

# Signal analysis to study the impact of tongue roughness on oral friction mechanisms with a custom-built tribometer

Miodrag Glumac, Véronique Bosc, Paul Menut, Marco Ramaioli, Frederic Restagno, Sandrine Mariot, Vincent Mathieu

### ▶ To cite this version:

Miodrag Glumac, Véronique Bosc, Paul Menut, Marco Ramaioli, Frederic Restagno, et al.. Signal analysis to study the impact of tongue roughness on oral friction mechanisms with a custom-built tribometer. Biotribology, 2023, 35-36, pp.100257. 10.1016/j.biotri.2023.100257. hal-04213997

## HAL Id: hal-04213997 https://hal.inrae.fr/hal-04213997

Submitted on 21 Sep 2023  $\,$ 

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial - NoDerivatives 4.0 International License

1	Signal analysis to study the impact of
2	tongue roughness on oral friction
3	mechanisms with a custom-built
4 5	tribometer
6 7	Miodrag Glumac <sup>a</sup> , Véronique Bosc <sup>a</sup> , Paul Menut <sup>a</sup> , Marco Ramaioli <sup>a</sup> , Frédéric Restagno <sup>b</sup> , Sandrine Mariot <sup>b</sup> , Vincent Mathieu <sup>a,*</sup>
° 9	<sup>a</sup> Université Paris-Saclay, INRAE, AgroParisTech, UMR SayFood, 91120, Palaiseau, France
10	<sup>b</sup> Université Paris-Saclay, CNRS, Laboratoire de Physique des Solides, 91400, Orsay, France
11	
12	
13	
14	
15	
16	
17	
18	
19	
20	*Corresponding author:
21	Vincent Mathieu
22	Paris-Saclay Food and Bio-product Engineering Research Unit (SayFood UMR 782)
23	Paris Saclay, INRAE, AgroParisTech
24	22, place de l'Agronomie
25	91120 Palaiseau, France
26	Email: vincent.mathieu@inrae.fr
	1

#### 27 Abstract

A custom-built tribometer was employed to investigate the impact of the roughness of 28 deformable tongue mimicking surfaces (TMS) on friction mechanisms occurring under the 29 effect of lubrication with Newtonian solutions of glycerol. TMSs with modulated roughness 30 (range of asperity heights Ra: 20-140 µm) were manufactured from gels of polyvinyl alcohol 31 (PVA). Newtonian aqueous solutions of glycerol covering a wide range of viscosity (1-1400 32 mPa.s) were used as simple food models spread on the TMSs. The tribological behavior of the 33 system was studied during shear back and forth movements. The ratio between tangential and 34 35 normal forces was analyzed both in terms of average values and of fluctuations, over specific 36 time periods set at the end of motion and rest steps. The average values of friction level were reported to increase when (i) the roughness of the TMSs increased and when (ii) the viscosity 37 of glycerol solutions decreased. These trends could be consistent with mixed lubrication. The 38 fluctuations of friction level during motion steps were for their part generally of higher 39 amplitude as the roughness of the surface increased, with main frequencies ranging from 10 to 40 41 20 Hz. The study demonstrates the importance (i) of the biological relevance of tongue properties (contact areas, rigidity, and asperity heights) and (ii) of the thorough analysis of 42 43 tangential to normal force ratio to better understand the complex mechanisms of friction occurring in the mouth during food consumption. 44

45

Keywords: Food oral processing; Texture perception; Oral tribology; Biomimicry; Tongue
roughness; Food viscosity.

#### 48 1. Introduction

Texture perceptions of food encompass multiple sensory stimuli associated with the 49 structural and mechanical properties of food [1,2]. In particular, tactile features sensed when 50 food interacts with oral surfaces are among the main focuses of food texture investigations [3]. 51 Complementary to sensory analysis, the understanding of the physical and mechanical 52 phenomena that can impact texture perceptions requires the development of experimental 53 approaches that integrate both the characteristics of the food and the complex properties of the 54 organs involved during oral processing [4]. Various prototypes attempting to more or less 55 completely mimic all the stages of food oral processing have thus been designed in recent years 56 57 [5]. Among these different stages, food manipulation by the tongue has been the subject of 58 particular attention [6]. Indeed, the tongue allows the continuous evaluation of the mechanical 59 transformations undergone by the food while guiding it towards the different organs of the 60 mouth to unfold the strategy making it possible to obtain a food bolus ready to be swallowed 61 under safe and comfortable conditions.

62 In particular, oral tribology approaches have been deployed to unravel thin-film lubrication phenomena and to try to uncover relevant friction factors and events that happen 63 between the tongue and the palate during eating [7,8]. Systematic and comprehensive reviews 64 explained in depth the current understanding of oral tribological investigations and their 65 influence on sensory perceptions [9,10]. The importance of emulating more closely real oral 66 conditions was well highlighted. To achieve these objectives, it is necessary to go beyond the 67 68 classic framework allowed by commercial tribology devices, either by adapting them or by designing completely new ones. Taking into account the complex properties of the tongue is a 69 recognized prerequisite to realistically address the tribological behavior of food [11,12]. 70

71 Accounting for tongue rigidity led to significant growth in oral tribology studies in recent years, in particular with the use of PDMS as the most widespread substrate [13]. Human 72 73 tongue's elastic modulus has been measured to be around 10 kPa at rest and 120 kPa when contracted [6]. With cryogels of polyvinyl alcohol (PVA), our group has chosen a material that 74 75 allows reaching a few tens of kPa (thus sticking at best to physiological orders of magnitude) 76 [14]. The hydrophilic character of PVA gels (they are largely composed of water) [15] gives 77 them wettability properties which are relevant compared to those of the tongue. This is thus an 78 additional advantage of PVA gels to the detriment of PDMS, insofar as friction properties have 79 been shown to be highly influenced by the hydrophobicity of the tribopairs [16]. The complex nature of tongue motions during friction with the palate also led some authors to the 80

consideration of not only linear but also circular or elliptical motions which were shown to drastically influence friction properties [17]. Finally, we can note a growing interest in the role of saliva on oral friction for various applications, such as the development of thickeners to treat dysphagia problems [18], the use of oral care products [19], as well as for understanding food oral processing [20].

Current emerging trends are to take into account the complex topographical properties of the tongue induced by the lingual papillae that cover the tongue's surface [21]. In a recent study, tongue roughness properties measured in human volunteers were related to lubrication behaviors and smoothness perception [22]. In studies focused on uniaxial compressions between tongue and palate, the roughness of the tongue has been identified as a key parameter that can influence the distribution and transmission of mechanical stresses at the tongue-palate interface, but also the spreading patterns of the fluids located at the interface [23,24].

Tongue roughness insights are also implemented in various custom tribological 93 instruments to make them more in line with oral conditions [7,25]. More generally, the effect 94 of surface roughness of soft tribopairs made of hydrogels has been the subject of different 95 96 studies which are not limited to food science applications but are also of interest to communities 97 of biomedical engineering, bioscience, or even soft robotics. Under lubrication with water, 98 smooth PVA hydrogels with varied rigidity have been paired with rigid glass substrates with different roughness properties, demonstrating a velocity dependence of friction attributed to 99 100 surface contact dynamics [26]. Roughness has also been considered directly on hydrogels that were paired with smooth glass surfaces [27]. Confocal laser microscopy was used to visualize 101 102 the different contact behaviors at the interface. The differences in lubrication regimes observed between smooth and rough gels were shown to diminish when the normal load increased. 103

104 Friction phenomena have also been investigated between tribopairs both made up of 105 soft hydrogels of different natures, and submerged in water [28]. The system consisted of 106 hemispherical probes and flat substrates with varied roughness properties obtained by molding 107 on sandpaper sheets (grit size varying between 8 and 200 µm, which makes sense in relation to 108 the topographic characteristics of the tongue). Conducted under physiologically relevant conditions for tongue-palate interactions (shearing velocity of 20 mm.s<sup>-1</sup>, normal pressure up to 109 7 kPa), this work revealed two friction regimes. In the first regime, corresponding to low normal 110 111 loads, friction was shown to vary with surface roughness and hydrogels' stiffness. Beyond a certain threshold of contact pressure, a second friction regime attributed to smoothening of 112 113 asperities led to a constant friction coefficient and was shown to be constant across roughness,

and found to be material dependent. More recently, two papers proposed original 3-D printing 114 of molds to generate soft substrates with controlled roughness [29,30]. The asperities were 115 made up of cylindrical pillars whose height, diameter, and density could be custom-designed, 116 following different symmetrical arrangement diagrams for their patterning. In the first paper, 117 the tribopair was composed of a rigid spherical probe paired with texturized PDMS substrates, 118 in presence of suspensions of particles in mixtures of water and glycerol [30]. The area density 119 of pillars was shown to promote lubrication, while distinct frictional behaviors were reported 120 121 when the rigidity of the particles was varied. In the second one, the substrates were paired with 122 a soft hemispherical probe submerged in water which made it possible to show the importance of the morphology and the overall spatial patterning of the asperities in the case of gel-gel 123 124 friction. The bending and the density of the pillars were identified as important factors having an impact on the effective contact surface between the probe and the substrate, and on 125 126 subsequent friction phenomena. The surface of the probe which effectively interacts with the substrate also has to be taken into account and compared with the dimensions of the asperities. 127

