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1 Signal analysis to study the impact of
2 tongue roughness on oral friction
3 mechanisms with a custom-built
4 tribometer
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27 **Abstract**

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

45

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

48 1. Introduction

49 Texture perceptions of food encompass multiple sensory stimuli associated with the
50 structural and mechanical properties of food [1,2]. In particular, tactile features sensed when
51 food interacts with oral surfaces are among the main focuses of food texture investigations [3].
52 Complementary to sensory analysis, the understanding of the physical and mechanical
53 phenomena that can impact texture perceptions requires the development of experimental
54 approaches that integrate both the characteristics of the food and the complex properties of the
55 organs involved during oral processing [4]. Various prototypes attempting to more or less
56 completely mimic all the stages of food oral processing have thus been designed in recent years
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
63 lubrication phenomena and to try to uncover relevant friction factors and events that happen
64 between the tongue and the palate during eating [7,8]. Systematic and comprehensive reviews
65 explained in depth the current understanding of oral tribological investigations and their
66 influence on sensory perceptions [9,10]. The importance of emulating more closely real oral
67 conditions was well highlighted. To achieve these objectives, it is necessary to go beyond the
68 classic framework allowed by commercial tribology devices, either by adapting them or by
69 designing completely new ones. Taking into account the complex properties of the tongue is a
70 recognized prerequisite to realistically address the tribological behavior of food [11,12].

71 Accounting for tongue rigidity led to significant growth in oral tribology studies in
72 recent years, in particular with the use of PDMS as the most widespread substrate [13]. Human
73 tongue's elastic modulus has been measured to be around 10 kPa at rest and 120 kPa when
74 contracted [6]. With cryogels of polyvinyl alcohol (PVA), our group has chosen a material that
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
80 nature of tongue motions during friction with the palate also led some authors to the

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

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

93 Tongue roughness insights are also implemented in various custom tribological
94 instruments to make them more in line with oral conditions [7,25]. More generally, the effect
95 of surface roughness of soft tribopairs made of hydrogels has been the subject of different
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
99 different roughness properties, demonstrating a velocity dependence of friction attributed to
100 surface contact dynamics [26]. Roughness has also been considered directly on hydrogels that
101 were paired with smooth glass surfaces [27]. Confocal laser microscopy was used to visualize
102 the different contact behaviors at the interface. The differences in lubrication regimes observed
103 between smooth and rough gels were shown to diminish when the normal load increased.

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
109 conditions for tongue-palate interactions (shearing velocity of 20 $\text{mm}\cdot\text{s}^{-1}$, normal pressure up to
110 7 kPa), this work revealed two friction regimes. In the first regime, corresponding to low normal
111 loads, friction was shown to vary with surface roughness and hydrogels' stiffness. Beyond a
112 certain threshold of contact pressure, a second friction regime attributed to smoothing of
113 asperities led to a constant friction coefficient and was shown to be constant across roughness,

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

128 These different studies are essential to understand friction mechanisms involving rough
129 hydrogels. Nevertheless, most of these studies are based on the use of rheometers with rotational
130 geometries involving hemispherical probes on flat substrates. To explore contact surfaces that
131 are more representative of the contact between the tongue and the palate, new tribological
132 systems must therefore be designed and deployed. The implementation of tongue roughness in
133 oral tribology studies thus led to the consideration of new tribopairs with increased surface area,
134 leading to improved physiological relevance and paving the way for investigating the behavior
135 of complex and heterogeneous food models (e.g. presence of particles, mixtures of phases). It
136 is in particular for this purpose that a new custom-built tribometer was designed and presented
137 by our group in a recent publication [14]. The device allows the generation of a contact area of
138 approximately 10 cm² between the artificial tongue and palate, which is almost half of the total
139 surface of the hard palate, estimated at around 20 cm² [31]. Such a configuration thus offers
140 improved physiological relevance, when compared to that of conventional commercial
141 tribopairs. Still, with the aim of closer emulating in-mouth conditions, the use of two orthogonal
142 translation stages makes it possible to impose complex sequences of movements, combining
143 simultaneously both compression and shearing, exactly as we do when we eat. This marks the
144 main originality of our approach in the general context of the growing scientific community's
145 interest in soft tribology applied to food oral processing. The proof-of-concept publication made
146 it possible to perform a first scan of the different operational factors that can be varied on the

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].

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

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

173

174 2. Material and methods

175 2.1. Newtonian solutions of glycerol

176 Newtonian solutions of glycerol were prepared and used as lubricants for the
177 tribological measurements. As the experiments were conducted with fixed shear velocity and
178 normal force, varying the viscosity of the solutions made it possible to change the lubrication
179 regime and move along the Stribeck curve. Mixtures of glycerol (purity $\geq 99.0\%$, Thermo
180 Fisher Scientific, Waltham, MA, USA) and water were considered. Six solutions were prepared
181 in total, labeled based on their glycerol content (w/w %): G₁₀₀ (pure glycerol), G₉₇, G₉₃, G₈₅,
182 G₅₀, and G₀ (water). Concentration levels were defined based on literature data, in order to have
183 a progressive graduation of the viscosity level between G₀ (the thinnest) and G₁₀₀ (the thickest)
184 [33]. Water was added to glycerol in glass containers and placed under magnetic mixing for 30
185 minutes. The viscosity of the obtained solutions was measured on a rheometer (Physica MCR
186 301, Anton Paar, GmbH, Austria) with concentric cylinders (CC27/T200/SS), at 20° C.

187 The well-known and established Newtonian behavior was checked through
188 logarithmically increasing and decreasing shear rates (1-1000 s⁻¹). The average and standard
189 deviation values of viscosity at 50 s⁻¹ obtained after five replications are provided in Table 1,
190 50 s⁻¹ being recommended in the literature as a relevant shear rate for food oral processing [34].
191 A well-known non-linear behavior of viscosity versus glycerol concentration was confirmed
192 (exponential trend).

193

194 **Table 1.** Viscosity of glycerol and water mixtures measured at 50 s⁻¹ shear rate and 20° C
195 temperature. Standard deviation values were below 10⁻² mPa.s and G₀ value (water) was
196 taken from a literature report [35].

Solution label	G ₀	G ₅₀	G ₈₅	G ₉₃	G ₉₇	G ₁₀₀
Viscosity (mPa.s)	1	6	106	351	728	1352

197

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

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

203 of 2 h. The obtained solution was then poured in rectangular parallelepiped molds (dimensions:
204 length 80 mm, width 45 mm, thickness 25 mm). The objective was to prepare TMSs with
205 asperities in a range that is reminiscent of human tongue asperity heights [36,37]. The roughness
206 was obtained by covering the bottom face of the molds (80 × 45 mm) with sandpaper (Leman,
207 Saint-Clair-de-la-Tour, France) with varied classes of grain sizes: P₂₄, P₃₆, P₄₀, P₈₀, and P₁₀₀
208 (defined by the Federation of European Producers of Abrasives). These classes correspond to
209 the number of meshes per inch square of sieve surface used to size the grains: the higher the
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
212 smoother than the smoothest sandpaper sheet considered. The molds filled with PVA solution
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
216 laboratory kept at 20° C. After unmolding, TMSs were all stored under the same conditions:
217 they were placed in hermetic boxes, immersed in water, and maintained at ambient laboratory
218 temperature (20°C). Under these conditions, PVA cryogels can be stored for several months
219 without their mechanical properties to be altered. In the present case, a week passed after the
220 manufacture of the TMSs, before the start of the experiments. Then, all the experiments were
221 carried out over a period of about a month.

