properties (viscosity, particle presence), TMS properties (surface roughness, bulk rigidity), and operational parameters (normal stress, shearing velocity). The measurements with the set-up were found to be repeatable, confirming its reliability. Particle presence led to increases in friction coefficient values, while food viscosity showed less of an influence, comparatively. Increases in the surface roughness and bulk rigidity of the TMSs led to a pronounced augmentation of the friction coefficient values. The friction coefficient values showed dependence on normal stress, increase in normal stress led to significant decrease in friction. Moreover, friction notably increased between the lowest and highest shearing velocities. In conclusion, this set-up proved to be efficient and reliable in measuring friction coefficient values and variation, paving the way for a better understanding of oral tribology and its dynamic nature.

Keywords

Soft tribology, Oral processing, Friction coefficient, Biomimetic set-up

1. Introduction

The quest to understand and model consumers' sensorial perceptions of food is now of paramount interest in efforts to develop products for target populations. Food texture perception is an important aspect of the overall sensorial appreciation of food. This physiological process has recently gained the attention of the scientific community, and especially that of researchers seeking to elucidate the mechanisms behind perceptions like mouth feel and astringency. Soft tribology has emerged as a prime technique for investigating friction phenomena between soft oral surfaces and food during oral processing. There is a growing body of research dedicated to these oral tribological phenomena that describes the dependence of friction forces on lubrication and surface properties and the resulting impact on different sensorial perceptions pertaining to texture and mouth feel (Krop, Hetherington, Holmes, Miquel, & Sarkar, 2019; Liu, Stieger, van der Linden, & van de Velde, 2015; Stokes, Boehm, & Baier, 2013). In a recent review, Panouillé, Saint-Eve, & Souchon (2016) summarized the instrumental and sensorial methods regularly employed to understand food perceptions. The authors underscored that linking physical measurements (mechanical, rheological, and tribological) to sensorial assessment methodologies can be difficult, mainly due to challenge of replicating *in vivo* conditions. Rudge, Scholten, & Dijkman (2019) have further detailed the challenges tied to relating tribological measurements and the perceived textural attributes of food that arise from the complexity of the oral cavity (contact mechanisms, motions, surface roughness, rigidity, and lubrication).

Linking tribological results with sensory perceptions is also arduous because of the adaptability constraints of commercially available instruments and the inability of contact mechanisms and surface properties to better mimic real oral physiological conditions. The limited selection of contact geometry, (e.g., ball-on-disc, pin-on-disc), movements (linear or rotating), and surfaces is highly restricting. It is also important to point out that, in most of the oral tribology studies where a small contact area is applied, the suspended heterogeneities (closer to the threshold of particle perception) in semisolid or aqueous foods are often ignored. These constraints have been highlighted by Pradal & Stokes (2016), who rightly argue that there is a need to choose a "physiologically relevant tribological system" in order to apply tribology as a measure for predicting texture perception. Many recent studies have therefore tried employing custom-built tribological set-ups (Chen, Liu, & Prakash, 2014; Mo, Chen, & Wang, 2019), which are mainly designed to allow for greater flexibility in

adapting motion, normal stress, shearing velocity, and contact geometry as needed. Therefore, in-house development or customization of tribometers to mimic in-mouth movements could be a solution (Rudge et al., 2019).

Furthermore, when looking for suitable oral surface mimics, it should be kept in mind that the human tongue is a complex muscular organ with a peculiar surface topology. Its dorsal surface bears several types of papillae that play a major role in mechanical interactions with food. There are four types of papillae on the surface of the tongue: filiform, fungiform, foliate, and circumvallate (Jung, Akita, & Kim, 2004; Ranc, Servais, Chauvy, Debaud, & Mischler, 2006). The filiform papillae are present at high densities across the tongue's surface, greatly contributing to its overall roughness. The human tongue is also a complex biological tissue from a mechanical perspective. Napadow, Chen, Wedeen, & Gilbert (1999) have described the tongue as a hydrostatic organ that keeps its volume constant during compression or motion but that simultaneously changes its rigidity. The shear elastic modulus of the human tongue has been measured using several techniques: mechanical indentation ($G = 0.38$ kPa) (Gerard, Ohayon, Luboz, Perrier, & Payan, 2005), mechanical compression (Ishihara et al., 2013), and magnetic resonance elastography ($G = 2.67$ kPa) (Cheng, Gandevia, Green, Sinkus, & Bilston, 2011). The tongue's stiffness, however, changes significantly between its "rest" state ($E = 12.2 \pm 4.2$ kPa) and its "contracted" state ($E = 122.5 \pm 58.5$ kPa) (Ishihara et al., 2013).

Peculiarities of the tongue tissue such as rigidity and surface roughness might have a complex and synergistic role in oral tribology; they must therefore be well accounted for in experimental set-ups. Attempts have been made to recreate real physiological parameters as best as possible by using biological tongue tissues or polymer surfaces that can mimic the wettability and deformability of the tongue (Carpenter et al., 2019; Dresselhuis, de Hoog, Cohen Stuart, & van Aken, 2008). However, there are some constraints associated with these novel surfaces as well. Once biopsied, biological tissues rapidly lose their mechanical properties, making it difficult to preserve the tissue's surface profile and rigidity. Artificial surfaces, such as those made with polydimethylsiloxane (PDMS), need to be carefully modified to properly replicate surface roughness, rigidity, and wettability.

In this study, we present a custom-built tribological set-up with the aim of better integrating the surface, mechanical, and kinematic characteristics of the tongue. The greater objective is to create a set-up that can enhance our understanding of the changes in

friction forces over time during the oral processing of food. The set-up was designed to have a large degree of contact in tongue-palate geometry, thus resembling real oral anatomy, and to provide flexibility in terms of shearing velocity and displacement. Also, a novel tongue-mimicking sample (TMS hereafter) made of a polyvinyl alcohol (PVA) hydrogel was used. PVA is a water-soluble synthetic polymer that is well known for its application in biomedical engineering, namely for developing artificial soft tissues and mimicking oral mucosa (Chatelin et al., 2014; Fromageau et al., 2007; Gennisson et al., 2007; Jiang, Liu, & Feng, 2011; Mamada, Fridrici, Kosukegawa, Kapsa, & Ohta, 2011). The rigidity of the hydrogels made from PVA can also be controlled by varying the number and the kinetics of freezing and thawing cycles. This ability to customize the rigidity and imprintability of the surface roughness profiles of hydrogels made PVA a suitable fit for our study. To investigate the feasibility of this new set-up, cottage cheese with or without suspended cellulose particles was used as a model food. It allowed the explicit incorporation of microscale heterogeneities into the food system and an analysis of how friction was affected by normal stress, shearing velocity, TMS roughness, and TMS rigidity.

2. Materials and methods

2.1. Model food system

Cottage cheese (Calin extra [0% fat], Yoplait, Boulogne-Billancourt, France) with and without suspended cellulose particles (5% w/w; Vivapur, JRS Pharmaceuticals, Rosenberg, Germany) was used as a model food. The median sizes of the two sets of cellulose particles used in this study were 15 μm (Vivapur 105) and 250 μm (Vivapur 200); in this article, they are hereafter referred to as “small” and “large” particles, respectively. The choice of non-fat cottage cheese as the carrier medium stemmed from the fact that, in one of our preliminary sensory studies, panelists were able to well rank the levels of added heterogeneities in this particular medium (Tournier, Poette, Rachidi, Septier, Martin, & Feron, 2018). Furthermore, the cottage cheese was used in both “undiluted” and “diluted” forms. The diluted cottage cheese was mixed with water (50% w/w). The 50% dilution factor was chosen to mimic the dilution of cottage cheese with saliva when the food is in close proximity to the tongue surface (Brodkorb et al., 2019; Doyennette et al., 2014; Laguna, Farrell, Bryant, Morina, & Sarkar, 2017). Solutions of glucose syrup (Caullet, Erquinghem-Lys, France) made with water were used as Newtonian fluids for rheological and

tribological comparisons; three different concentrations (0%, 49%, and 67% w/w) were employed.