128 These different studies are essential to understand friction mechanisms involving rough hydrogels. Nevertheless, most of these studies are based on the use of rheometers with rotational 129 geometries involving hemispherical probes on flat substrates. To explore contact surfaces that 130 are more representative of the contact between the tongue and the palate, new tribological 131 systems must therefore be designed and deployed. The implementation of tongue roughness in 132 oral tribology studies thus led to the consideration of new tribopairs with increased surface area, 133 leading to improved physiological relevance and paving the way for investigating the behavior 134 of complex and heterogeneous food models (e.g. presence of particles, mixtures of phases). It 135 is in particular for this purpose that a new custom-built tribometer was designed and presented 136 137 by our group in a recent publication [14]. The device allows the generation of a contact area of approximately 10 cm<sup>2</sup> between the artificial tongue and palate, which is almost half of the total 138 139 surface of the hard palate, estimated at around 20 cm<sup>2</sup> [31]. Such a configuration thus offers improved physiological relevance, when compared to that of conventional commercial 140 tribopairs. Still, with the aim of closer emulating in-mouth conditions, the use of two orthogonal 141 translation stages makes it possible to impose complex sequences of movements, combining 142 simultaneously both compression and shearing, exactly as we do when we eat. This marks the 143 main originality of our approach in the general context of the growing scientific community's 144 145 interest in soft tribology applied to food oral processing. The proof-of-concept publication made it possible to perform a first scan of the different operational factors that can be varied on the 146

147 newly designed device. The importance of the normal force and shear velocity parameters on 148 the friction phenomena could logically be highlighted [14]. Before going further with complex 149 sequences mixing compressional and shearing motions, this newly designed in-house 150 equipment requires going through validation stages through simplified protocols, in order to 151 test and approve more in depth the reliability of the extracted data. This is all the more important 152 since, as underlined in a recent review, each tribology system has its specificities, making 153 comparisons between studies complicated [13].

For this, we propose to explore the benefits to be drawn from this custom-made system, which provides access to raw force signal data and thus offers all degrees of freedom for analyzing them as finely as desired. Unlike conventional commercial tribometers, the analysis is thus not restricted to the friction coefficient measured in steady state dynamics. It is also possible to analyze the transient phases, or to study the characteristics of fluctuations over time, as a few rare but very interesting articles have done [32].

In the present study, the objective is thus to implement the custom build tribometer 160 previously introduced by our team, to characterize in an original way the impact of the 161 162 roughness properties of the tongue on the phenomena of friction against the palate. Tongue mimicking surfaces covering physiologically relevant ranges of roughness asperity heights 163 were designed and implemented on the device. Cycles alternating between shearing motions 164 and rest phases were thus imposed between tongue mimicking surfaces and an aluminum plate 165 166 mimicking the human hard palate. Constant conditions of shearing velocity and normal force were imposed, and the use of Newtonian solutions of glycerol covering a wide spectrum of 167 viscosities (representative of that of the liquid and semi-liquid foods that we consume) made it 168 possible to vary the lubrication regime. Original processing methods were implemented to 169 analyze the ratio between tangential and normal forces, both in terms of levels of amplitude and 170 of fluctuations during dynamic friction steps, but also in terms of residual levels during rest 171 periods. 172

#### 174 2. Material and methods

#### 175 2.1. Newtonian solutions of glycerol

Newtonian solutions of glycerol were prepared and used as lubricants for the 176 tribological measurements. As the experiments were conducted with fixed shear velocity and 177 178 normal force, varying the viscosity of the solutions made it possible to change the lubrication regime and move along the Stribeck curve. Mixtures of glycerol (purity  $\geq$  99.0%, Thermo 179 180 Fisher Scientific, Waltham, MA, USA) and water were considered. Six solutions were prepared in total, labeled based on their glycerol content (w/w %): G100 (pure glycerol), G97, G93, G85, 181 G<sub>50</sub>, and G<sub>0</sub> (water). Concentration levels were defined based on literature data, in order to have 182 a progressive graduation of the viscosity level between  $G_0$  (the thinnest) and  $G_{100}$  (the thickest) 183 [33]. Water was added to glycerol in glass containers and placed under magnetic mixing for 30 184 minutes. The viscosity of the obtained solutions was measured on a rheometer (Physica MCR 185 301, Anton Paar, GmbH, Austria) with concentric cylinders (CC27/T200/SS), at 20° C. 186

The well-known and established Newtonian behavior was checked through
logarithmically increasing and decreasing shear rates (1-1000 s<sup>-1</sup>). The average and standard
deviation values of viscosity at 50 s<sup>-1</sup> obtained after five replications are provided in Table 1,
50 s<sup>-1</sup> being recommended in the literature as a relevant shear rate for food oral processing [34].
A well-known non-linear behavior of viscosity versus glycerol concentration was confirmed
(exponential trend).

193

194**Table 1.** Viscosity of glycerol and water mixtures measured at 50 s<sup>-1</sup> shear rate and 20° C195temperature. Standard deviation values were below  $10^{-2}$  mPa.s and  $G_0$  value (water) was196taken from a literature report [35].

Solution label	$G_0$	G50	G85	G93	G97	G100
Viscosity (mPa.s)	1	6	106	351	728	1352

197

**198** 2.2. Manufacturing and characterization of Tongue Mimicking Surfaces (TMSs)

Six types of Tongue Mimicking Surfaces (TMSs) were designed, each one
corresponding to a given level of roughness. TMSs were made from polyvinyl alcohol (PVA)
cryogels. PVA (MW 89,000–98,000, 99% hydrolyzed, Sigma Aldrich, Saint-Louis, USA) was
dissolved in water (10%, w/w), heated to 80 °C and kept under magnetic steering for a duration

of 2 h. The obtained solution was then poured in rectangular parallelepiped molds (dimensions: 203 length 80 mm, width 45 mm, thickness 25 mm). The objective was to prepare TMSs with 204 asperities in a range that is reminiscent of human tongue asperity heights [36,37]. The roughness 205 was obtained by covering the bottom face of the molds  $(80 \times 45 \text{ mm})$  with sandpaper (Leman, 206 Saint-Clair-de-la-Tour, France) with varied classes of grain sizes: P24, P36, P40, P80, and P100 207 (defined by the Federation of European Producers of Abrasives). These classes correspond to 208 the number of meshes per inch square of sieve surface used to size the grains: the higher the 209 210 class number, the smaller the grain size and the smoother the surface. A silicone sheet was used 211 to prepare the last TMS. Such surface had a qualitative visual appearance that appeared smoother than the smoothest sandpaper sheet considered. The molds filled with PVA solution 212 213 underwent a total of two freezing and thawing cycles, thus allowing the solutions to gel with 214 the desired rigidity [38]. The freeze steps were done at -20 °C in a cold storage room (Isobar 215 N.V., Belgium) and lasted 16 h, while the thawing ones lasted 8 h in the air-conditioned laboratory kept at 20° C. After unmolding, TMSs were all stored under the same conditions: 216 217 they were placed in hermetic boxes, immersed in water, and maintained at ambient laboratory temperature (20°C). Under these conditions, PVA cryogels can be stored for several months 218 219 without their mechanical properties to be altered. In the present case, a week passed after the manufacture of the TMSs, before the start of the experiments. Then, all the experiments were 220 221 carried out over a period of about a month.

A texture analyzer (TA.XTplus, Stable Micro System, Surrey, United Kingdom) was 222 223 used to measure the Young's modulus on two out of the six TMSs (the smoothest and the roughest). A planar circular probe with dimensions greater that the surface of the TMSs was 224 used. The protocol was a strain rate of 5%, with a compression speed of 10 mm.s<sup>-1</sup> (six replicates 225 226 per TMS). The slope of the stress-strain curve was assessed during both the loading and unloading phases of the test. The stiffness values obtained during the loading and unloading 227 phases were respectively 29.4  $\pm$  1.0 kPa and 30.2  $\pm$  0.5 kPa for the roughest TMS, and 31.8  $\pm$ 228 229 0.2 kPa and 30.6  $\pm$  0.2 kPa for the smoothest. No major differences could be noted between 230 both samples, confirming that all TMSs had the same rigidity.

The roughness of the TMSs was analyzed by profilometry (DektakXT<sup>®</sup>, Bruker, USA). Tested samples included one TMS per class of roughness (six samples). Three one-dimensional profiles were performed for each TMS analyzed (each was 30 mm long), with a 45° rotation between one profile and the next, in order to cover as well as possible the area of interest for tribology measurements. The profilometry probe was a stylus with a 2  $\mu$ m radius, the force was

1 mg, and the achieved resolution was 1.66  $\mu$ m/pt, at a constant speed of 500  $\mu$ m.s<sup>-1</sup>. The data 236 from each one-dimensional profile (signals of the measured asperity height as a function of the 237 tip scan distance) was processed individually on MATLAB (The MathWorks, Natick, 238 Massachusetts, USA). On the 1-D profiles, the absence of qualitative differences between the 239 slopes of the ascending and descending phases of the indenter suggested that the settings have 240 made it possible to limit potential scratching effects. The processing of the profiles and the 241 242 calculation of the roughness parameters were carried out following the instructions provided in 243 the ISO 4287 standard. Filters were applied on the raw measured surface profiles to isolate the 244 waviness from the roughness components of the profiles (the first one being due to a lack of flatness and not to the shape of asperities). The cut-off length  $\lambda_c$  used in the filter was set to 10 245 246 mm, which is ten times higher that the highest grain size of the coarsest sandpaper used, and which also corresponds to the course of shear motions implemented for the tribological tests 247 248 described hereafter. Two main roughness parameters were calculated from the filtered profiles: the arithmetical mean height (Ra) and the mean width of the profile elements (RSm). Ra is the 249 250 arithmetic average of the deviations from the mean line of the surface profiles, calculated over 251 the whole length of the one-dimensional scan. The Ra parameter is therefore linked to the 252 vertical amplitude of the roughness. RSm for its part was calculated as the average value of the distance between the changes of sign of the height of the profiles (crossing of the average 253 height). This parameter, therefore, provides information on the width of the asperities. The 254 mean and standard deviations of Ra and RSm values obtained from the three one-dimensional 255 256 scans performed on each TMS were then calculated.