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

231 The roughness of the TMSs was analyzed by profilometry (DektakXT[®], Bruker, USA).
232 Tested samples included one TMS per class of roughness (six samples). Three one-dimensional
233 profiles were performed for each TMS analyzed (each was 30 mm long), with a 45° rotation
234 between one profile and the next, in order to cover as well as possible the area of interest for
235 tribology measurements. The profilometry probe was a stylus with a 2 μm radius, the force was

236 1 mg, and the achieved resolution was $1.66 \mu\text{m}/\text{pt}$, at a constant speed of $500 \mu\text{m}\cdot\text{s}^{-1}$. The data
237 from each one-dimensional profile (signals of the measured asperity height as a function of the
238 tip scan distance) was processed individually on MATLAB (The MathWorks, Natick,
239 Massachusetts, USA). On the 1-D profiles, the absence of qualitative differences between the
240 slopes of the ascending and descending phases of the indenter suggested that the settings have
241 made it possible to limit potential scratching effects. The processing of the profiles and the
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
245 flatness and not to the shape of asperities). The cut-off length λ_c used in the filter was set to 10
246 mm, which is ten times higher than the highest grain size of the coarsest sandpaper used, and
247 which also corresponds to the course of shear motions implemented for the tribological tests
248 described hereafter. Two main roughness parameters were calculated from the filtered profiles:
249 the arithmetical mean height (R_a) and the mean width of the profile elements (R_{Sm}). R_a is the
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 R_a parameter is therefore linked to the
252 vertical amplitude of the roughness. R_{Sm} for its part was calculated as the average value of the
253 distance between the changes of sign of the height of the profiles (crossing of the average
254 height). This parameter, therefore, provides information on the width of the asperities. The
255 mean and standard deviations of R_a and R_{Sm} values obtained from the three one-dimensional
256 scans performed on each TMS were then calculated.

257 In addition to the one-dimensional measurements, for each of the six roughness levels
258 studied, two-dimensional measurements were performed with the same profilometry
259 equipment, consisting of 125 successive one-dimensional profiles performed with the same
260 settings. With a spacing of $20 \mu\text{m}$ between each profile, it was possible to cover a surface of
261 $2.5 \times 3.0 \text{ mm}$, to have two-dimensional representations for the qualitative visualization of the
262 surface morphology.

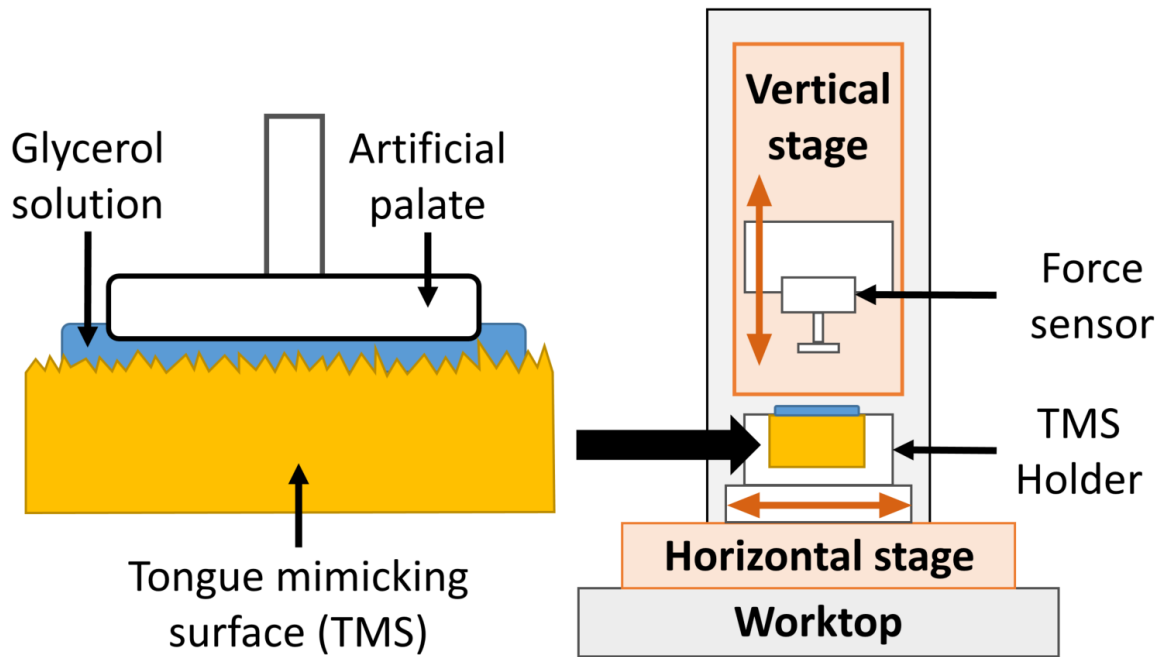
263 2.3. Custom-built tribometer

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

269 Hennigsdorf, Germany) with a measurement range of ± 50 N and an accuracy of 1%. The
270 manufacturer indicates a sensitivity to transverse forces (cross-talk) of 1% of the measuring
271 range at full load. Fillets were made on the edges of the palate (radius 2 mm) so as to limit the
272 risk of damaging the TMSs during friction phases. During the design of the system, the distance
273 between the sensor and the surface of the palate on which friction operates was reduced as much
274 as possible (approximately 3 cm), in order to limit undesired bending effects, induced by the
275 moment arm which applies to the force sensor. Indeed, it is important to note that the technology
276 of strain gauge sensors is based on the principle of deflecting under load. Specifications from
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
280 several millimeters. Under these conditions, the inclination of the palate caused by the twisting
281 of the sensor must have a limited impact on the contact, which remains distributed over the
282 entire lower face of the palate plate. A tongue holder part (with a parallelepipedic cavity
283 adjusted to the dimensions of the TMSs) was attached to the horizontal stage. Both translation
284 stages are displacement-controlled. LabVIEW[®] software (N.I., Austin, Texas, USA) was used
285 to (i) control and acquire the position of the translation stages undergoing imposed sequences
286 of motions and (ii) acquire in real-time the data from the force sensors using a bridge module
287 with a 25 kHz sampling rate (NI-9237, N.I., Texas, USA).