A strict protocol was developed after a series of preliminary tests to ensure that the different model food types had experienced the same mechanical history before being used in the experiments (the tribological and rheological tests). The different model food types were thus prepared in identical quantities (8 g) and in identical containers. Once all the ingredients had been added, the mixtures were subject to magnetic stirring (750 rpm, 20°C) for a period of 30 minutes, just before being used in the different experiments. However, it is important to mention that the stirring did not cause any rheological changes to the system, as confirmed by measuring the viscosity of samples (protocol described below) throughout the course of a complete set of experiments.

For the viscosity measurements of the cottage cheese types, a rheometer (HAAKE RheoStress 600, Thermo Fisher Scientific, Waltham, USA) with parallel-plate geometry ($d = 35 \text{ mm}$) was used to obtain flow curves (at 20 °C, with shear rates between 2 and 450 s^{-1} and a 1 mm operating gap); five replicates were performed. The absence of time dependency of the foods’ rheological properties was also validated by checking the agreement between the flow curves obtained for increasing and decreasing shear rates.

The viscosity values of the water and the glucose solutions were measured using cone-plate geometry ($d = 60 \text{ mm}$, $\alpha = 2$) at 20 °C. The applied shear rate was between 2 to 450 s^{-1} , and an operating gap of 90 μm was employed. Due to sensitivity issues, especially at the lower shear rate, only the mean values obtained over 10 s^{-1} were plotted, which assumed that the viscosity of the Newtonian fluids remained independent of the shear rate. The measured mean values were 1.2 mPa.s \pm 0.1, 10.9 mPa.s \pm 0.4, and 52.9 \pm 0.4 mPa.s for the water, the 49% glucose solution, and the 67% glucose solution, respectively. These values are also in accordance with those found in our previous study (Mathieu et al., 2018).

2.2. Development of the bio-mimicking tongue-palate set-up

The development of the bio-mimicking oral tribological set-up aimed to simulate more realistic contact geometry, surface pairing, and shearing motion. The process thus required carefully selecting and assembling commercially available structural parts as well as designing and fabricating tailored parts (Figure 1). These steps are discussed in detail below.

2.2.1. Fabrication of the tongue-mimicking samples

The TMSs (Figure 2a) employed in this study were made from PVA solutions. To begin with, PVA (MW 89,000 - 98,000, 99% hydrolyzed (degree of saponification), Sigma Aldrich, Saint-Louis, USA) was dissolved in ultra-pure water (10% w/w) and then subject to constant magnetic stirring at 80 °C for 2 h. The solution was subsequently cooled to room temperature. Cuboidal molds (80 mm x 45 mm, 25 mm in height) were completely filled with the solution.

To produce rough surfaces, the bottom rectangular side of the molds was covered with a sheet of P40 (grain size = 425µm, ISO/Federation of European Producers of Abrasives) sand paper (Norton, Saint-Gobain, France). This approach was taken to simplify the surface topology for this first feasibility study. The real surface of the human tongue has a complex topography, with asperities whose heights range from 42.5 to 101.4 µm (Uemori, Kakinoki, Karaki, & Kakigawa, 2012); this complexity is difficult to replicate *in vitro*. In this study, two contrasting surface profiles were prepared: one without sand paper (referred to hereafter as “smooth”) and the other one with P40 sand paper (referred to hereafter as “rough”). The molds were then sealed and subjected to cycles of freezing and thawing, which helped to achieve the desired level of rigidity (Fromageau et al., 2007). During each cycle, the TMSs were frozen at -20 °C for 16 h and then thawed at 18°C for 8 h. Finally, the TMSs were unmolded and stored in reverse-osmosis-treated water at room temperature (20°C) for several months. The Young’s moduli of the TMSs were estimated by performing uniaxial compression tests using a texture analyzer (TA.XT plus, Stable Micro System, Surrey, United Kingdom; compression speed: 1 mm/s; strain rate of up to 20%; at least 3 replicates performed). Two types of TMSs were obtained—soft TMSs after 3 cycles (referred to hereafter as “soft”; 50.17 ± 1.46 kPa), and hard TMSs after 5 cycles (referred to hereafter as “hard”; 100.78 ± 2.12 kPa).

2.2.2. Structural elements of the set-up

The device included two linear translation stages (L-511.60AD10, Physik Instrumente (PI), Karlsruhe, Germany) (Figure 1) that were positioned perpendicularly over a worktop (B4560L, Thorlabs, New Jersey, USA) designed to isolate the set-up from external vibrations. The translational stages had a displacement amplitude of 155 mm with an accuracy of 0.05 µm and a minimum relative displacement of 0.488 µm. The maximum displacement speed was 90 mm.s⁻¹. According to the literature, during the oral processing of liquid foods, an average tongue movement speed ranges from 2.1 mm.s⁻¹ to 32.43 mm.s⁻¹ (average 10.34

± 4.92 mm.s⁻¹) (Peng & Miethke, 2000). The chosen translation stages made it possible to reproduce such *in vivo* movements. The set-up also comprised different tailored parts (Volpi S.R.O., Brastislava, Slovakia), including an aluminum plate (rectangular, 45 mm x 25 mm) that was attached to the vertical translational stage and that played the role of the hard palate. This aluminum surface was smooth relative to the surfaces of the TMSs. To control the force applied by the palate, a three-axis force sensor (K3D60a ± 50 N, ME Systeme, Hennigsdorf, Germany) with a measurement range of ± 50 N and an accuracy class of 1% was chosen. The horizontal translation stage on the other side was equipped with a rectangular holder for the model tongue.

2.2.3. Machine-user interface

A LabVIEW (National Instruments, Texas, USA) based interface was also developed to operate the biomimetic set-up. The interface was used to adjust the positioning of the translational stages and to impose specific sequences of motion by programming the stage motor controller (C.884.4DC, 4 channels, Physik Instrumente, Karlsruhe, Germany). The controller supported functions such as linear vector motion, point-to-point motion, and user-definable trajectories. It also served to record operating data related to stage position. In addition, to facilitate the acquisition of force, a bridge module (NI-9237, National Instruments, Texas, USA) was used to provide an efficient sampling rate (50 kS/s/ch).

2.3. Test protocol

In the first step of the test protocol, a TMS was taken out of the water in which it had been stored; excess surface water was gently removed by absorbent paper until no traces of water were seen on the paper. The TMS was then placed into the cavity on the horizontal translation stage. The experiments were performed at room temperature (20° C) because it was hard to match the surface temperature of the TMS to that of the oral cavity in this custom-made set-up. This fact could have had an impact on PVA rigidity, which is temperature sensitive.

In our early experiments, we identified that the results were strongly impacted by the amount and spreading pattern of the food deposited on the surface of the TMS. In this feasibility study, it was necessary to find robust and reproducible experimental conditions to be able to compare products and operating conditions. After a long series of preliminary tests, a protocol was developed and applied very strictly with regards to food deposition and spreading. In each experiment, 0.25 g of the model food was deposited in the form of droplets on the surface of the TMS (see Figure 2b). The

sample was then spread over the TMS using a spatula until an even visual aspect was obtained (see Figure 2c). Once this step was completed, the aluminum plate was brought in contact with the TMS until the target value of the normal load was reached. As a consequence, similar initial conditions of spreading were attained for all the experiments, regardless of the rheological complexity of the food type (e.g., viscosity, yield stress).

Although the set-up was designed for complex sequences of motion, in this study, we investigated a simple protocol based exclusively on the shearing motion of the horizontal stage (along the “x” axis) at constant velocity and a fixed position of the vertical stage (along the “z” axis) (Figure 1). Once the target normal load had been achieved, the experimental sequence was launched. The experimental sequence consisted of four identical cycles of motion. Each cycle was composed of a 10 mm displacement of the horizontal plate in the “x” axis at a set velocity, a 1.5 s pause, a backward movement at the same velocity to return to the starting point, and another 1.5 s pause. It was necessary to incorporate a 1.5 s pause to separate the forward and backward movements but also to investigate the relaxation phenomena that may occur with these soft surfaces. At the end of the experimental sequence, the TMS was washed carefully with water to remove any residual food from the surface.