In addition to the one-dimensional measurements, for each of the six roughness levels studied, two-dimensional measurements were performed with the same profilometry equipement, consisting of 125 successive one-dimensional profiles performed with the same settings. With a spacing of 20  $\mu$ m between each profile, it was possible to cover a surface of 2.5 × 3.0 mm, to have two-dimensional representations for the qualitative visualization of the surface morphology.

263 2.3. Custom-buit tribometer

The custom-built tribometer used in this study was previously described in detail in a recent proof of concept study [14]. A schematic representation of the system is provided in Figure 1. In brief, two translation stages were perpendicularly positioned on top of a worktop. A rectangular aluminum plate  $(45 \times 25 \text{ mm})$  attached to the vertical stage has the role of the hard palate and was coupled with a three-axis force sensor (K3D60a, ME Systeme,

Hennigsdorf, Germany) with a measurement range of ±50 N and an accuracy of 1%. The 269 270 manufacturer indicates a sensitivity to transverse forces (cross-talk) of 1% of the measuring range at full load. Fillets were made on the edges of the palate (radius 2 mm) so as to limit the 271 risk of damaging the TMSs during friction phases. During the design of the system, the distance 272 between the sensor and the surface of the palate on which friction operates was reduced as much 273 274 as possible (approximately 3 cm), in order to limit undesired bending effects, induced by the moment arm which applies to the force sensor. Indeed, it is important to note that the technology 275 of strain gauge sensors is based on the principle of deflecting under load. Specifications from 276 277 the manufacturer indicate that this model has a deflection of 100 µm under full load (50 N) and 278 here, the sensor was not used for more than 20% of its measurement range. Moreover, the level 279 of normal load imposed in the present experiments leads to a deformation of the TMSs by several millimeters. Under these conditions, the inclination of the palate caused by the twisting 280 281 of the sensor must have a limited impact on the contact, which remains distributed over the entire lower face of the palate plate. A tongue holder part (with a parallelepipedic cavity 282 283 adjusted to the dimensions of the TMSs) was attached to the horizontal stage. Both translation stages are displacement-controlled. LabVIEW® software (N.I., Austin, Texas, USA) was used 284 285 to (i) control and acquire the position of the translation stages undergoing imposed sequences of motions and (ii) acquire in real-time the data from the force sensors using a bridge module 286 287 with a 25 kHz sampling rate (NI-9237, N.I., Texas, USA).

288 2.4. Friction test protocol

The full experimental protocol of a single tribological test is described hereafter. Before the start of a test, the TMS was removed from the water container in which it is kept for storage, and the excess water with which it is covered was removed with absorbent paper (KIMTECH Science, Kimberly-Clark Europe Limited, Surrey, UK). Then, after visually checking that there is no excess water left on the upper surface of the TMS nor on the paper, the TMS was positioned in the tongue holder of the tribological setup.



Figure 1. Schematic representation of the custom-built tribometer. The lower part includes a
 TMS positioned on a horizontal translation stage (used to impose shearing movements). The
 upper part includes the rigid artificial palate and a force sensor, both mounted on a vertical
 translation stage (used to apply the normal force).

300 A volume of 0.25 mL of a given glycerol solution was deposited on top of the TMS, in 301 such a way that the solution would cover the whole surface area between the TMS and the aluminum plate playing the role of the palate, following previously established protocols [14]. 302 303 Then, the aluminum plate was lowered until flush with the surface of the TMS, allowing to ensure the regular distribution and the spreading of glycerol solutions, with some excess 304 305 expelled all around the aluminum plate's sides. Finally, the artificial palate was again lowered, until reaching a target value of normal force equal to 10 N (~9 kPa stress, based on the 306 307 aluminum plate geometry). As the maximum compressive force between the tongue and the 308 palate has been estimated at between 30 and 70 kPa [39,40], the value of normal load retained 309 here seems relevant, especially for a product that does not need to be crushed. Once this starting position was reached, the testing sequence protocol was triggered without delay. The test 310 311 protocol consisted of repeating a cycle five times during which shearing motions alternated with rest steps, in the absence of vertical motions. Figure 2 (a) represents the measurements of 312 the variations of the position of the horizontal translation stage as a function of time during a 313 cycle. The absence of curvature during the transient phases of acceleration and deceleration of 314 the stage reveals that these phases are very short, both with respect to the scale of the duration 315

of a cycle of movements and with respect to the kinetics of evolution of the measured forces.The four steps of a cycle are labeled in different colors and consist in what follows:

- Step #1: the horizontal translation stage moves forward in a total of 10 mm distance
  with a constant shearing velocity of 10 mm.s<sup>-1</sup>;
- Step #2: a first holding step is observed for 1.5 s, with both stages held stationary;

- Step #3: the horizontal translation stage moves back to its initial position with the same
 constant shearing velocity of 10 mm.s<sup>-1</sup>;

- Step #4: a second holding step is observed for 1.5 s.

While tongue velocity can be up to 200 mm.s<sup>-1</sup> [11], the velocity usually associated with liquid food consumption was for its part shown to be less than 30 mm.s<sup>-1</sup> [41]. The operational parameter of shearing velocity chosen for the experiments on the tribometer is thus relevant to conditions during normal eating.

For each TMS and each solution investigated, six replications were done on the 328 tribological setup. All tribological measurements were done at room temperature (20 °C). The 329 current version of the custom-built tribometer does not yet allow measurements under 330 physiologically relevant temperatures (around 35°C in the oral cavity), therefore imposing to 331 332 work at ambient laboratory temperature (20°C). This difference has consequences on the viscosity of the solutions, and therefore potentially on the characteristics of the contact. 333 However, the diversity of glycerol solutions considered here makes it possible to cover a large 334 part of the broad spectrum of viscosities encountered in oral conditions. 335



Figure 2. (a) Displacement of the horizontal translation stage during one out of the 338 five cycles composing a tribological test. (b) Corresponding curves of the ratio between 339 tangential and normal forces provided in the case of TMS  $T_{140}$  (molded on  $P_{36}$  sandpaper) for 340 two conditions of lubrication:  $G_0$  in yellow and  $G_{100}$  in purple. Motion steps (rest steps, 341 342 respectively) are represented on a blue (orange, respectively) background. The solid red lines delimited by red dotted vertical lines at the end of each step mark the intervals on which the 343 344 analysis of the force ratio signal was focused in the paper:  $I_1$  and  $I_3$  at the end of motion steps, *I*<sub>2</sub> and *I*<sub>4</sub> at the end of rest steps. 345

346 2.5. Processing and analysis of tangential to normal force ratio

The analysis of the signals recorded from the force sensor was performed using MATLAB (The MathWorks, Natick, Massachusetts, USA). The analysis was focused on the channels corresponding to normal and tangential loads. The signal processing is described schematically in Figure 3. It compiles the exhaustive description of the different processing steps allowing to obtain several quantitative indicators of interest from the raw signals. The following text takes them up step by step.



Figure 3. Block diagram of the different signal processing steps followed to derive the five
 quantitative friction parameters discussed in the present study from the raw signals of force
 measured during the experiments.