288 2.4. Friction test protocol

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



295

296 **Figure 1.** Schematic representation of the custom-built tribometer. The lower part includes a
 297 TMS positioned on a horizontal translation stage (used to impose shearing movements). The
 298 upper part includes the rigid artificial palate and a force sensor, both mounted on a vertical
 299 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
 302 aluminum plate playing the role of the palate, following previously established protocols [14].
 303 Then, the aluminum plate was lowered until flush with the surface of the TMS, allowing to
 304 ensure the regular distribution and the spreading of glycerol solutions, with some excess
 305 expelled all around the aluminum plate's sides. Finally, the artificial palate was again lowered,
 306 until reaching a target value of normal force equal to 10 N (~9 kPa stress, based on the
 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
 310 position was reached, the testing sequence protocol was triggered without delay. The test
 311 protocol consisted of repeating a cycle five times during which shearing motions alternated
 312 with rest steps, in the absence of vertical motions. Figure 2 (a) represents the measurements of
 313 the variations of the position of the horizontal translation stage as a function of time during a
 314 cycle. The absence of curvature during the transient phases of acceleration and deceleration of
 315 the stage reveals that these phases are very short, both with respect to the scale of the duration

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

318 - Step #1: the horizontal translation stage moves forward in a total of 10 mm distance
319 with a constant shearing velocity of 10 mm.s^{-1} ;

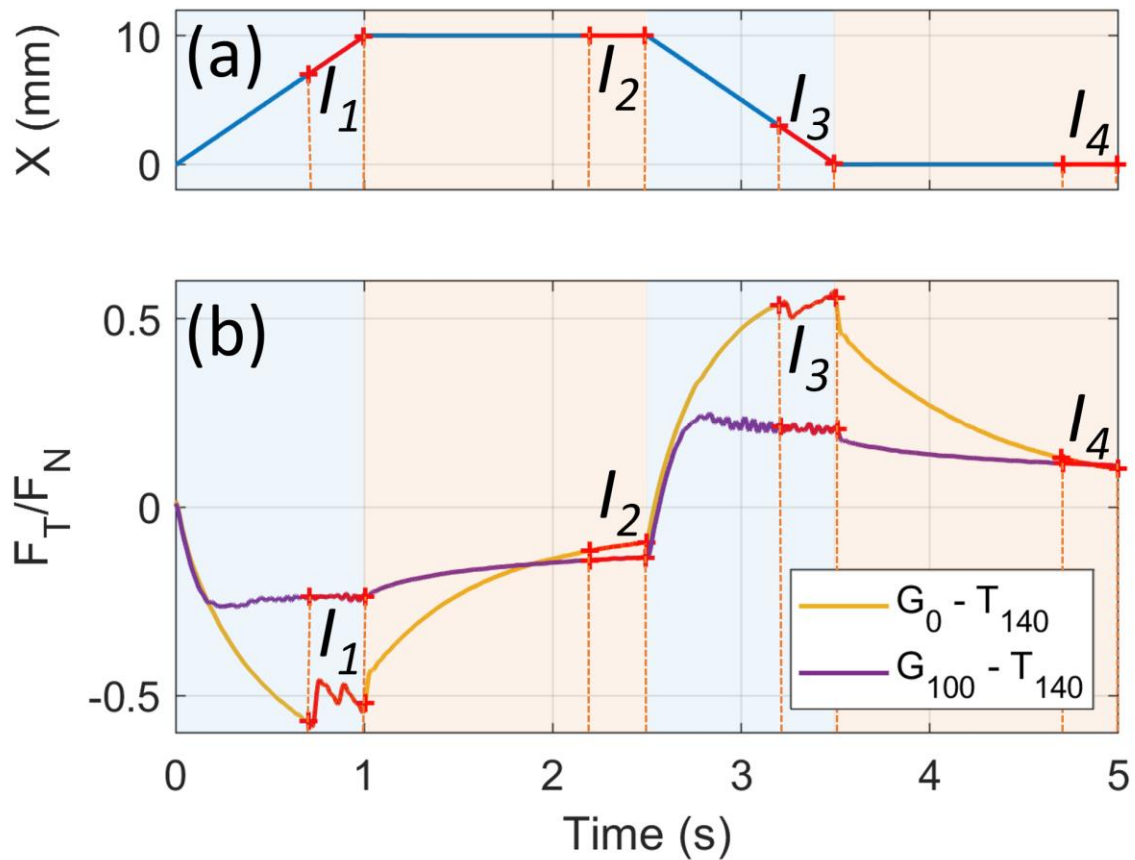
320 - Step #2: a first holding step is observed for 1.5 s, with both stages held stationary;

321 - Step #3: the horizontal translation stage moves back to its initial position with the same
322 constant shearing velocity of 10 mm.s^{-1} ;

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

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

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



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Figure 2. (a) Displacement of the horizontal translation stage during one out of the five cycles composing a tribological test. (b) Corresponding curves of the ratio between tangential and normal forces provided in the case of TMS T_{140} (molded on P_{36} sandpaper) for two conditions of lubrication: G_0 in yellow and G_{100} in purple. Motion steps (rest steps, 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 analysis of the force ratio signal was focused in the paper: I_1 and I_3 at the end of motion steps, I_2 and I_4 at the end of rest steps.

346

2.5. Processing and analysis of tangential to normal force ratio

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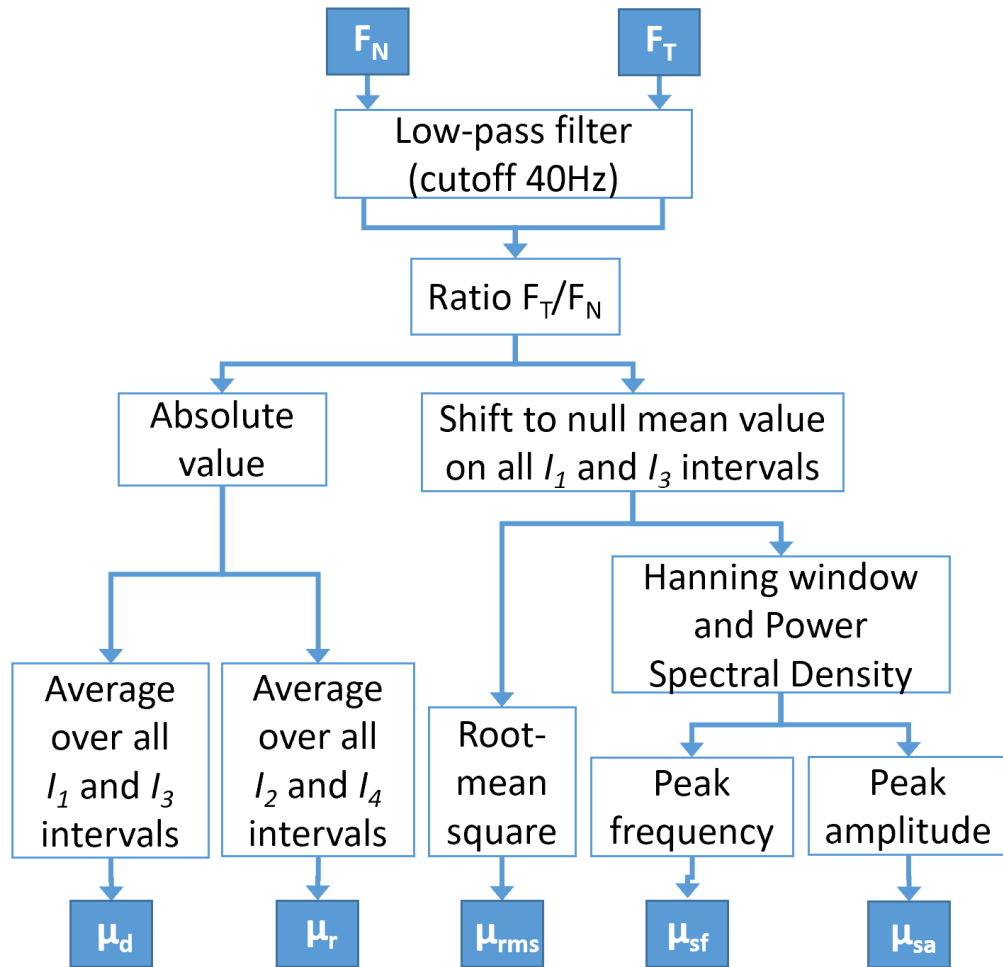
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The analysis of the signals recorded from the force sensor was performed using MATLAB (The MathWorks, Natick, Massachusetts, USA). The analysis was focused on the channels corresponding to normal and tangential loads. The signal processing is described 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.