The experiments were performed with different applied normal loads (5, 10, 15, and 20 N with a shearing velocity of 10 mm/s) and different shearing velocities (5, 10, 20, and 30 mm/s at a normal load of 10 N). The normal load values were divided by the palate’s surface area in contact with the TMS to convert them into normal stress values (range of 4.5 kPa to 18 kPa). The choice of these normal stress values was made keeping in mind the maximum isometric tongue pressure (50 kPa on average) reported by Alsanei, Chen, & Ding (2015). However, as this study employed a semisolid food matrix, which does not require high levels of tongue contraction, the chosen values were deliberately kept low when compared to those reported in the above-mentioned article.

2.4. Data processing and set-up validation

The raw force data (tangential and normal) obtained from the sensor were run through a low-pass filter (frequency threshold: 100-Hz) to improve the signal-to-noise ratio while respecting the sensor’s response time. Then, the filtered force values and the horizontal plate displacement data for each experiment were fed into a custom-built MATLAB program (The MathWorks, Massachusetts, USA). For each experiment, the four cycles (forward and backward) of the movement sequence were studied. The program made it possible

to visualize the variation in normal force and tangential force throughout the sequence of motion.

For each cycle, friction coefficient values were quantified by synchronizing the following data (represented in two plots; Figure 3a): (i) the position of the horizontal plate (the one holding the TMS) over time and (ii) the ratio of tangential force (F_T) to normal force (F_N) over time. With the stage displacement data, time windows (0.3 s) before the movement stopped (marked as 1 and 2 for the first motion cycle, in Figure 3b) were isolated. These time windows were chosen to be in the steady domain of the variation in friction coefficient values. Then, to obtain an overall friction coefficient value for one cycle, the values of the F_T/F_N ratio (for time windows 1 and 2) were averaged over each cycle. The obtained friction coefficient discussed in this study thus does not take into consideration the potential differences between forward and backward phases. All the friction measurements were estimated using at least six replicates.

Statistical tests were performed using XLSTAT (Addinsoft, Paris, France) to determine whether significant differences existed among treatments. T-tests were used when the measurements were normally distributed, and Kruskal-Wallis tests were used when they were not. Multiple comparison tests were performed to identify which groups differed significantly. The alpha level for the statistical tests was 0.05.

3. Results and discussion

The feasibility, reliability and robustness of the set-up presented in this study were tested by measuring how the friction coefficient values were affected by changes in food properties (viscosity, particle presence), TMS properties (surface roughness, bulk rigidity) and operational parameters (normal stress, shearing velocity).

3.1. Role of food matrix viscosity and heterogeneity

When surfaces are lubricated, as in the oral cavity, friction phenomena greatly depend on the properties of the lubricant (saliva or the food itself). The Stribeck curve shows that lubricant viscosity is one of the important factors governing friction (Chen & Stokes, 2012). However, in the case of a food system, the matrix is more complex because it contains heterogeneities that, in turn, impact the overall friction mechanism. Therefore with this developed set-up with parallel and planar surfaces, it was of utmost importance to investigate how friction forces at the interface were affected by the synergistic role of food viscosity and heterogeneity.

First, viscosity flow curves were studied for the different cottage cheese types (diluted or undiluted; with or without particles; Figure 4). As expected, all the cottage cheeses showed shear thinning responses with increases in shear rate, confirming their non-Newtonian behavior. Also, the undiluted cottage cheese displayed much higher viscosity than did the diluted cottage cheese throughout the experiments. The presence of particles in both the diluted and undiluted cottage cheeses led to an increase in viscosity. However, particle size did not seem to have any impact (given the overlap in standard deviation). Moreover, diluting the cottage cheese had a much more pronounced effect on viscosity than did incorporating suspended particles of any size. It should also be noted that, even when shearing took place, the mean viscosity of the undiluted cottage cheese (both with/without particles) remained far above the mean viscosity of the glucose solutions (plotted as a reference gray line). However, the diluted cottage cheese (without particles) displayed a drop in viscosity at lower shear rate ($< 10 \text{ s}^{-1}$), matching the mean viscosity of the 67% glucose solution; it further declined at high shear rate, reaching a mean viscosity comparable to that of the 49% glucose solution. A similar trend was seen for the diluted cottage cheese with particles, although its mean viscosity remained far above that of the 49% glucose solution.

Given the confirmation of the distinct rheological behaviors of the cottage cheese types, tongue-palate shearing tests were performed on rough and soft TMSs to investigate the friction behavior of the tribological system. For the friction measurements, normal stress and shearing velocity were fixed at 9 kPa and 10 mm/s, respectively. Mean friction coefficient values were obtained for the glucose solutions (Newtonian fluids; Figure 5a) and the cottage cheese types (non-Newtonian fluids; Figure 5b). The friction coefficient values of the three glucose solutions were not significantly different; the solutions did, however, differ in viscosity. The cottage cheese types also displayed significant differences in viscosity. In contrast, there was no significant difference in the friction coefficient values of the diluted versus undiluted cottage cheese. However, relating friction coefficient and viscosity values is difficult in the case of non-Newtonian fluids, as the gap between the tribo-pair in the set-up changes over the course of shearing, making it impossible to accurately estimate the corresponding value of the shear rate.

Interestingly, the presence of particles in the cottage cheese clearly had a significant impact on the friction coefficient values and proved to be a key governing factor (independent of the impact of particle presence on cottage cheese viscosity). Water absorption by the

particles (and the resulting changes in the free water content of the cottage cheese) could hypothetically have explained the differences in lubricity among cottage cheese models. However, our results provide little support for this hypothesis (Figure 5b). In the cottage cheese without particles, dilution barely affected the lubrication properties even with the drastic drop in viscosity (similar friction coefficient values). According to the particle supplier, the maximum water absorption capacity of the microcrystalline cellulose particles used in this study is less than 2.7 g/100 g. Moreover, their concentration in the cottage cheese types was only 5% (w/w). As a consequence, the ability of these particles to absorb water from the cottage cheese likely had negligible effects in comparison to the dilution treatment.

The above results thus demonstrate that the set-up described here can measure steady and repeatable friction forces for model foods that vary in rheological behavior. The friction coefficient values for the undiluted cottage cheese without particles fell within the range of values reported in Laguna et al. (2017), which measured the friction coefficient values of low-fat cream cheese and yogurts that were undiluted or diluted with artificial saliva (1:1 ratio) using a ball-on-disk traction tribometer (PDMS tribo-pair).

3.2. Role of surface roughness

Surface roughness is also known to greatly impact friction mechanisms. Tallian (1967) introduced the parameter Λ , which is defined as the ratio between the thickness of the lubricant film and the roughness of the moving surfaces. This parameter expresses the ability of the lubricant film to prevent direct contact between two surfaces and is directly related to the lubrication regime ($\Lambda > 3$ for elastohydrodynamic and hydrodynamic regimes, $1 < \Lambda < 3$ for mixed lubrication, and $\Lambda < 1$ for boundary lubrication). Nonetheless, the roughness of the tongue remains sparsely accounted for in oral tribological studies. Bongaerts, Fourtouni, & Stokes (2007) rightly pointed out that, in the case of soft surfaces, surface asperities may become deformed and result in a complex elastohydrodynamic regime of lubrication. Therefore, taking into consideration TMS roughness was one of the key requirements for making the set-up as similar as possible to a real oral surface.

In this study, we compared two surface profiles, rough and smooth, which were created by molding TMSs with and without sandpaper, respectively. The rigidity of both model tongues was similar (soft: 50.17 ± 1.46 kPa). Three types of cottage cheese were used to examine the effects of surface roughness: diluted cottage cheese without particles, with small particles, and with large particles. Normal stress and shearing velocity were kept constant at values similar to those

in the experiments described in section 3.1 (9 kPa and 10 mm/s, respectively).