357 At first, to improve the signal-to-noise ratio and to eliminate undesirable components such as oscillations corresponding to 50 Hz power supply, a low pass filter (infinite impulse 358 response filter, 6<sup>th</sup> order, cut-off 40 Hz) was applied to all normal (F<sub>N</sub>) and tangential (F<sub>T</sub>) force 359 signals. The cut-off frequency was determined based on the Fourier spectrum of raw force 360 signals acquired in the absence of mechanical stresses. The recorded bandwidth (0-40 Hz) thus 361 makes it possible to keep the dynamic information consistent with the technology of the strain 362 gauge sensors used. However, it is important to note that applying a filter at such a low 363 frequency loses a lot of information that would be relevant to the range of sensitivity of the 364 mechanoreceptors of the tongue. Exploring frequency bands that are more representative of the 365 sensitivity range of mechanoreceptors will thus require the use of other methodologies in the 366 future. 367

Then, a particular effort was devoted to the analysis of the ratio between tangential and 368 normal forces (directly related to friction). Figure 2 (b) shows examples of the evolution of the 369 ratio between tangential and normal forces  $(F_T/F_N)$  during the first cycle of a test sequence 370 (TMS molded with  $P_{36}$  sandpaper) for two conditions of lubrication:  $G_0$  in (b) and  $G_{100}$  in (c). 371 These examples are representative of the diversity of the trends observed throughout the 372 different tested conditions (which are all provided separately in Figure 4). Quantitative 373 information was extracted from the amplitude of this ratio, focusing on time windows defined 374 375 at the end of each of the four steps composing a cycle. They are represented in red color in 376 Figure 2. A compromise had to be found between time windows as large as possible to contain a maximum of information on the fluctuations of F<sub>T</sub>/F<sub>N</sub>, but also sufficiently narrow to ensure 377 378 encompassing a period of time during which the average level of F<sub>T</sub>/F<sub>N</sub> tends to reach a plateau and therefore varies moderately. The duration of these intervals (0.3 s) was set based on the 379 380 overall observation of the trends of all the tests, and after a series of attempts of calculation with different duration values. For each step of each cycle, the average values of  $|F_T/F_N|$  (absolute 381 382 value of  $F_T/F_N$ ) over the corresponding time windows were determined (time windows  $I_1, I_2, I_3$ ). and  $I_4$  for steps #1, #2, #3, and #4, respectively). A preliminary analysis of these average values 383 384 showed that there was no benefit in studying separately the information related to the forward and backward motions (either the motion steps #1 and #3 or the consecutive rest steps #2 and 385 386 #4), nor to study a possible evolution of these mean values cycle after cycle during a test. In all cases, the differences or variations were not significant with respect to the intervals formed by 387 the standard deviations. Consequently, it was decided to calculate, for each test, the average of 388 the absolute value of the F<sub>T</sub>/F<sub>N</sub> ratio of (i) all the forward and backward motion step intervals 389  $(I_1 \text{ and } I_3)$  and (ii) all the rest step intervals  $(I_2 \text{ and } I_4)$ . In what follows, the obtained average 390 ratios during motion steps are referred to as  $\mu_d$  ("d" for dynamic), while the average ratios 391 during rest steps are referred to as  $\mu_r$  ("r" for residual). 392

393 The fluctuations over time in  $F_T/F_N$  ratio were studied on the time intervals  $I_1$  and  $I_3$  (0.3) s at the end of motion steps #1 and #3). For each time interval, a shift to a null mean value was 394 395 first applied. As an example, Figure 5 displays all the shifted signals for the first interval  $I_1$ . A first indicator was then built based on the root-mean-square (RMS) of the obtained signals. This 396 397 indicator describes in a global way the amplitude of the fluctuations of F<sub>T</sub>/F<sub>N</sub>. In addition, a frequency spectrum calculation was performed by computing the power spectral density of all 398 399 the time windows  $I_1$  and  $I_3$ , applied after windowing by a Hanning window. The amplitude and 400 the frequency of the peak of the spectrum between 0 and 40 Hz were extracted (bandwidth of

the noise reduction low pass filter described above). In a very similar way to what was done for the calculations of  $\mu_d$ , for each test, mean values of the parameters of RMS, frequency, and amplitude of the spectrum peak were calculated over all the time intervals  $I_1$  and  $I_3$  composing a test (see Figure 3). The resulting indicators are referred hereafter to as  $\mu_{rms}$ ,  $\mu_{sf}$ , and  $\mu_{sa}$  (for root mean square, spectrum frequency, and spectrum amplitude, respectively).

The mean values and standard deviations of each of the parameters studied ( $\mu_d$ ,  $\mu_r$ ,  $\mu_{rms}$ , 407  $\mu_{sf}$ , and  $\mu_{sa}$ ) were calculated over the six repetitions performed for any given set of conditions. 408 Results were represented in the form of histograms or plots of the mean values of these 409 repetitions, for which the error bars correspond to the standard deviations. Data analysis and 410 graphical visualizations were done with MATLAB (The MathWorks, Natick, Massachusetts, 411 USA).





413 *Figure 4.* Evolution of  $F_T/F_N$  as a function of time during the first cycle of the different 414 tribological tests conducted with different lubrication conditions (one plot for each of the six 415 solutions) and different TMSs (one color per type of TMS).



417 **Figure 5.**  $F_T/F_N$  ratio as a function of time during the interval  $I_1$  (0.3 s before the end of the 418 first shearing motion) of the first cycle of a tribological test. Each box corresponds to a 419 specific glycerol solution, while the colors detailed in the legend correspond to the different 420 TMSs. The signals were shifted to have a null mean value and then to facilitate the 421 comparison of the levels of fluctuations of  $F_T/F_N$  across the different conditions.

416

#### 423 3. Results and discussion

424 This results and discussion section first focuses on the characterization of the roughness of the TMSs, which is the factor having received the most extensive attention for the objectives 425 of this study. The discussion then revolves around the results of the tribology measurements 426 427 carried out by implementing the different roughness properties under variable lubrication conditions. These tribological results are discussed in two separate sub-sections. The first sub-428 section is dedicated to the analysis of the average level of amplitude of the ratio F<sub>T</sub>/F<sub>N</sub> during 429 430 the motion and the rest steps (related to  $\mu_d$  and  $\mu_r$ , respectively). The second focuses on the fluctuations of the ratio  $F_T/F_N$  during the motion steps (with the analysis of  $\mu_{rms}$ ,  $\mu_{sf}$ , and  $\mu_{sa}$ ), 431 432 and their complementarity with the amplitude measurements discussed in the previous section.

433

#### 435 3.1. Roughness properties of the TMSs

The topography of the TMSs was characterized in order to analyze (i) the impact of the 436 imprint material used in the molding process (sandpapers or silicone sheet) on the height and 437 width of TMSs asperities, and (ii) the physiological relevance of obtained roughness properties. 438 439 The average and standard deviation values of Ra and RSm parameters, obtained on the six types of TMSs, are represented in the form of histograms in Figure 6. The legends in the abscissa axis 440 441 correspond to the materials used to imprint the roughness to the TMSs: five abrasive paper references (P<sub>24</sub>, P<sub>36</sub>, P<sub>40</sub>, P<sub>80</sub>, and P<sub>100</sub>) and a silicone sheet (Sil). Quite expectantly, the general 442 trend was that the higher the SEPA class of sandpaper roughness (from rough P24 to smooth 443 P<sub>100</sub> sandpaper), the lower the obtained values of Ra and RSm. If RSm values seem to 444 445 correspond well to the grit size of the sandpapers, the Ra values are for their part an order of magnitude lower. Shrinking phenomena previously evidenced for PVA artificial tongues [14] 446 447 may explain the discrepancy between sandpaper grit size and Ra values. When looking closer, 448 the TMS prepared with P<sub>36</sub> sandpaper class had a higher asperity height Ra than the TMS prepared with the roughest sandpaper (P<sub>24</sub>). Differences in the wetting abilities of the abrasive 449 surfaces by the PVA solution might be expected according to the roughness characteristics of 450 the sandpaper. For rough surfaces, air might be entrapped at the bottom of the valleys of the 451 asperities, affecting the resulting roughness of the print. These observations show the 452 importance of characterizing the TMSs after their manufacturing, as the reliable reproduction 453 of the roughness of the molds is a very complex task. 454





456 Figure 6. Mean and standard deviation values of Ra and RSm roughness parameters,
457 measured for six types of TMSs: five were molded on sandpaper sheets (from P<sub>24</sub> to P<sub>100</sub>)
458 while the last one was molded on a silicone sheet (Sil).

The two parameters Ra and RSm were shown to follow similar trends across the 459 different TMSs. As Ra is generally considered as the reference roughness property in the 460 461 literature, in the rest of the manuscript, the six types of TMSs have been labeled according to their average Ra value (rounded up to the next ten microns): T<sub>20</sub>, T<sub>30</sub>, T<sub>40</sub>, T<sub>70</sub>, T<sub>120</sub>, and T<sub>140</sub>. 462 Table 2 provides the correspondence between the name given to each TMS, the material on 463 which they were molded (silicone or sandpaper), the grit size in the case of sandpaper 464 (according to the SEPA classification), and the mean and standard deviation values of Ra and 465 RSm actually measured. Hereafter, the results will be systematically presented by classifying 466 the TMSs in increasing order of the mean Ra value. 467

Table 2. Table of the different TMSs, indicating their names, the material on which they were
molded (silicone or sandpaper), the grit size in the case of sandpaper (according to the SEPA)

471 classification), and the average and standard deviation values of Ra and RSm actually

472

TMS label	T <sub>20</sub>	T <sub>30</sub>	$T_{40}$	T <sub>70</sub>	T <sub>120</sub>	T <sub>140</sub>
Imprint material	Silicone	P <sub>100</sub>	P <sub>80</sub>	P <sub>40</sub>	P <sub>24</sub>	P <sub>36</sub>
Grit size (µm)	-	160	200	400	750	550
Ra (µm)	$16 \pm 3$	$25 \pm 2$	$33 \pm 8$	$67 \pm 5$	$116 \pm 5$	$138\pm9$
RSm (µm)	$198 \pm 3$	$171 \pm 5$	$225\pm1$	$397\pm3$	$718 \pm 2$	$685 \pm 8$

measured.