353

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

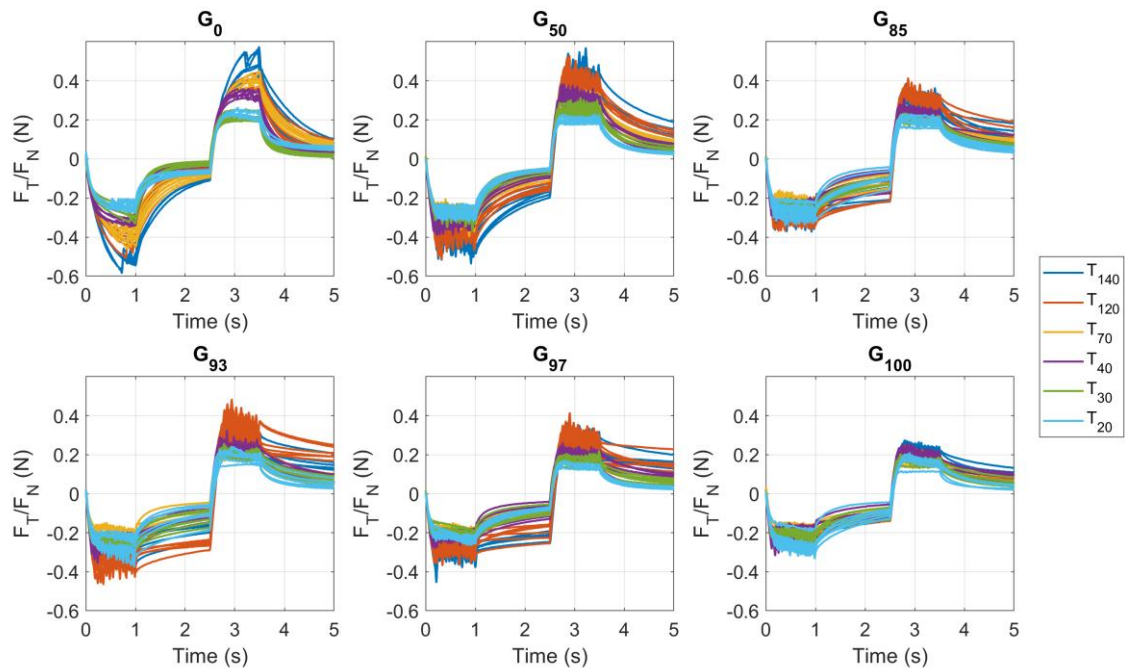
357 At first, to improve the signal-to-noise ratio and to eliminate undesirable components
 358 such as oscillations corresponding to 50 Hz power supply, a low pass filter (infinite impulse
 359 response filter, 6th order, cut-off 40 Hz) was applied to all normal (F_N) and tangential (F_T) force
 360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

368 Then, a particular effort was devoted to the analysis of the ratio between tangential and
369 normal forces (directly related to friction). Figure 2 (b) shows examples of the evolution of the
370 ratio between tangential and normal forces (F_T/F_N) during the first cycle of a test sequence
371 (TMS molded with P₃₆ sandpaper) for two conditions of lubrication: G_0 in (b) and G_{100} in (c).
372 These examples are representative of the diversity of the trends observed throughout the
373 different tested conditions (which are all provided separately in Figure 4). Quantitative
374 information was extracted from the amplitude of this ratio, focusing on time windows defined
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
377 a maximum of information on the fluctuations of F_T/F_N , but also sufficiently narrow to ensure
378 encompassing a period of time during which the average level of F_T/F_N tends to reach a plateau
379 and therefore varies moderately. The duration of these intervals (0.3 s) was set based on the
380 overall observation of the trends of all the tests, and after a series of attempts of calculation with
381 different duration values. For each step of each cycle, the average values of $|F_T/F_N|$ (absolute
382 value of F_T/F_N) over the corresponding time windows were determined (time windows I_1 , I_2 , I_3 ,
383 and I_4 for steps #1, #2, #3, and #4, respectively). A preliminary analysis of these average values
384 showed that there was no benefit in studying separately the information related to the forward
385 and backward motions (either the motion steps #1 and #3 or the consecutive rest steps #2 and
386 #4), nor to study a possible evolution of these mean values cycle after cycle during a test. In all
387 cases, the differences or variations were not significant with respect to the intervals formed by
388 the standard deviations. Consequently, it was decided to calculate, for each test, the average of
389 the absolute value of the F_T/F_N ratio of (i) all the forward and backward motion step intervals
390 (I_1 and I_3) and (ii) all the rest step intervals (I_2 and I_4). In what follows, the obtained average
391 ratios during motion steps are referred to as μ_d (“d” for dynamic), while the average ratios
392 during rest steps are referred to as μ_r (“r” for residual).