The means and standard deviations of the friction coefficient were measured for the three cottage cheese types on smooth and rough TMSs (Figures 6a and 6b). There was an evident impact of surface roughness on friction coefficient values (p -values < 0.0001 for the comparisons of each cottage cheese type on rough vs. soft TMSs). For all three cottage cheese types, higher friction coefficients were obtained with the rough versus smooth TMSs. The results thus suggest that the food is less able to prevent contact between the TMS and the palate in the case of the rough TMSs than in the case of the smooth TMSs. One possible explanation for this observation is that the introduction of asperities to the rough TMSs may have led to the more efficient spreading of lubricant, resulting in a thinner gap between the tribo-pair.

Additionally, although the trend was not statistically significant, the value of the friction coefficient seemed to be constant with respect to the number of shearing cycles for the rough TMSs but showed a decrease from the first to second cycle for the smooth TMSs. A more effective spreading of the lubricant film on the rough surface could once again explain this pattern. The initial application of normal stress could have maximized the spreading of the lubricant on the rough surface, and, consequently, the shearing cycles that followed would have had no further impact on film thickness, resulting in a constant friction coefficient value. On the other hand, on the smooth surface, the application of the same level of normal stress might not have led to maximal spreading, which was later achieved by the first shearing cycle.

It is also worth noticing that, compared to the smooth surface, the rough surface made it possible to slightly better segregate the cottage cheese types with or without particles. Also, there was a trend for friction coefficient values to be slightly higher for cottage cheese with large particles than for cottage cheese with small particles, even if this difference was not statistically significant at a given particle concentration, normal load, and shearing velocity. However, it could be that there are certain combinations of operational parameters (normal stress and shearing velocity) and TMS properties (roughness and rigidity) that could better segregate the results in relation to particle size.

3.3. Role of operational parameters: normal stress and shearing velocity

When studying the feasibility of this tribological set-up, it was imperative to investigate the evolution of friction forces in response to variation in normal stress and shearing velocity. The Stribeck curve can clarify how

these parameters (in tandem with lubricant viscosity) can govern the lubrication regime of the system by impacting lubricant film thickness.

When studying the impact of normal stress, the experiments were performed with a rough artificial tongue with a rigidity of 50.17 ± 1.46 kPa (soft) and diluted cottage cheese containing small versus large particles. The means and standard deviations of the friction coefficient were measured for six replicates of both cottage cheese types across a normal stress range of 4.5–18 kPa and at a constant shearing velocity of 10 mm/s (Figure 7a). It is evident from these results that increases in normal stress (from 4.5 kPa to 13.5 kPa) led to a significant decline in friction coefficient values. However, for the highest normal stress value, the decrease in the friction coefficient was not significant, suggesting a nonlinear response. This trend was observed for both cottage cheese types. A similar dependency of the friction coefficient on the normal load was also reported by Chojnicka, De Jong, De Kruif, & Visschers (2008) for two different protein dispersions (ovalbumin and whey protein isolates). These trends reflect that the system can occur somewhere between the hydrodynamic and the mixed lubrication regimes as contact between the palate and the TMS becomes more pronounced with increased normal stress. However, to identify the exact lubrication regime, the complete Stribeck curve needs to be built. It is also worth noting that, with the increase in normal load, the reproducibility of the results improved considerably. An explanation is that, when the normal load is increased, there is an improvement in the signal-to-noise ratio of the measured forces.

Additionally, the effect of variation in shearing velocity at a given normal stress was also studied. Results were obtained on the rough surface for diluted cottage cheese containing small and large particles at a normal stress of 9 kPa and shearing velocities of 5, 10, 20, and 30 mm/s (Figure 7b). Here, the difference in the friction coefficient values at the maximum and minimum velocities was significant: values were higher at 30 mm/s than at 5 mm/s. However, increases within the intermediate velocities did not have a statistically significant effect. It may be that, at the given normal stress, higher velocities need to be tested.

3.4. Role of TMS rigidity

During the complex *in vivo* scenario of food oral processing, tongue rigidity and shearing velocity shift in order to change friction forces and thus better perceive certain textures. The PVA-based TMSs in this study provided an opportunity to compare friction measurements for two different rigidity values. A hard TMS (100.78 ± 2.12 kPa) was therefore introduced into the experimental design, and its results were

compared to those for the soft TMS (50.17 ± 1.46 kPa). The bulk rigidity values of both the soft and hard TMSs were similar to those reported by Ishihara et al. (2013) for relaxed and contracted human tongues. Both TMSs had rough surface profiles.

To begin with, experiments were performed on both the TMSs without any food. Normal stress and shearing velocity were 9 kPa and 10 mm/s, respectively. It was found that having lower rigidity imparted higher friction force (Figure 8a). In the case of the non-lubricated soft surface, the adhesion of the hydrogel to the aluminum probe might have created a backward force, resulting in a higher friction force. For the lower rigidity surface, the deformation of the asperities was higher under compression, which, in turn, resulted in a larger contact area and thus higher adhesion between the TMS and the palate.

Then, experiments were performed using diluted cottage cheese containing small and large particles. Two different values of normal stress (9 kPa and 18 kPa) and shearing velocity (10 mm/s and 20 mm/s) were tested. For the sake of simplicity, only the results pertaining to the cottage cheese with small particles are presented because the cottage cheese with large particles showed similar trends (Figures 8b and 8c). The friction behavior of the two TMSs under lubricated conditions was opposite to that observed under non-lubricated conditions (Figure 8a). The hard TMS led to higher friction coefficient values than did the soft TMS, regardless of the level of normal stress or shearing velocity. This reversal in friction behavior between situations with and without food is clearly due to the lubrication properties of the diluted cottage cheese. In the absence of the food (i.e., dry contact), friction was driven by adhesion, which was greater for soft TMSs, as explained above. In contrast, during lubricated contact, the cottage cheese restricted absolute contact between the aluminum palate and TMSs and also altered the adhesion properties of the hydrophilic PVA surface. Higher deformation of the soft TMSs (compared to the hard TMSs) also made it easier to evenly spread the lubricating film, preventing any dry adhesive contact between the TMS and the palate.

Furthermore, the responses to changes in normal stress or shearing velocity were similar to those observed in the previous sections. Increases in the normal load and the shearing velocity led to decreases and increases, respectively, in the friction coefficient values. These results again confirm that variation in such operational parameters could govern the lubrication regime and may sometimes enable the transition from one regime to another. Furthermore, it was also evident that changes in the friction coefficient values were more pronounced in the case of the TMS with higher rigidity. Apart from this higher rigidity, the

freezing and thawing cycles of the PVA might also have influenced the surface asperities (especially in terms of asperity height), which could be one of the possible explanations for the higher friction coefficient values. Finally, with the exception of surface roughness, all the physiological properties mimicked here (rigidity, normal load, shearing velocity) are highly likely to change based on how the consumer adapts his/her oral strategy to a food's properties and how he/she manipulates food in the mouth. The results of this study show that varying these parameters greatly affected the friction coefficient values. Consequently, this set-up opens the door to exploring the relationships between oral strategies and their consequences for friction behaviors. Finally, this set-up with deformable PVA could be useful for any *in vitro* research examining the dynamics of texture perception.

4. Conclusions

In this study, a tribological set-up was successfully developed to achieve more realistic oral conditions for investigating tribological mechanisms during food oral processing. The set-up made it possible to use deformable tongue-mimicking samples (TMSs) made with polyvinyl alcohol (PVA), which facilitated the imprinting of a particular level of surface roughness and the management of bulk rigidity. Moreover, like with any other conventional tribological equipment, it was possible to apply different ranges of normal stress, shearing velocity, and displacement sequences.