473

474 Figure 7 shows the 2-D images of profilometry obtained on the six types of TMSs. They make it possible to qualitatively confirm, from  $T_{20}$  to  $T_{140}$ , the increase in the height and width 475 476 of the asperities, consistently with the measured values of Ra and RSm. Nevertheless, it is noticeable that the qualitative differences in visual appearance between the TMSs  $T_{20}$  and  $T_{30}$ 477 478 are more pronounced than what the gap of measured values of Ra and RSm would suggest. One hypothesis that could explain this is that for low roughness levels, the cut-off length  $\lambda_c$  of the 479 applied pre-processing filters is less suitable for separating the roughness and waviness 480 components of the profiles. The reliability of the values of the resulting roughness parameters 481 can thus be affected. Subsequently, in the following, we will therefore keep in mind that the 482 TMS T<sub>20</sub> (made from a silicone sheet) is smoother than the TMS T<sub>30</sub> (obtained from P<sub>100</sub>, the 483 484 smoothest of the five types of sandpapers).

485 The average values of Ra ranged from 15.6 to 137.9 µm, and were thus shown to be physiologically relevant after comparison with in vivo measurements from the literature. Such 486 487 measurements are particularly complex *in situ* because the surfaces to characterize are difficult to access and pose great technical problems because of their irregularity and their high 488 deformability. Most studies rely on the *ex situ* analysis of casts, which raises the question of 489 potential loss of information between the roughness properties of the reference surface (that 490 491 one wishes to characterize) and those from the molds on which the measurements are actually carried out. This challenge has been tackled by several teams who have conducted essential 492 493 work to characterize the orders of magnitude of the height of human tongue asperities in recent 494 publications. The distribution of the height of tongue asperities could thus be estimated to range 495 from 20.9 to 121.9 µm in a first study including 58 participants [42], and from 40.0 to 160.0  $\mu$ m in a more recent one with 71 volunteers [36]. Differences could also be noticed between fungiform (390.0 ±72.0 µm) and filiform (195.0 ±30.0 µm) papillae [37]. Although presenting slight differences attributable to the technical difficulties mentioned above and to interindividual variability, these precious orders of magnitude turn out to be in good agreement with the measurements carried out on the TMSs of the study, thus validating their physiological relevance. The analysis of the tribology results below is thus based on experiments carried out under topographical conditions consistent with the physiological environment.

503



504

505

506

*Figure 7.* 2-*D* images of profilometry obtained on the six types of TMSs, where the height of the profile is coded in color.

#### 507 3.2.Impact of TMS roughness on friction amplitude levels

508 Figure 2 (b) represents the evolution of  $F_T/F_N$  as a function of time during the first cycle 509 for two tests conducted on the roughest TMS, but with different lubrication conditions: pure water  $(G_0)$  in yellow, and pure glycerol  $(G_{100})$  in purple. These examples illustrate the diversity 510 511 of the trends observed throughout the different tested conditions, which are all available in Figure 4. During the motion steps (between 0 and 1 s and between 2.5 and 3.5 s), two well-512 513 known phases of evolution of the ratio between tangential and normal forces may be distinguished. During the first phase (which can be referred to as static phase), a progressive 514 515 increase in  $|F_T/F_N|$  may reflect the elastic deformations undergone in the bulk of TMSs when 516 the slip threshold has not been crossed. This phase may therefore depend on the rigidity of the 517 TMS and on the level of adhesion between the surfaces of the TMS and of the palate. The second phase (referred to as dynamic phase) may correspond to crossing of the friction cone. 518 519 The sliding between the palate and the TMS then occurs (stick-slip), while the ratio  $F_T/F_N$ 520 fluctuates around a plateau value (which corresponds to what is called friction coefficient). The duration of these two phases varies greatly across the different experimental conditions. Figure 521 522 2 (b) shows two of the most distinct scenarios that can be observed on the entire dataset, both obtained with the roughest TMS ( $T_{140}$ ). On these examples, lubrication with thin  $G_0$  led to a 523 high level of friction reached at the end of a long static phase. Contrarily, lubrication with thick 524 G<sub>100</sub> displayed a low level of friction after a short static phase. Hereafter, friction analysis was 525 526 focused on the plateau values of  $|F_T/F_N|$  reached at the end of the motion and rest steps of the tests ( $\mu_d$  and  $\mu_r$ ). 527

528

#### **3.2.1.** Friction levels in two extreme cases of lubrication

The behavior of coefficients  $\mu_d$  (magnitude of  $|F_T/F_N|$  at the end of motion steps) and  $\mu_r$ (at the end of the rest steps) will first be discussed in the two extreme cases of lubrication by pure water and pure glycerol (G<sub>0</sub> and G<sub>100</sub>). In Figure 8, the average values of  $\mu_d$  and  $\mu_r$  have been plotted as a function of the mean Ra roughness values measured on the different TMSs.

Lubrication with the most viscous solution ( $G_{100}$ ) led to the lowest values of  $\mu_d$ , with, if any, a moderate roughness dependence observed across the six TMSs. Combined with the short durations of static friction phases observed during the motion steps and already reported in the raw curves provided in Figure 4, these observations suggest that the hydrodynamic lift exerted by  $G_{100}$  may be high enough to avoid any direct contact between the asperities of the TMSs and the palate plate (for these conditions of shearing velocity and normal force). The most probable hypothesis is thus that under these conditions, the system gets close to the hydrodynamic regime. Contrastingly, lubrication with the thinnest solution (G<sub>0</sub>) led to an increase of  $\mu_d$  with roughness, starting from a low level close to that of G<sub>100</sub> for the smoothest TMS and moving away from it as the TMSs become rougher. This increase of  $\mu_d$  with roughness may be associated with an increase of the effective area of contact between the asperities of the TMS and the palate. Such trends are thus consistent with the mixed regime of lubrication.

545 If  $\mu_d$  coefficient can be directly compared to the friction coefficient commonly assessed with commercial tribometers, the residual friction level  $\mu_r$  characterized during rest steps is less 546 547 classic. Food oral processing being composed of alternating phases of motion and rest, following the evolution of the friction ratio F<sub>T</sub>/F<sub>N</sub> during motionless steps may also provide 548 549 relevant information about tongue-food-palate mechanical interactions (with consequences on 550 texture perception). The originality of this custom-built tribometer is that it offers complete 551 freedom in the sequences of movements to impose, with the access to full raw data for analyzing force signals at any time during a test. For each individual condition of lubrication and 552 553 roughness,  $\mu_r$  was found to be lower than  $\mu_d$ , reflecting the tendency of the system to adapt itself to the mechanical stresses applied during the motion steps. These particular plots do not make 554 it possible to identify a clear trend of dependence of  $\mu_r$  on the roughness of the TMSs or on the 555 type of lubricant. Indeed, independently from the level of friction reached at the end of a shear 556 motion, rest periods generally enabled the recovery of similar residual levels of  $|F_T/F_N|$  before 557 moving to the next motion step. The amplitude of the decrease of  $|F_T/F_N|$  observed both for G<sub>0</sub> 558 559 and G<sub>100</sub> during rest steps could thus be directly linked to the magnitude reached at the end of motion steps. When shear motions are stopped, the hydrodynamic pressure exerted by the fluid 560 at the interface suddenly drops. The fluid in question then flows out of the space under the 561 562 palate plate and at least part of the asperities of the TMS comes into direct contact with the plate. Resulting adhesion between the TMS and the palate may lead to residual stresses within 563 564 the TMS, which can give rise to mechanical relaxation phenomena.



**Figure 8.** Average and standard deviation values of friction parameters  $\mu_d$  (during motion steps) and  $\mu_r$  (during rest steps) as a function of TMS roughness, for the two extreme cases of lubrication considered:  $G_0$  and  $G_{100}$ .

569 Based on the trends of  $\mu_d$  and  $\mu_r$  observed in the cases of lubrication with the thinnest and the thickest solutions, the following part of the discussion suggests taking a closer look at 570 571 what happens when the viscosity is gradually varied. Indeed, fixing normal stress and shearing 572 velocity and varying the viscosity as it has been done here is one of the possible strategies to progressively investigate transitions through lubrication regimes [43]. Mixtures of glycerol and 573 water were considered here as they are commonly used in classical tribological investigations 574 for the construction of Stribeck curves [44], and they make it possible to cover much of the 575 spectrum of viscosity properties of the liquid foods we consume. It is also interesting to note 576 577 that the literature reports that from 80 to 100% glycerol concentration, reorganizations take place in the solutions, resulting in a sharp increase in compressibility [45]. 578

579

565

580

#### **3.2.2. Friction levels in intermediate cases of lubrication**

Figures 9 (a) and (b) represent the variations of  $\mu_d$  and  $\mu_r$  as a function of lubricant viscosity for the six TMSs. From the smoothest to the roughest TMS, an increased dependence of  $\mu_d$  on viscosity is observed, with a decreasing trend which may be characteristic of the mixed regime of lubrication. As the TMSs become smoother, an attenuation of the decay of  $\mu_d$  is observed, with  $\mu_d$  levels becoming lower. Such trend may suggest that for smoother TMSs, the system reaches the transition phase between mixed and hydrodynamic regimes.