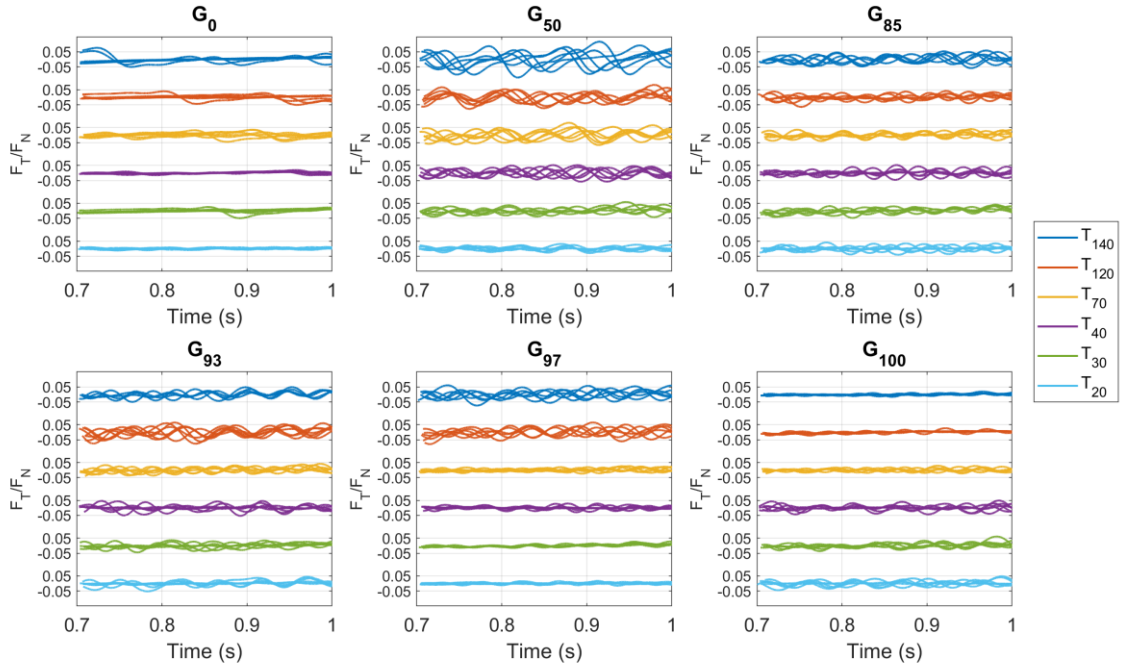
393 The fluctuations over time in F_T/F_N ratio were studied on the time intervals I_1 and I_3 (0.3
394 s at the end of motion steps #1 and #3). For each time interval, a shift to a null mean value was
395 first applied. As an example, Figure 5 displays all the shifted signals for the first interval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

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

406 The mean values and standard deviations of each of the parameters studied (μ_d , μ_r , μ_{rms} ,
 407 μ_{sf} , and μ_{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).



412
 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).



416

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.

422

423 3. Results and discussion

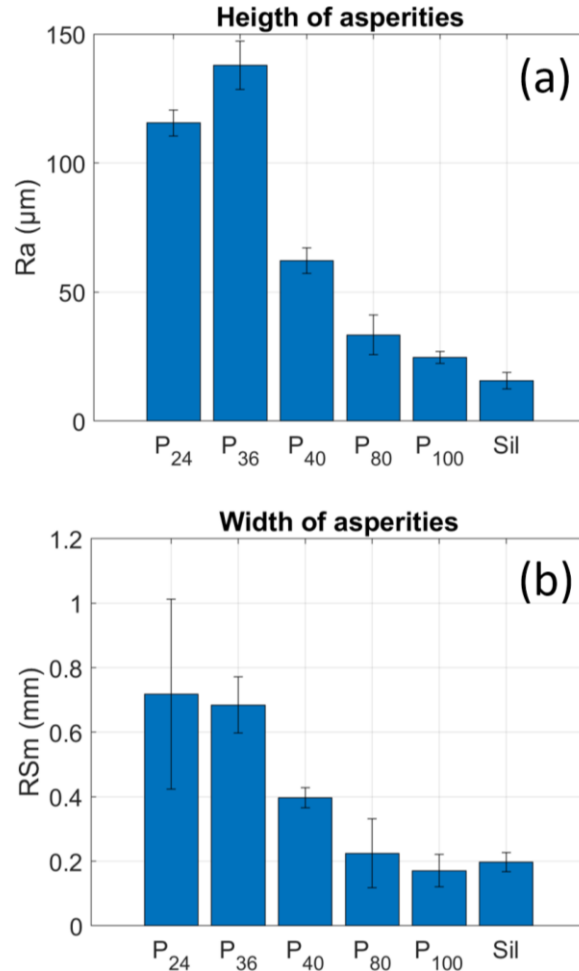
424 This results and discussion section first focuses on the characterization of the roughness
 425 of the TMSs, which is the factor having received the most extensive attention for the objectives
 426 of this study. The discussion then revolves around the results of the tribology measurements
 427 carried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

433

434

435 3.1. Roughness properties of the TMSs

436 The topography of the TMSs was characterized in order to analyze (i) the impact of the
437 imprint material used in the molding process (sandpapers or silicone sheet) on the height and
438 width of TMSs asperities, and (ii) the physiological relevance of obtained roughness properties.
439 The average and standard deviation values of Ra and RSm parameters, obtained on the six types
440 of TMSs, are represented in the form of histograms in Figure 6. The legends in the abscissa axis
441 correspond to the materials used to imprint the roughness to the TMSs: five abrasive paper
442 references (P₂₄, P₃₆, P₄₀, P₈₀, and P₁₀₀) and a silicone sheet (Sil). Quite expectantly, the general
443 trend was that the higher the SEPA class of sandpaper roughness (from rough P₂₄ to smooth
444 P₁₀₀ sandpaper), the lower the obtained values of Ra and RSm. If RSm values seem to
445 correspond well to the grit size of the sandpapers, the Ra values are for their part an order of
446 magnitude lower. Shrinking phenomena previously evidenced for PVA artificial tongues [14]
447 may explain the discrepancy between sandpaper grit size and Ra values. When looking closer,
448 the TMS prepared with P₃₆ sandpaper class had a higher asperity height Ra than the TMS
449 prepared with the roughest sandpaper (P₂₄). Differences in the wetting abilities of the abrasive
450 surfaces by the PVA solution might be expected according to the roughness characteristics of
451 the sandpaper. For rough surfaces, air might be entrapped at the bottom of the valleys of the
452 asperities, affecting the resulting roughness of the print. These observations show the
453 importance of characterizing the TMSs after their manufacturing, as the reliable reproduction
454 of the roughness of the molds is a very complex task.



455

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 P₂₄ to P₁₀₀)
 458 while the last one was molded on a silicone sheet (Sil).

459 The two parameters Ra and RSm were shown to follow similar trends across the
 460 different TMSs. As Ra is generally considered as the reference roughness property in the
 461 literature, in the rest of the manuscript, the six types of TMSs have been labeled according to
 462 their average Ra value (rounded up to the next ten microns): T₂₀, T₃₀, T₄₀, T₇₀, T₁₂₀, and T₁₄₀.
 463 Table 2 provides the correspondence between the name given to each TMS, the material on
 464 which they were molded (silicone or sandpaper), the grit size in the case of sandpaper
 465 (according to the SEPA classification), and the mean and standard deviation values of Ra and
 466 RSm actually measured. Hereafter, the results will be systematically presented by classifying
 467 the TMSs in increasing order of the mean Ra value.

468

469 **Table 2.** Table of the different TMSs, indicating their names, the material on which they were
 470 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 measured.