The feasibility and reliability of the set-up was investigated by examining the dynamics of different food types and TMSs in response to variation in different operational parameters such as normal stress and shearing velocity. For each set of test conditions, friction coefficient values were reproducible. The results obtained for the cottage cheese containing suspended cellulose microcrystals highlighted the importance of accounting for the complexity of tongue rigidity and roughness to better comprehend the frictional phenomena involved. Parameters such as the normal stress or the shearing velocity between the tongue and the palate were shown to be important drivers of variation in the friction coefficient at the tongue-food interface. However, these parameters were also found to be tightly linked to TMS properties like roughness and rigidity. The addition of microscale heterogeneities to the cottage cheese did result in an increase in friction coefficient values, but it was also interesting to note that the results did not segregate based on particle size for a given operational parameter. This information can further be used to hypothesize that there could be unique combinations

of normal stress and shearing velocity for a given TMS that might result in the segregation of results based on different types of heterogeneities (size or shape). However, such work would require a more detailed experimental design, which is a goal for future research.

The friction coefficient was the main physical property analyzed in this study. However, the force sensor used in the bio-mimicking set-up offers many other opportunities for understanding the physical phenomena occurring between the tongue and the palate during shearing motion. Examining the relaxation phenomena that take place right after the displacement steps could reveal how the asperities of the tongue surface behave and recover their initial shape after having been subjected to shear stresses, with respect to the presence of a lubricating film or food bolus. Another objective for future work will be to quantify and to investigate the origin of the possible differences in friction coefficient between forward and backward motions (potentially related to the level of residual tangential stress at the end of relaxation steps). Our study represents the first instance of PVA being used as a model tongue; this approach shows promise but must be improved over the course of future studies. However, to better mimic the topology of the human tongue, it will be necessary to focus on new techniques for molding surfaces and analyzing surface profiles. Real or artificial saliva could also be used to mimic lubrication and friction mitigation in the mouth. Also, in future studies, a larger degree of variation in normal stress and shearing velocity should be explored to better establish the relationship between the friction coefficient and the Stribeck curve. Finally, the set-up itself can be modified to perform more realistic motions (e.g., oscillatory, translational) and to allow more robust control and automation.

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Figure 1

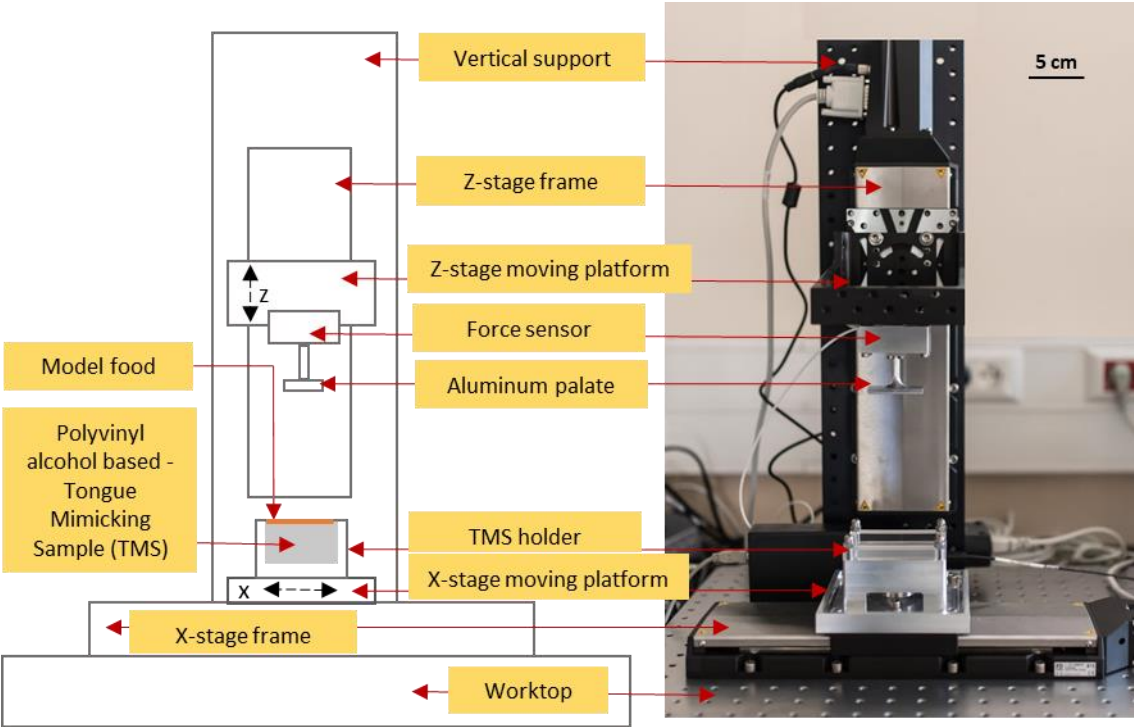


Figure 1: Schematic representation (left) and photograph (right) of the experimental set-up. At the top of the set-up is a rectangular aluminum plate (acting as the palate) that is mounted on a 3-axis force sensor. This sensor is attached to the z-axis moving platform, which is used to apply a controlled normal load. At the bottom of the set-up, a film of liquid food is deposited and spread across the surface of a tongue-mimicking sample (TMS). The position of the TMS is secured by a holder attached to the x-axis moving platform, which creates the shearing motion between the TMS and the aluminum palate.

Figure 2

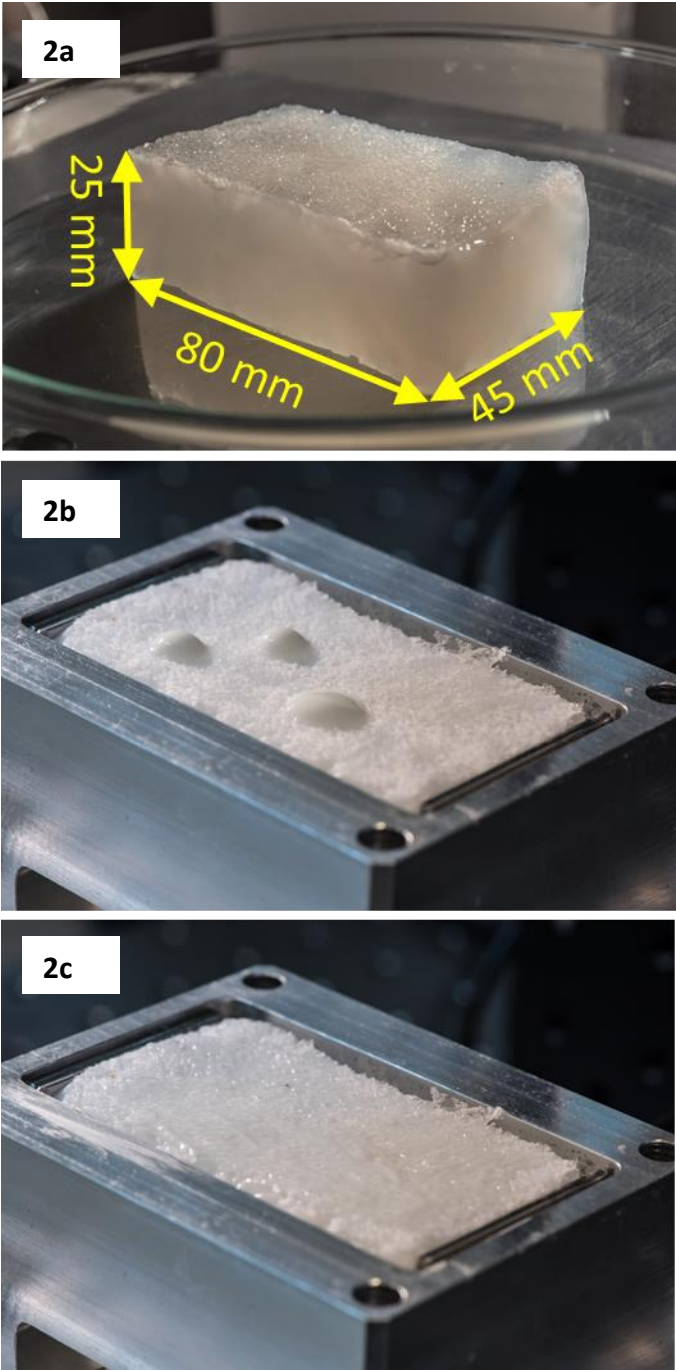


Figure 2: (a) Parallelepiped tongue-mimicking sample (TMS) made with polyvinyl alcohol; (b) the TMS in the device's holder, covered by 0.25 g of cottage cheese (in the form of three droplets); and (c) cottage cheese homogeneously spread across the whole surface of the TMS with a spatula right before positioning the TMS in contact with the aluminum palate and launching a test. The visual aspect of the surface after a test was similar.