587 Concerning the residual friction level  $\mu_r$ , no clear trends of viscosity-dependence could be identified. As already observed in Figure 8, each condition plotted in Figures 9 (a) and (b) 588 589 shows a value of  $\mu_r$  lower than its corresponding one of  $\mu_d$ . Interestingly, it can be noted that the curves of the six TMSs are ranked in the same order in Figures 9 (a) and (b): the smoother 590 591 the TMS, the lower the levels of  $\mu_d$  and  $\mu_r$ . Figure 9 (c) illustrates the possible relations between  $\mu_d$  and  $\mu_r$  by plotting them against each other for each test performed. The points of the same 592 593 color correspond to all the tests carried out with the same TMS (all lubrication conditions combined). The general scatter plot obtained does not seem to reveal a simple relationship 594 595 between the two parameters. As the values of  $\mu_d$  increase, the range of observed values for  $\mu_r$ 596 also increases. The residual level of friction at the end of the rest steps cannot therefore be 597 explained solely by the amplitude of the level reached at the end of the motion steps. Looking color by color (meaning roughness by roughness), we see that the measurement points 598 599 corresponding to the two smoothest TMSs ( $T_{20}$  and  $T_{30}$ ) group together in a limited space corresponding to the lowest values of  $\mu_r$  and  $\mu_d$  observed in the entire dataset. Conversely, for 600 601 rougher TMSs (from T<sub>40</sub> to T<sub>140</sub>, which cover more closely the topographic characteristics of the human tongue), much wider ranges of  $\mu_d$  and  $\mu_r$  values could be observed. As a 602 consequence, for this range of roughness properties, the information provided by the two 603 604 friction parameters  $\mu_d$  and  $\mu_r$  is not redundant, but complementary.



607 **Figure 9.** Average and standard deviation values of  $\mu_d$  (a) and  $\mu_r$  (b) as a function of 608 lubricant visocity for the six TMSs. In (c),  $\mu_d$  and  $\mu_r$  values plotted against each other for each 609 test performed, with points of the same color corresponding to tests carried out with the same 610 TMS (all lubrication conditions combined).

#### 611 3.3. Fluctuations of friction levels during motion steps

612 Most conventional tribology tools limit the analysis of force signals to the calculation of the friction coefficient, which is calculated over time intervals during which shears forces 613 are high enough to induce sliding between the tribopairs, as done in the present study with 614 parameter  $\mu_d$ . However, the ratio  $F_T/F_N$  evolves all along the time windows on which  $\mu_d$  is 615 calculated, and such dynamic behavior also deserves attention. Sanahuja et al. [32] have 616 617 highlighted with originality the importance of produced stick-slip effects resulting from 618 intermittent sliding motions during dynamic friction. These phenomena result in fluctuations in 619 the signal of the ratio between tangential and normal forces, the analysis of which unfortunately 620 remains too rare in the literature. Figure 5 gathers all the signals of  $F_T/F_N$  acquired at the end 621 the first shearing movement applied (shifted to a null mean value). This time window is the first out of the ten time windows used for the calculation of  $\mu_d$ . Varied behaviors of fluctuations in 622 623 F<sub>T</sub>/F<sub>N</sub> could be reported across the different lubrication and roughness conditions. Such fluctuations may carry information about the influence of tongue roughness and lubrication on 624 intermittent adhesion and sliding events at tongue-palate interface. Quantitative parameters 625 626 were thus built to analyze both the amplitude and the frequency of these fluctuations.

627 Figure 10 (a) describes the mean and standard deviation values of  $\mu_{\rm rms}$ , corresponding to the root-mean-square of  $F_T/F_N$  calculated on time windows  $I_1$  and  $I_3$  (at the end of the motion 628 629 steps). For most of the lubrication conditions considered, the general trend observed was that the rougher the TMS, the higher the reported levels of  $\mu_{\rm rms}$ . This tendency of the dependence of 630  $\mu_{rms}$  on the roughness of the TMSs supports the hypothesis that the level of normal force applied 631 632 in the present experiments is not sufficient to completely deform and flatten the asperities of the TMSs. The importance of the intermittence of contact and slip events at the interface 633 634 between the TMS and the palate testified by the high levels of  $\mu_{rms}$  is characteristic of the mixed 635 lubrication regime. However, when considering each TMS individually, the impact of the 636 viscosity of glycerol is more complex to conclude on. The smoother the TMS, the higher the reproducibility of the measurements (shorter error bars), the lower the amplitude of  $\mu_{rms}$ , and 637 638 the lower the differences reported across the six solutions. Conversely, the rougher the TMS, the lower the reproducibility but the higher the diversity of amplitude levels of  $\mu_{rms}$  observed 639 640 across the lubrication conditions. Interestingly, although G<sub>0</sub> and G<sub>100</sub> have been shown to 641 display the most contrasting levels of  $\mu_d$ , they behaved similarly with respect to  $\mu_{rms}$ . Indeed, both conditions led to the lowest levels of  $\mu_{rms}$ , with low variations across the different TMSs. 642 643 Oppositely,  $G_{50}$  led to the highest levels of  $\mu_{rms}$  reported on each of the TMSs, even though it

has a viscosity close to that of  $G_0$  and it gave values of  $\mu_d$  also close to those of  $G_0$ . These 644 645 discrepancies between the trends observed for the parameters  $\mu_d$  and  $\mu_{rms}$  are therefore interesting to highlight through the comparison figure of  $\mu_{rms}$  versus  $\mu_d$  proposed in Figures 10 646 (b). The measurement points of the two smoothest TMSs ( $T_{20}$  and  $T_{30}$ ) are gathered in a 647 restricted space combining low values of magnitude of friction level  $(\mu_d)$  and low amplitudes 648 of friction fluctuations ( $\mu_{rms}$ ). For rougher TMSs, higher levels were generally observed for 649 these two parameters, without being able to identify a clear trend of proportionality. This plot 650 651 highlights the complementarity of the friction parameters  $\mu_d$  and  $\mu_{rms}$ , and thus shows the 652 interest in extending the tribological characterizations beyond the friction coefficient alone.

It is interesting to relate these observations to the mechanisms of tactile perceptions. 653 654 Mechanoreceptors are specialized receptors connected with neural endings and are found in human tissues such as skin and also in oral mucosa tissues among which, of course, the tongue. 655 They can detect mechanical stimuli that cause deformations or some sort of distortions on the 656 tissue surface and translate them into electrical signals to the brain. One report described three 657 658 types of receptors in the tongue: SA1 is responsible for the form and texture of food, FA1 detects low-frequency vibrations, and SA2 detects tongue position and shape [46]. It is then 659 very interesting to underline that each piece of information brought by  $\mu_d$ ,  $\mu_r$ , and  $\mu_{rms}$  can be 660 associated with different types of sensory stimuli for different mechanoreceptors: slowly 661 adapting mechanoreceptors produce sustained responses to static stimulation (proportional to 662 the applied level of stress), while rapidly adapting mechanoreceptors produce transient 663 responses to the sudden changes in stress levels. Fluctuations characterized by  $\mu_{rms}$  could 664 therefore be particularly relevant for understanding the impacts of rapidly adapting receptors. 665 To determine the major frequencies encountered across these fluctuations, and their impact on 666 667 the global signal, the frequency response of the signals has been investigated.



668

669 **Figure 10.** (a) Average and standard deviation values of the root mean square  $\mu_{\rm rms}$  of  $F_T/F_N$ 670 during the 0.3 s before shear motions end. (b)  $\mu_{\rm rms}$  and  $\mu_d$  values plotted against each other 671 for each test performed, with points of the same color corresponding to tests carried out with 672 the same TMS (all lubrication conditions combined).

Figures 11 (a) and (b) describe the mean and standard deviation values of the frequency 674  $(\mu_{sf})$  and the amplitude  $(\mu_{sa})$  associated with the peak of the frequency spectrum of  $F_T/F_N$  signals 675 (taken from the 0.3 s before shear motions end) on all  $I_1$  and  $I_3$  intervals. The results show that 676  $\mu_{sf}$  (frequency at which the spectrum peak amplitude occurs) does not vary significantly 677 between the different roughness conditions. Except for the results obtained on G<sub>0</sub> (lowest 678 679 viscosity) which show lower frequencies, the average frequencies ranged between 10 and 20 Hz, without clear trends or statistical differences between the different roughness and 680 681 lubrication conditions. A relationship between this frequency  $\mu_{sf}$  and the characteristic width of

the asperities of the TMSs (RSm) could have been expected, but this is not the case. This 682 absence of relationship could be due to the random nature of the spatial distribution of the 683 asperities. Indeed, as the asperities do not have a periodic arrangement with respect to the 684 direction in which the shearing movement is operated, the alternations of the sliding and 685 sticking phases might not take place in phase with the width of the asperities. Furthermore, the 686 low pass filter at 40 Hz that had to be applied to the signals significantly reduces the frequency 687 content that can be analyzed. The range of sensitivity attributed to the mechanoreceptors present 688 in the tissues of oral mucosa is much broader (0.3 to 400 Hz) [32,47–50]. Although already 689 690 providing interesting information with sensors that are not entirely suitable, the study shows the interest in using sensor methods dedicated to vibration analysis. 691

The general shape of the plot related to the peaks of spectrum amplitude  $\mu_{sa}$  (Figure 11 (b)) is for its part very similar to that obtained for the average level  $\mu_{rms}$  (Figure 10 (a)), with a general tendency for  $\mu_{sa}$  to increase as the roughness of the TMSs increases. These results show that the amplitude of the fluctuations of  $F_T/F_N$  is essentially carried by the frequency component associated with the peak amplitude of the spectrum. Under these conditions, the relationship established in Figure 11 (c), where  $\mu_{rms}$  and  $\mu_{sa}$  are plotted against each other, only reflects the mathematical relationship between the amplitudes in the time and frequency domains.