TMS label	T ₂₀	T ₃₀	T ₄₀	T ₇₀	T ₁₂₀	T ₁₄₀
Imprint material	Silicone	P ₁₀₀	P ₈₀	P ₄₀	P ₂₄	P ₃₆
Grit size (μm)	-	160	200	400	750	550
Ra (μm)	16 ± 3	25 ± 2	33 ± 8	67 ± 5	116 ± 5	138 ± 9
RSm (μm)	198 ± 3	171 ± 5	225 ± 1	397 ± 3	718 ± 2	685 ± 8

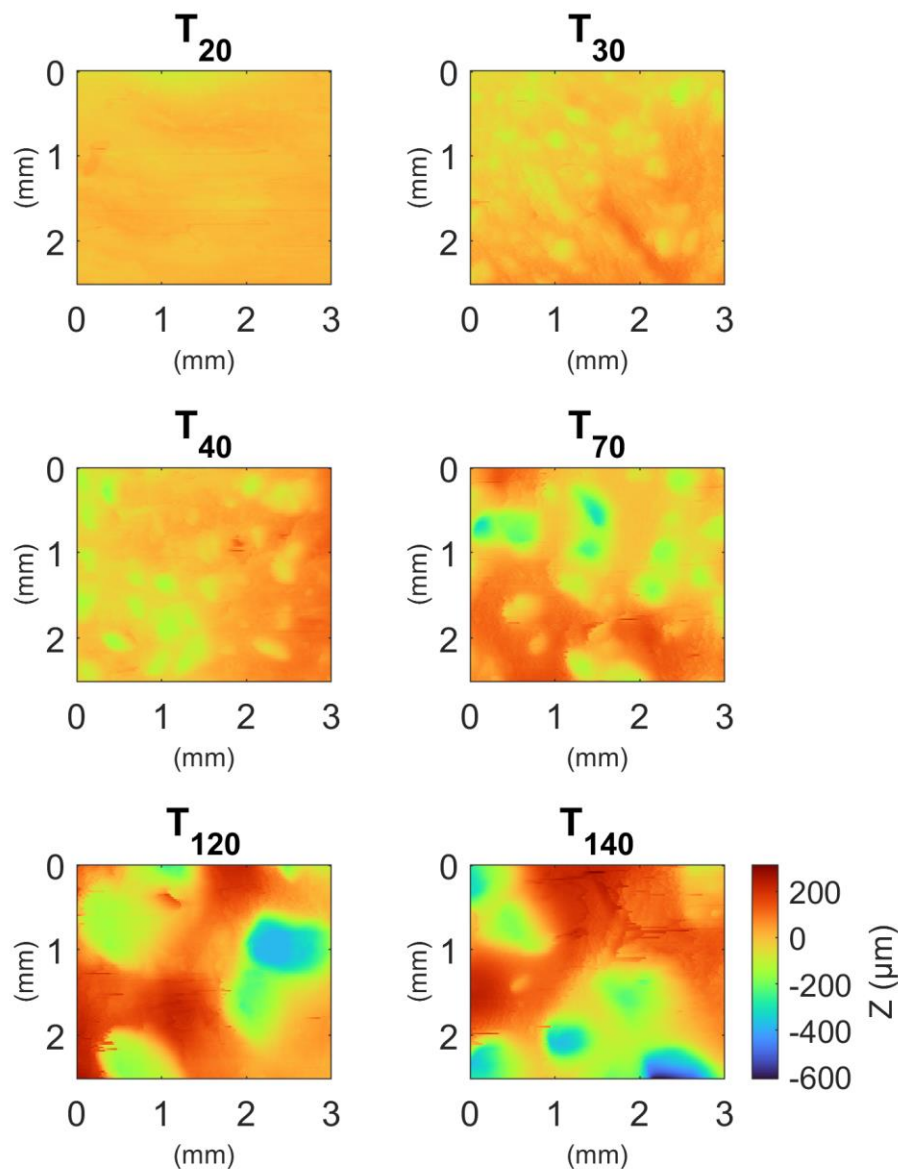
473

474 Figure 7 shows the 2-D images of profilometry obtained on the six types of TMSs. They
 475 make it possible to qualitatively confirm, from T₂₀ to T₁₄₀, the increase in the height and width
 476 of the asperities, consistently with the measured values of Ra and RSm. Nevertheless, it is
 477 noticeable that the qualitative differences in visual appearance between the TMSs T₂₀ and T₃₀
 478 are more pronounced than what the gap of measured values of Ra and RSm would suggest. One
 479 hypothesis that could explain this is that for low roughness levels, the cut-off length λ_c of the
 480 applied pre-processing filters is less suitable for separating the roughness and waviness
 481 components of the profiles. The reliability of the values of the resulting roughness parameters
 482 can thus be affected. Subsequently, in the following, we will therefore keep in mind that the
 483 TMS T₂₀ (made from a silicone sheet) is smoother than the TMS T₃₀ (obtained from P₁₀₀, the
 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
 486 physiologically relevant after comparison with *in vivo* measurements from the literature. Such
 487 measurements are particularly complex *in situ* because the surfaces to characterize are difficult
 488 to access and pose great technical problems because of their irregularity and their high
 489 deformability. Most studies rely on the *ex situ* analysis of casts, which raises the question of
 490 potential loss of information between the roughness properties of the reference surface (that
 491 one wishes to characterize) and those from the molds on which the measurements are actually
 492 carried out. This challenge has been tackled by several teams who have conducted essential
 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

496 μm in a more recent one with 71 volunteers [36]. Differences could also be noticed between
497 fungiform ($390.0 \pm 72.0 \mu\text{m}$) and filiform ($195.0 \pm 30.0 \mu\text{m}$) papillae [37]. Although presenting
498 slight differences attributable to the technical difficulties mentioned above and to inter-
499 individual variability, these precious orders of magnitude turn out to be in good agreement with
500 the measurements carried out on the TMSs of the study, thus validating their physiological
501 relevance. The analysis of the tribology results below is thus based on experiments carried out
502 under topographical conditions consistent with the physiological environment.

503



504

505 **Figure 7.** 2-D images of profilometry obtained on the six types of TMSs, where the
506 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
510 water (G_0) in yellow, and pure glycerol (G_{100}) in purple. These examples illustrate the diversity
511 of the trends observed throughout the different tested conditions, which are all available in
512 Figure 4. During the motion steps (between 0 and 1 s and between 2.5 and 3.5 s), two well-
513 known phases of evolution of the ratio between tangential and normal forces may be
514 distinguished. During the first phase (which can be referred to as static phase), a progressive
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
518 second phase (referred to as dynamic phase) may correspond to crossing of the friction cone.
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
521 duration of these two phases varies greatly across the different experimental conditions. Figure
522 2 (b) shows two of the most distinct scenarios that can be observed on the entire dataset, both
523 obtained with the roughest TMS (T_{140}). On these examples, lubrication with thin G_0 led to a
524 high level of friction reached at the end of a long static phase. Contrarily, lubrication with thick
525 G_{100} displayed a low level of friction after a short static phase. Hereafter, friction analysis was
526 focused on the plateau values of $|F_T/F_N|$ reached at the end of the motion and rest steps of the
527 tests (μ_d and μ_r).