Figure 3

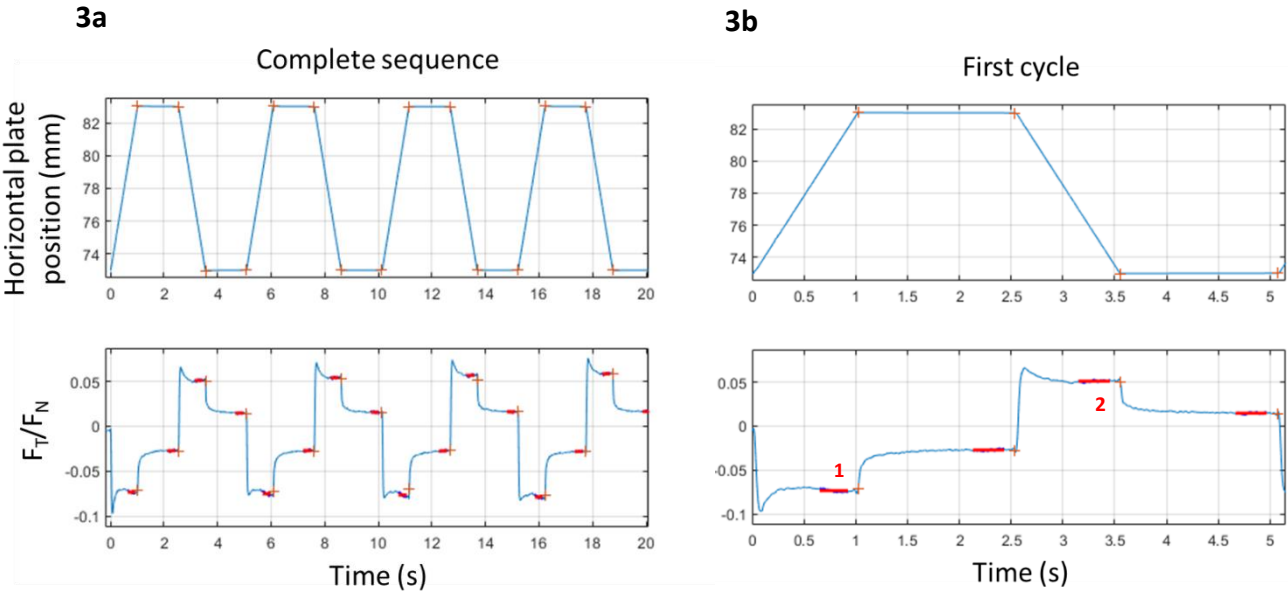


Figure 3: (a) Variation in horizontal plate displacement and the F_T/F_N ratio over time for an experimental sequence (TMS: soft and rough; cottage cheese: undiluted and without particles; normal stress: 9 kPa; shearing velocity: 10 mm/s)—the red highlights the time windows (0.3 s before the movement stops) used for calculating the friction coefficient at steady state and (b) variation in horizontal plate displacement and the F_T/F_N ratio over time exclusively for the first cycle, where the windows marked 1 and 2 were used to calculate the friction coefficient for the cycle.

Figure 4

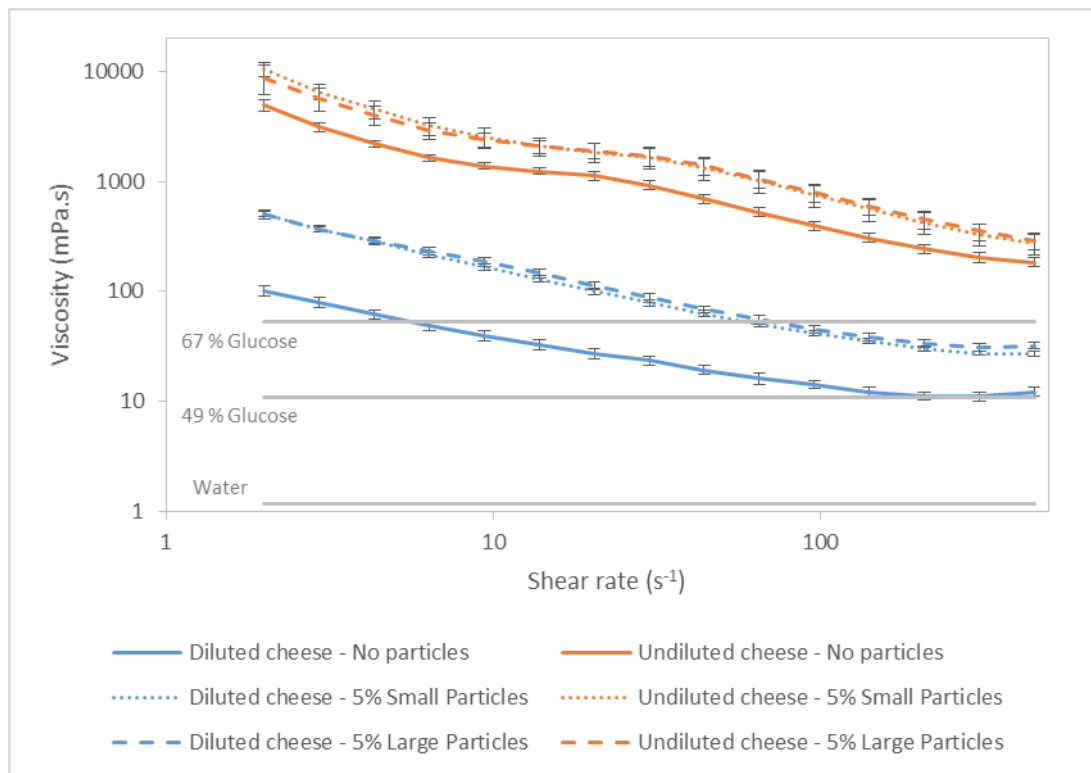


Figure 4: Flow curves for the different types of cottage cheese, with the mean viscosity values of the glucose solutions plotted as a reference.