700Figure 11. Average and standard deviation values of the spectrum frequency  $\mu_{sf}$  (in a), and of701the spectrum amplitude  $\mu_{sa}$  (in b) of  $F_T/F_N$  during the 0.3 s before shear motions end. (c)  $\mu_{sa}$ 702and  $\mu_{rms}$  values plotted against each other for each test performed, with points of the same703color corresponding to tests carried out with the same TMS (all lubrication conditions704combined).

#### 705 4. Conclusion

706 The artificial tongues made from PVA implemented on this custom-built tribometer confer the originality of being able to study the role of the roughness of the tongue by 707 considering a tribopair with a physiologically relevant contact surface. Furthermore, the 708 709 conduct of non-classical tribology test protocols (combining motion and rest steps) and the 710 analysis of the raw data of the ratio between tangential and normal forces constitute another 711 point of originality. Here, the average values of friction level observed at the end of motion steps were found to increase when (i) the roughness of the TMSs increased and when (ii) the 712 viscosity of glycerol solutions decreased. These trends could be consistent with mixed 713 714 lubrication. The decrease of friction level during rest steps showed a potential to monitor mechanical relaxation in the bulk of the TMSs. Finally, the fluctuations of friction level during 715 716 motion steps were for their part generally of higher amplitude as the roughness of the surface 717 increased. In the future, alternative methodologies may help to study these phenomena of 718 fluctuations in wider frequency bands (more representative of mechanoreceptor sensitivity). By 719 going further than the analysis of the friction coefficient to which tribology studies are often restricted, the study shows that deeper analyses of the signal of the friction level may therefore 720 721 provide additional knowledge, that could contribute to a better understanding of the mechanisms of texture perception. 722

In future works, the development of theoretical models could be considered, in order to attempt to predict the evolutions of the thickness of the lubricating film and of the morphology of the asperities of the TMSs as a function of time during the experiments. The identification of the lubrication regimes at which the system operates could thus be confirmed with more certainty.

728 As food oral processing cannot be represented just by pure shear back-and-forth motions as considered here for validation purposes, future work will require the usage of the full capacity 729 730 of the custom-built tribometer. Complex sequences of motions combining compression and shear can indeed be imposed, and the behavior of normal and tangential forces will be 731 732 investigated under these conditions (both in terms of amplitude and of fluctuations). Future 733 experiments will also consist of accounting for the tongue lubrication with human or artificial 734 saliva, and investigating the behavior of more complex model foods, ranging from semi-liquid to semi-solid products, with various degrees of heterogeneity. The validation of this newly 735 736 designed system may thus open up many opportunities for aiding in the development of novel food products adapted to the physiology of specific populations. 737

7	3	8
•	-	-

#### **739** 5. Credit author statement

740	Miodrag	Glumac:	Conceptualization,	Methodology,	Validation,	Formal	analysis,
741	Investigati	on, Resourc	es, Data curation, Wi	riting – original o	draft, Writing	– review	& editing,
742	Visualizati	on					

- 743 Véronique Bosc: Conceptualization, Writing Review & Editing
- 744 Paul Menut: Conceptualization, Writing Review & Editing
- 745 Marco Ramaioli: Conceptualization, Writing Review & Editing
- 746 Frédéric Restagno: Conceptualization, Ressources, Writing Review & Editing
- 747 Sandrine Mariot: Investigation, Ressources, Writing Review & Editing
- 748 Vincent Mathieu: Conceptualization, Methodology, Software, Validation, Formal analysis,
- 749 Investigation, Resources, Data curation, Writing original draft, Writing review & editing,
- 750 Visualization, Supervision, Project administration, Funding acquisition
- 751
- 752 6. Funding
- This work was financially supported by the QUSToFood project funded by the French NationalResearch Agency (ANR-17-CE21-004).
- 755
- 756 7. Declaration of interest
- 757 The authors have no conflicting financial or any other interests to declare.
- 758
- 759 8. Acknowledgements
- 760 The authors wish to acknowledge the crucial technical support provided by David Forest.

#### 761 9. References

- 762[1]A.S. Szczesniak, Texture is a sensory property, Food Quality and Preference. 13 (2002)
- 763 215–225. https://doi.org/10.1016/S0950-3293(01)00039-8.
- 764 [2] Chen, Food oral processing-A review, Food Hydrocolloids. 23 (2009) 1–25.
- 765 https://doi.org/10.1016/j.foodhyd.2007.11.013.
- 766 [3] J.R. Stokes, M.W. Boehm, S.K. Baier, Oral processing, texture and mouthfeel: From
- rheology to tribology and beyond, Current Opinion in Colloid and Interface Science. 18
  (2013) 349–359. https://doi.org/10.1016/j.cocis.2013.04.010.
- [4] E.C. Ketel, R.A. de Wijk, C. de Graaf, M. Stieger, Relating oral physiology and anatomy
- of consumers varying in age, gender and ethnicity to food oral processing behavior,
- 771 Physiology and Behavior. 215 (2020) 112766.
- 772 https://doi.org/10.1016/j.physbeh.2019.112766.
- [5] S. Panda, J. Chen, O. Benjamin, Development of model mouth for food oral processing
- studies: Present challenges and scopes, Innovative Food Science and Emerging
- 775 Technologies. 66 (2020) 102524. https://doi.org/10.1016/j.ifset.2020.102524.
- [6] S. Ishihara, S. Nakao, M. Nakauma, T. Funami, K. Hori, T. Ono, K. Kohyama, K.
- 777 Nishinari, Compression Test of Food Gels on Artificial Tongue and Its Comparison with
- Human Test, Journal of Texture Studies. 44 (2013) 104–114.
- 779 https://doi.org/10.1111/jtxs.12002.
- 780 [7] W. Xu, S. Yu, M. Zhong, A review on food oral tribology, Friction. 10 (2022) 1927–
- 781 1966. https://doi.org/10.1007/s40544-022-0594-9.
- [8] Q. Wang, Y. Zhu, J. Chen, Development of a simulated tongue substrate for in vitro soft
- "real" tribology study, Food Hydrocolloids. 120 (2021) 106991.
- 784 https://doi.org/10.1016/j.foodhyd.2021.106991.

- 785 [9] A. Sarkar, E.M. Krop, Marrying oral tribology to sensory perception: a systematic
- review, Current Opinion in Food Science. 27 (2019) 64–73.
- 787 https://doi.org/10.1016/j.cofs.2019.05.007.
- [10] C. Pradal, J.R. Stokes, Oral tribology: Bridging the gap between physical measurements
- and sensory experience, Current Opinion in Food Science. 9 (2016) 34–41.
- 790 https://doi.org/10.1016/j.cofs.2016.04.008.
- [11] A. Sarkar, E. Andablo-Reyes, M. Bryant, D. Dowson, A. Neville, Lubrication of soft
  oral surfaces, Current Opinion in Colloid and Interface Science. 39 (2019) 61–75.
- 793 https://doi.org/10.1016/j.cocis.2019.01.008.
- [12] H.M. Shewan, C. Pradal, J.R. Stokes, Tribology and its growing use toward the study of
- food oral processing and sensory perception, Journal of Texture Studies. 51 (2020) 7–22.
  https://doi.org/10.1111/jtxs.12452.
- [13] R.E. Rudge, E. Scholten, J.A. Dijksman, Advances and challenges in soft tribology with
- applications to foods, Current Opinion in Food Science. 27 (2019) 90–97.
- 799 https://doi.org/10.1016/j.cofs.2019.06.011.
- 800 [14] R. Srivastava, V. Bosc, F. Restagno, C. Tournier, P. Menut, I. Souchon, V. Mathieu, A
- 801 new biomimetic set-up to understand the role of the kinematic, mechanical, and surface
- characteristics of the tongue in food oral tribological studies, Food Hydrocolloids. 115
- 803 (2021). https://doi.org/10.1016/j.foodhyd.2021.106602.
- 804 [15] P. Kuchaiyaphum, G. Rifai, W. Yuuki, T. Yamauchi, Hyaluronic acid-poly(vinyl
- alcohol) composite cryo-gel for biofunctional material application, Polymers for
- 806 Advanced Technologies. 30 (2019) 94–100. https://doi.org/10.1002/pat.4447.
- 807 [16] S. Tsui, J. Tandy, C. Myant, M. Masen, P.M. Cann, Friction measurements with yoghurt
- in a simulated tongue-palate contact, Biotribology. 8 (2016) 1–11.
- 809 https://doi.org/10.1016/j.biotri.2016.02.001.