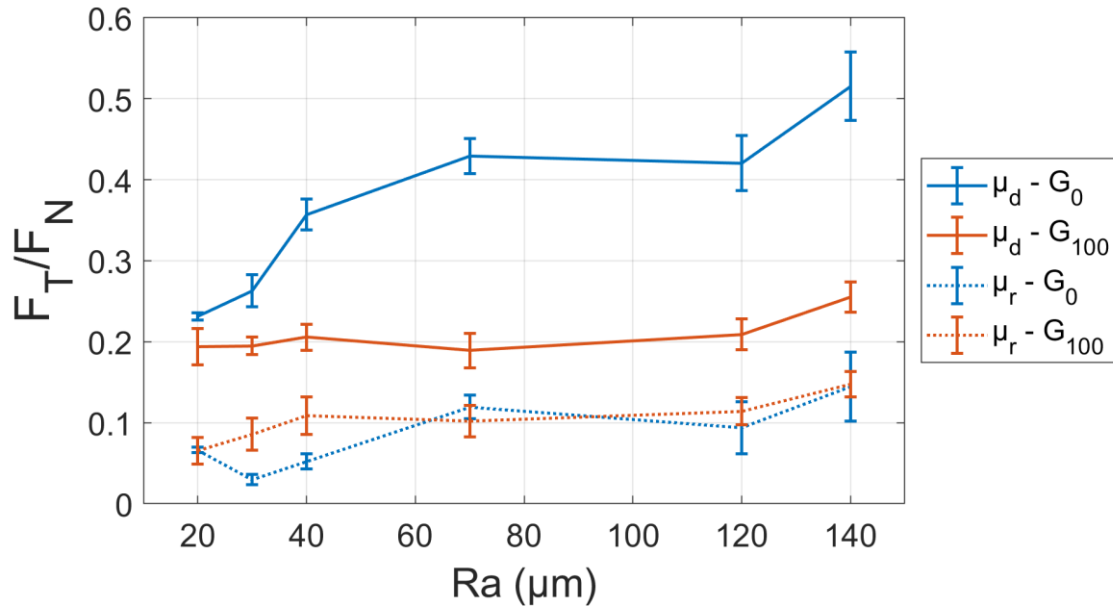
528 3.2.1. Friction levels in two extreme cases of lubrication

529 The behavior of coefficients μ_d (magnitude of $|F_T/F_N|$ at the end of motion steps) and μ_r
530 (at the end of the rest steps) will first be discussed in the two extreme cases of lubrication by
531 pure water and pure glycerol (G_0 and G_{100}). In Figure 8, the average values of μ_d and μ_r have
532 been plotted as a function of the mean Ra roughness values measured on the different TMSs.

533 Lubrication with the most viscous solution (G_{100}) led to the lowest values of μ_d , with, if
534 any, a moderate roughness dependence observed across the six TMSs. Combined with the short
535 durations of static friction phases observed during the motion steps and already reported in the
536 raw curves provided in Figure 4, these observations suggest that the hydrodynamic lift exerted
537 by G_{100} may be high enough to avoid any direct contact between the asperities of the TMSs and
538 the palate plate (for these conditions of shearing velocity and normal force). The most probable

539 hypothesis is thus that under these conditions, the system gets close to the hydrodynamic
540 regime. Contrastingly, lubrication with the thinnest solution (G_0) led to an increase of μ_d with
541 roughness, starting from a low level close to that of G_{100} for the smoothest TMS and moving
542 away from it as the TMSs become rougher. This increase of μ_d with roughness may be
543 associated with an increase of the effective area of contact between the asperities of the TMS
544 and the palate. Such trends are thus consistent with the mixed regime of lubrication.

545 If μ_d coefficient can be directly compared to the friction coefficient commonly assessed
546 with commercial tribometers, the residual friction level μ_r characterized during rest steps is less
547 classic. Food oral processing being composed of alternating phases of motion and rest,
548 following the evolution of the friction ratio F_T/F_N during motionless steps may also provide
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
552 force signals at any time during a test. For each individual condition of lubrication and
553 roughness, μ_r was found to be lower than μ_d , reflecting the tendency of the system to adapt itself
554 to the mechanical stresses applied during the motion steps. These particular plots do not make
555 it possible to identify a clear trend of dependence of μ_r on the roughness of the TMSs or on the
556 type of lubricant. Indeed, independently from the level of friction reached at the end of a shear
557 motion, rest periods generally enabled the recovery of similar residual levels of $|F_T/F_N|$ before
558 moving to the next motion step. The amplitude of the decrease of $|F_T/F_N|$ observed both for G_0
559 and G_{100} during rest steps could thus be directly linked to the magnitude reached at the end of
560 motion steps. When shear motions are stopped, the hydrodynamic pressure exerted by the fluid
561 at the interface suddenly drops. The fluid in question then flows out of the space under the
562 palate plate and at least part of the asperities of the TMS comes into direct contact with the
563 plate. Resulting adhesion between the TMS and the palate may lead to residual stresses within
564 the TMS, which can give rise to mechanical relaxation phenomena.



565

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

569 Based on the trends of μ_d and μ_r observed in the cases of lubrication with the thinnest
 570 and the thickest solutions, the following part of the discussion suggests taking a closer look at
 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
 573 progressively investigate transitions through lubrication regimes [43]. Mixtures of glycerol and
 574 water were considered here as they are commonly used in classical tribological investigations
 575 for the construction of Stribeck curves [44], and they make it possible to cover much of the
 576 spectrum of viscosity properties of the liquid foods we consume. It is also interesting to note
 577 that the literature reports that from 80 to 100% glycerol concentration, reorganizations take
 578 place in the solutions, resulting in a sharp increase in compressibility [45].

579

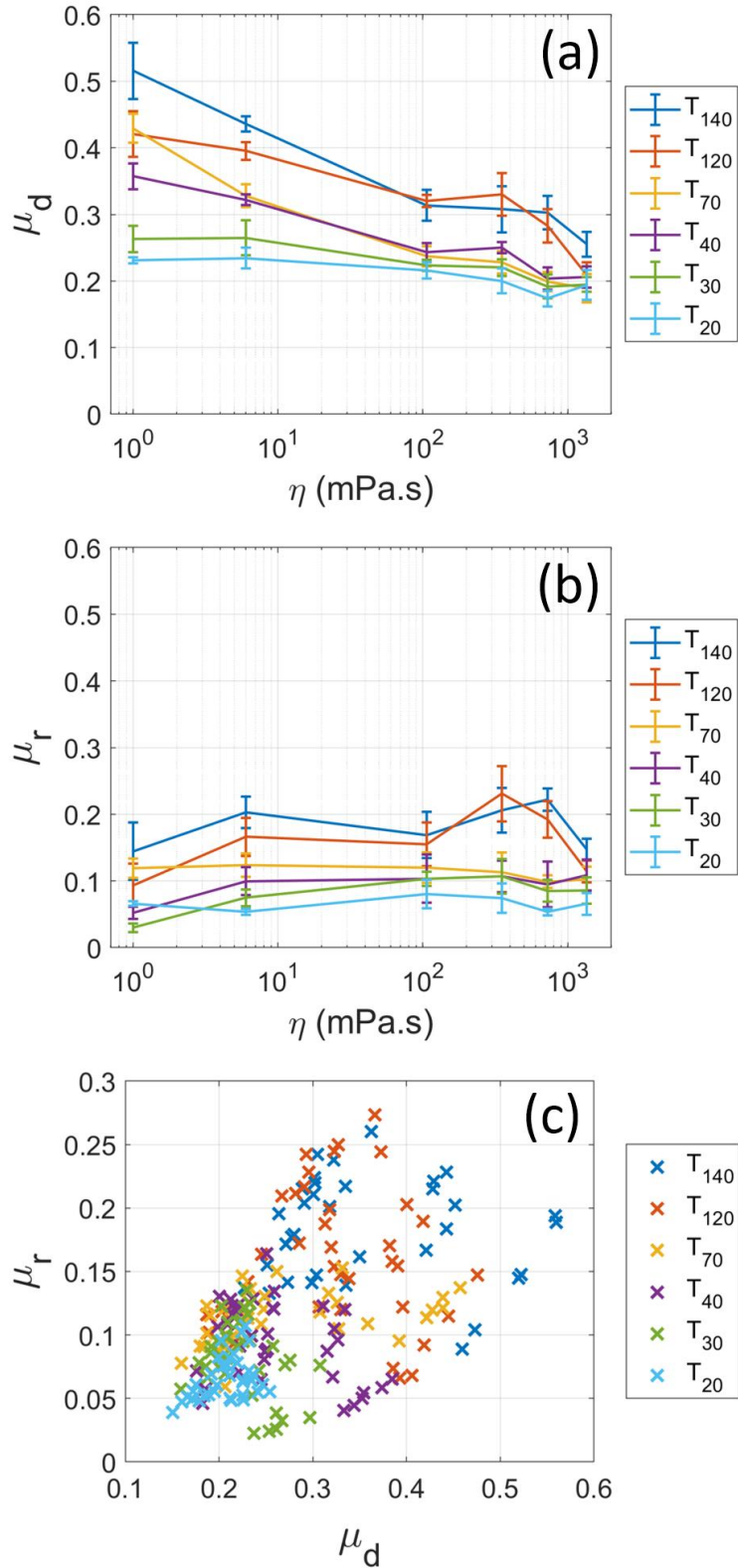
580 3.2.2. Friction levels in intermediate cases of lubrication