Figure 5

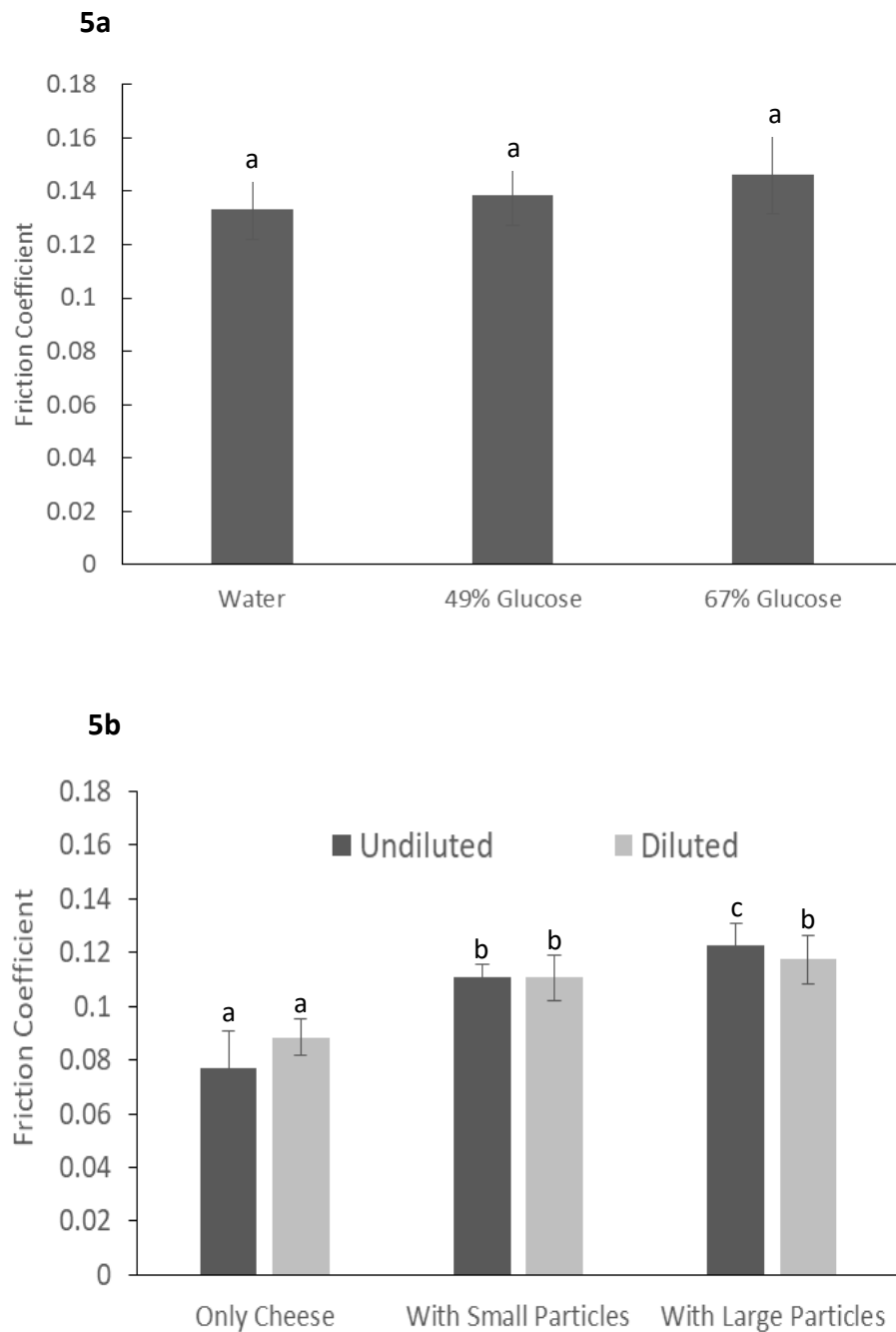


Figure 5: (a) Friction coefficient values for the glucose solutions (0%, 49%, and 67%) and (b) friction coefficient values for the different types of cottage cheese (undiluted/diluted, with/without particles—small and large). Normal stress and shearing velocity were 9 kPa and 10 mm/s, respectively. The error bars represent the standard deviations across six replicates. The differences in letters indicate significant differences between groups.

Figure 6

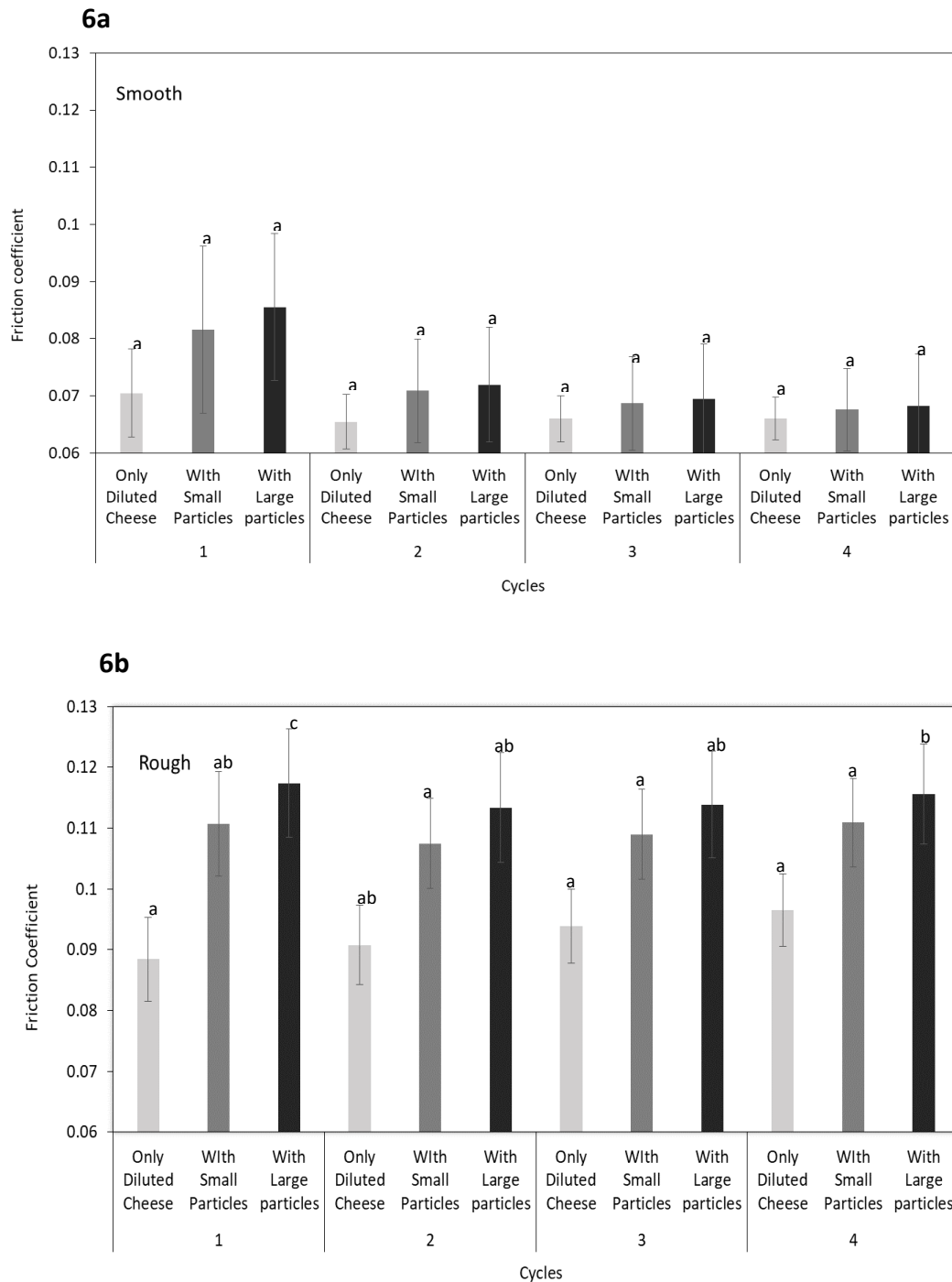


Figure 6: Friction coefficient values for the diluted cottage cheese with or without particles (small or large) on soft TMs with (a) a smooth surface profile and (b) a rough surface profile. Normal stress and shearing velocity were 9 kPa and 10 mm/s, respectively. The error bars represent the standard deviations across six replicates. The differences in letters indicate significant differences between groups. The p-values for the comparisons of the results for the two cottage cheese types on the soft and rough profiles were all < 0.0001.