- 810 [17] M.A. van Stee, E. de Hoog, F. van de Velde, Oral Parameters Affecting Ex-vivo
- 811 Tribology, Biotribology. 11 (2017) 84–91. https://doi.org/10.1016/j.biotri.2017.05.001.
- 812 [18] O. Torres, A. Yamada, N.M. Rigby, T. Hanawa, Y. Kawano, A. Sarkar, Gellan gum: A
- new member in the dysphagia thickener family, Biotribology. 17 (2019) 8–18.
- 814 https://doi.org/10.1016/j.biotri.2019.02.002.
- 815 [19] H. Cai, Y. Li, J. Chen, Rheology and Tribology Study of the Sensory Perception of Oral
- 816 Care Products, Biotribology. 10 (2017) 17–25.
- 817 https://doi.org/10.1016/j.biotri.2017.03.001.
- [20] A. Araiza-Calahorra, A.R. Mackie, G. Feron, A. Sarkar, Can tribology be a tool to help
- tailor food for elderly population?, Current Opinion in Food Science. 49 (2023) 100968.
- 820 https://doi.org/10.1016/j.cofs.2022.100968.
- [21] B.L. Miles, Z. Wu, K.S. Kennedy, K. Zhao, C.T. Simons, Elucidation of a lingual
- detection mechanism for high-viscosity solutions in humans, Food and Function. 13
- 823 (2022) 64–75. https://doi.org/10.1039/d1fo02460d.
- [22] X.X. Wang, J. Chen, X.X. Wang, In situ oral lubrication and smoothness sensory
- perception influenced by tongue surface roughness, Journal of the Science of Food and
  Agriculture. 102 (2022) 132–138. https://doi.org/10.1002/jsfa.11339.
- [23] M. Mantelet, R. Srivastava, F. Restagno, I. Souchon, V. Mathieu, Real time ultrasound
- assessment of contact progress between food gels and tongue mimicking surfaces during
- a compression, Food Hydrocolloids. 109 (2020).
- 830 https://doi.org/10.1016/j.foodhyd.2020.106099.
- [24] M. Mantelet, F. Restagno, I. Souchon, V. Mathieu, Using ultrasound to characterize the
- tongue-food interface: An in vitro study examining the impact of surface roughness and
- lubrication, Ultrasonics. 103 (2020) 106095.
- https://doi.org/10.1016/j.ultras.2020.106095.

- 835 [25] A. Araiza-Calahorra, A.R. Mackie, G. Feron, A. Sarkar, Can tribology be a tool to help
- tailor food for elderly population?, Current Opinion in Food Science. 49 (2023) 100968.
  https://doi.org/10.1016/j.cofs.2022.100968.
- 838 [26] T. Tominaga, T. Kurokawa, H. Furukawa, Y. Osada, J.P. Gong, Friction of a soft
- hydrogel on rough solid substrates, Soft Matter. 4 (2008) 1645–1652.
- 840 https://doi.org/10.1039/b802568a.
- [27] S. Yashima, N. Takase, T. Kurokawa, J.P. Gong, Friction of hydrogels with controlled
  surface roughness on solid flat substrates, Soft Matter. 10 (2014) 3192–3199.
- 843 https://doi.org/10.1039/c3sm52883a.
- [28] R.E.D. Rudge, E. Scholten, J.A. Dijksman, Natural and induced surface roughness
- 845 determine frictional regimes in hydrogel pairs, Tribology International. 141 (2020)
- 846 105903. https://doi.org/10.1016/j.triboint.2019.105903.
- [29] R. Rudge, E. Scholten, J.A. Dijksman, A matter of morphology: The role of asperity
- characteristics in hydrogel friction, Tribology International. 174 (2022) 107694.
- 849 https://doi.org/10.1016/j.triboint.2022.107694.
- [30] B.L. Taylor, T.B. Mills, Surface texture modifications for oral processing applications,
  Biotribology. 23 (2020) 100132. https://doi.org/10.1016/j.biotri.2020.100132.
- [31] L.M.C. Collins, C. Dawes, The Surface Area of the Adult Human Mouth and Thickness
- of the Salivary Film Covering the Teeth and Oral Mucosa, Journal of Dental Research.
- 854 66 (1987) 1300–1302. https://doi.org/10.1177/00220345870660080201.
- [32] S. Sanahuja, R. Upadhyay, H. Briesen, J. Chen, Spectral analysis of the stick-slip
- phenomenon in "oral" tribological texture evaluation, Journal of Texture Studies. 48
- 857 (2017) 318–334. https://doi.org/10.1111/jtxs.12266.
- 858 [33] M.L. Sheely, Glycerol Viscosity Tables, Industrial and Engineering Chemistry. 24
- 859 (1932) 1060–1064. https://doi.org/10.1021/ie50273a022.

- 860 [34] Jason R. Stokes, Principles and Practices of Instrumental Characterisation for Eating and
- 861 Sensory Perception Studies, in: Jianshe Chen, L. Engelen (Eds.), Food Oral Processing:
- Fundamentals of Eating and Sensory Perception, 1st ed., Blackwell Publishing Ltd, John
- 863 Wiley & Sons, Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ,
- 864 UK, 2012: pp. 227–263.
- 865 [35] A.A. Aleksandrov, M.S. Trakhtengerts, Viscosity of water at temperatures of -20 to
- 866 150°C, Journal of Engineering Physics. 27 (1974) 1235–1239.
- 867 https://doi.org/10.1007/BF00864022.
- [36] X. Wang, X. Wang, R. Upadhyay, J. Chen, Topographic study of human tongue in
- relation to oral tribology, Food Hydrocolloids. 95 (2019) 116–121.
- 870 https://doi.org/10.1016/j.foodhyd.2019.04.022.
- [37] E. Andablo-Reyes, M. Bryant, A. Neville, P. Hyde, R. Sarkar, M. Francis, A. Sarkar, 3D
- 872 Biomimetic Tongue-Emulating Surfaces for Tribological Applications, ACS Applied
- 873 Materials and Interfaces. 12 (2020) 49371–49385.
- 874 https://doi.org/10.1021/acsami.0c12925.
- [38] P. Giusti, L. Lazzeri, N. Barbani, P. Narducci, A. Bonaretti, M. Palla, L. Lelli,
- 876 Hydrogels of poly(vinyl alcohol) and collagen as new bioartificial materials Part I
- 877 Physical and morphological characterization, Journal of Materials Science: Materials in
- 878 Medicine. 4 (1993) 538–542. https://doi.org/10.1007/BF00125590.
- [39] W.A. Alsanei, J. Chen, Studies of the Oral Capabilities in Relation to Bolus
- 880 Manipulations and the Ease of Initiating Bolus Flow, Journal of Texture Studies. 45
- 881 (2014) 1–12. https://doi.org/10.1111/jtxs.12041.
- [40] L. Laguna, R.A. Barrowclough, J. Chen, A. Sarkar, New Approach to Food Difficulty
- 883 Perception: Food Structure, Food Oral Processing and Individual's Physical Strength,
- Sournal of Texture Studies. 47 (2016) 413–422. https://doi.org/10.1111/jtxs.12190.

- [41] C. Peng, P.-G. Jost-Brinkmann, R.-R. Miethke, C.-T. Lin, Ultrasonographic 885 886 Measurement of Tongue Movement During Swallowing, Journal of Ultrasound in Medicine. (2000) 15-20. https://doi.org/10.7863/jum.2000.19.1.15. 887 [42] N. Uemori, Y. Kakinoki, J. Karaki, H. Kakigawa, New method for determining surface 888 roughness of tongue, Gerodontology. 29 (2012) 90-95. https://doi.org/10.1111/j.1741-889 2358.2011.00509.x. 890 891 [43] Y. Xu, B. Cartwright, L. Advincula, C. Myant, J.R. Stokes, Generalised scaling law for soft contact tribology: Influence of load and asymmetric surface deformation, Tribology 892 International. 163 (2021) 107192. https://doi.org/10.1016/j.triboint.2021.107192. 893 894 [44] J.M. Kim, F. Wolf, S.K. Baier, Effect of varying mixing ratio of PDMS on the consistency of the soft-contact Stribeck curve for glycerol solutions, Tribology 895 International. 89 (2015) 46–53. https://doi.org/10.1016/j.triboint.2014.12.010. 896 897 [45] L. Negadi, B. Feddal-Benabed, I. Bahadur, J. Saab, M. Zaoui-Djelloul-Daouadji, D. Ramjugernath, A. Negadi, Effect of temperature on density, sound velocity, and their 898 derived properties for the binary systems glycerol with water or alcohols, Journal of 899
- 900 Chemical Thermodynamics. 109 (2017) 124–136.
- 901 https://doi.org/10.1016/j.jct.2017.01.011.
- 902 [46] L. Engelen, Oral Receptors, in: J. Chen, L. Engelen (Eds.), Food Oral Processing:
- 903 Fundamentals of Eating and Sensory Perception, 1 st ed., Blackwell Publishing Ltd,
- 904 2012: pp. 15–43. https://doi.org/10.1002/9781444360943.
- 905 [47] N. Asamura, N. Yokoyama, H. Shinoda, Selectively stimulating skin receptors for tactile
- display, IEEE Computer Graphics and Applications. 18 (1998) 32–37.
- 907 https://doi.org/10.1109/38.734977.
- 908 [48] F. Shao, X.J. Chen, C.J. Barnes, B. Henson, A novel tactile sensation measurement
- 909 system for qualifying touch perception, Proceedings of the Institution of Mechanical
  - 39

- 910 Engineers, Part H: Journal of Engineering in Medicine. 224 (2010) 97–105.
- 911 https://doi.org/10.1243/09544119JEIM658.
- 912 [49] G.A. Van Aken, Modelling texture perception by soft epithelial surfaces, Soft Matter. 6
- 913 (2010) 826–834. https://doi.org/10.1039/b916708k.
- [50] R. Upadhyay, N. Brossard, J. Chen, Mechanisms underlying astringency: Introduction to
- an oral tribology approach, Journal of Physics D: Applied Physics. 49 (2016) 104003.
- 916 https://doi.org/10.1088/0022-3727/49/10/104003.