Figure 7

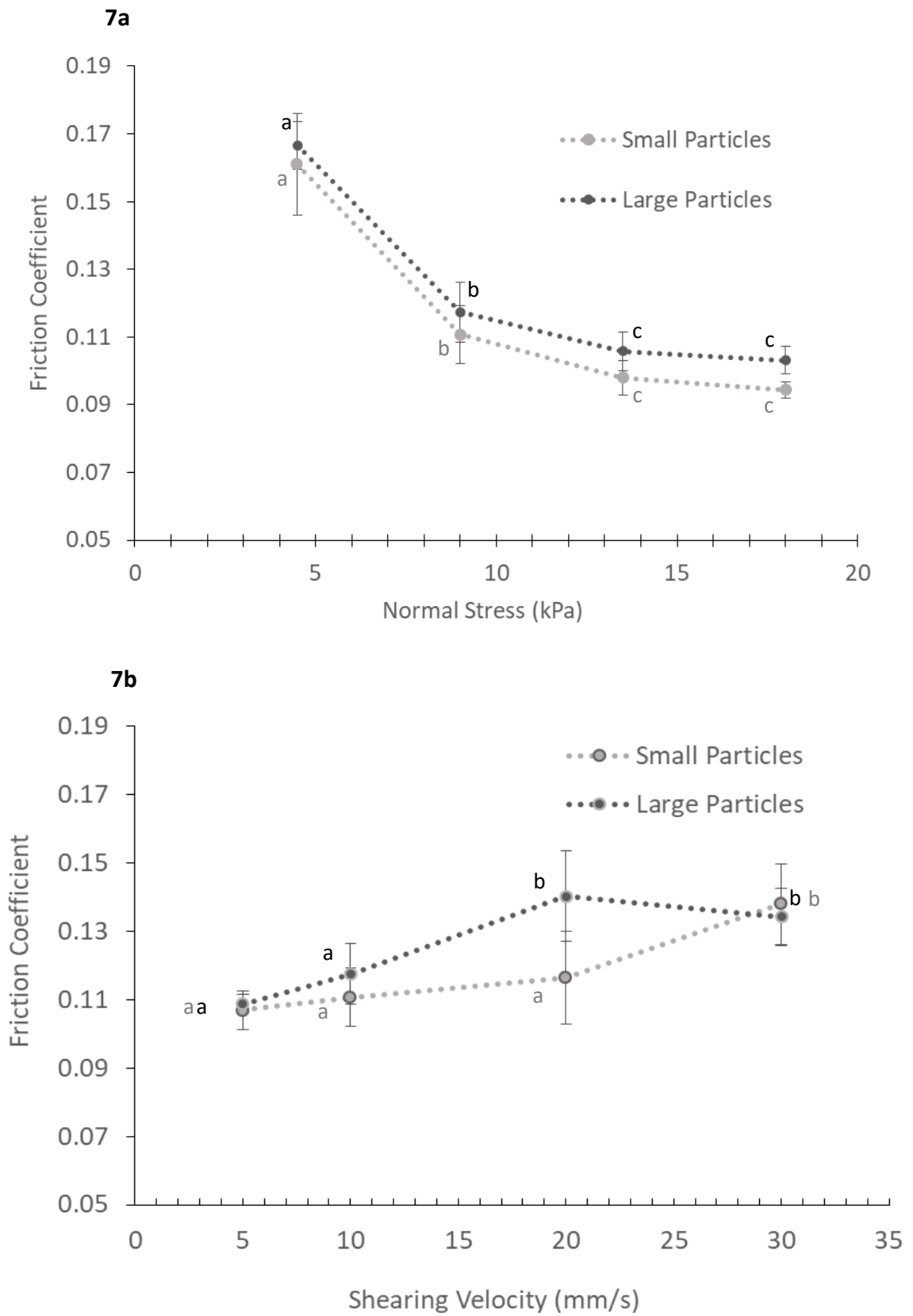


Figure 7: Friction coefficient values for the diluted cottage cheese with small or large particles on the soft or rough TMSs under the following conditions: (a) variable normal stress and a fixed shearing velocity of 10 mm/s and (b) variable shearing velocity and a fixed normal stress of 9 kPa. The error bars represent the standard deviations across six replicates. The differences in letters indicate significant differences between groups.

Figure 8

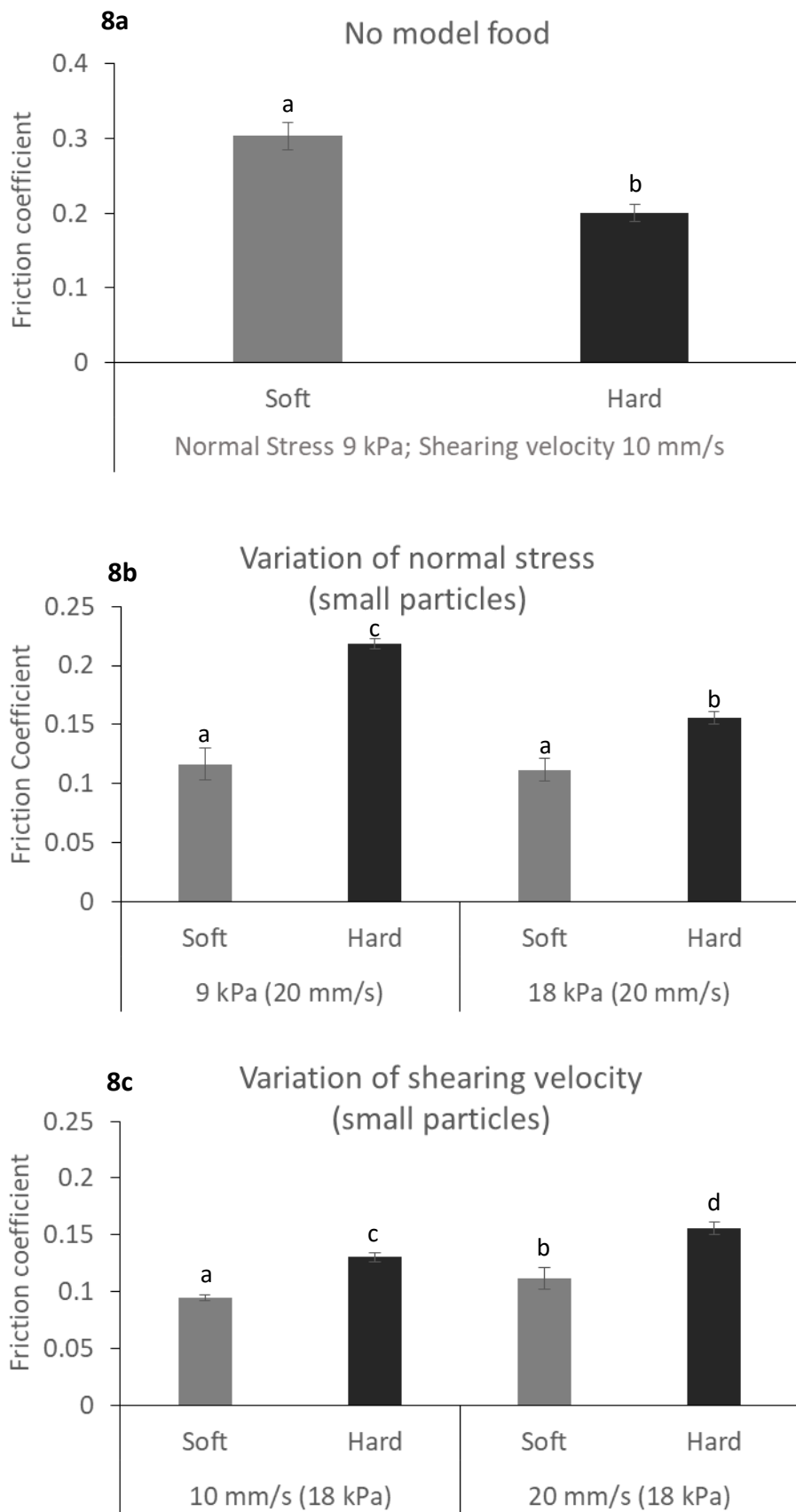


Figure 8: (a) Friction coefficient values on hard and soft TMSs with rough surface profiles when no food was present; (b) friction coefficient values on hard and soft TMSs with rough surface profiles when using diluted cottage cheese with small or large particles under conditions of variable normal stress; and (c) friction coefficient values on hard and soft TMSs with rough surface profiles when using diluted cottage cheese with small or large particles under conditions of variable shearing velocity. The error bars represent the standard deviations across six replicates. The differences in letters indicate significant differences between groups.