581 Figures 9 (a) and (b) represent the variations of μ_d and μ_r as a function of lubricant
 582 viscosity for the six TMSs. From the smoothest to the roughest TMS, an increased dependence
 583 of μ_d on viscosity is observed, with a decreasing trend which may be characteristic of the mixed
 584 regime of lubrication. As the TMSs become smoother, an attenuation of the decay of μ_d is

585 observed, with μ_d levels becoming lower. Such trend may suggest that for smoother TMSs, the
586 system reaches the transition phase between mixed and hydrodynamic regimes.

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

605



606

607 **Figure 9.** Average and standard deviation values of μ_d (a) and μ_r (b) as a function of
 608 lubricant viscosity for the six TMSs. In (c), μ_d and μ_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).

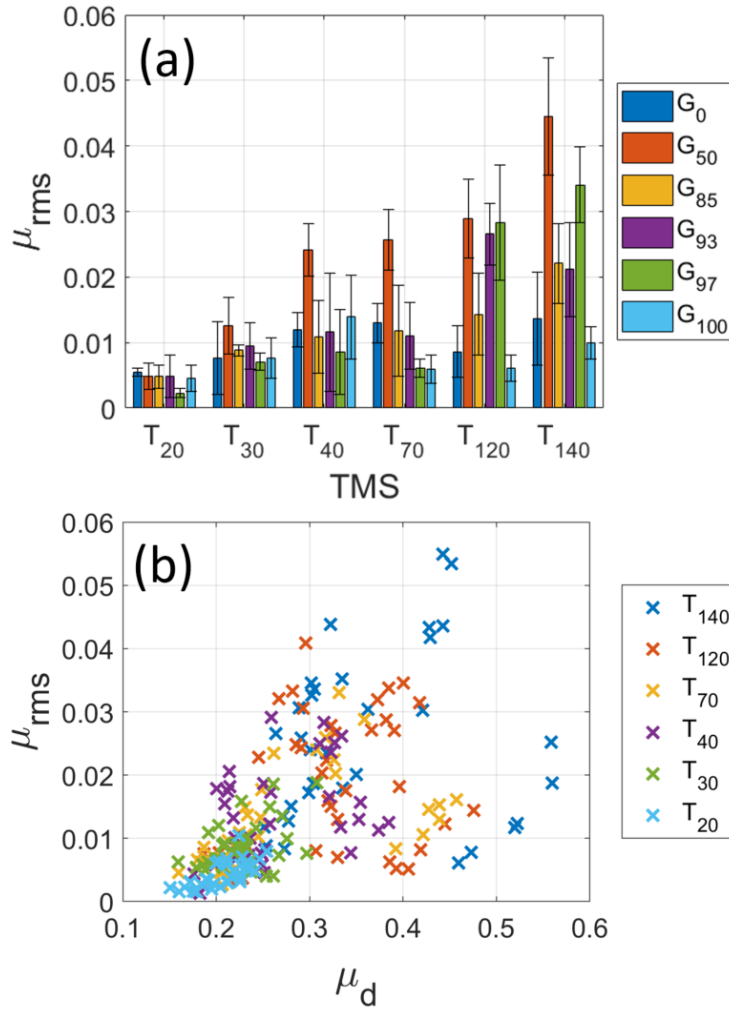
611 3.3. Fluctuations of friction levels during motion steps

612 Most conventional tribology tools limit the analysis of force signals to the calculation
613 of the friction coefficient, which is calculated over time intervals during which shears forces
614 are high enough to induce sliding between the tribopairs, as done in the present study with
615 parameter μ_d . However, the ratio F_T/F_N evolves all along the time windows on which μ_d is
616 calculated, and such dynamic behavior also deserves attention. Sanahuja et al. [32] have
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
622 out of the ten time windows used for the calculation of μ_d . Varied behaviors of fluctuations in
623 F_T/F_N could be reported across the different lubrication and roughness conditions. Such
624 fluctuations may carry information about the influence of tongue roughness and lubrication on
625 intermittent adhesion and sliding events at tongue-palate interface. Quantitative parameters
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 μ_{rms} , corresponding
628 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
629 steps). For most of the lubrication conditions considered, the general trend observed was that
630 the rougher the TMS, the higher the reported levels of μ_{rms} . This tendency of the dependence of
631 μ_{rms} on the roughness of the TMSs supports the hypothesis that the level of normal force applied
632 in the present experiments is not sufficient to completely deform and flatten the asperities of
633 the TMSs. The importance of the intermittence of contact and slip events at the interface
634 between the TMS and the palate testified by the high levels of μ_{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
637 reproducibility of the measurements (shorter error bars), the lower the amplitude of μ_{rms} , and
638 the lower the differences reported across the six solutions. Conversely, the rougher the TMS,
639 the lower the reproducibility but the higher the diversity of amplitude levels of μ_{rms} observed
640 across the lubrication conditions. Interestingly, although G_0 and G_{100} have been shown to
641 display the most contrasting levels of μ_d , they behaved similarly with respect to μ_{rms} . Indeed,
642 both conditions led to the lowest levels of μ_{rms} , with low variations across the different TMSs.
643 Oppositely, G_{50} led to the highest levels of μ_{rms} reported on each of the TMSs, even though it

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

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



668

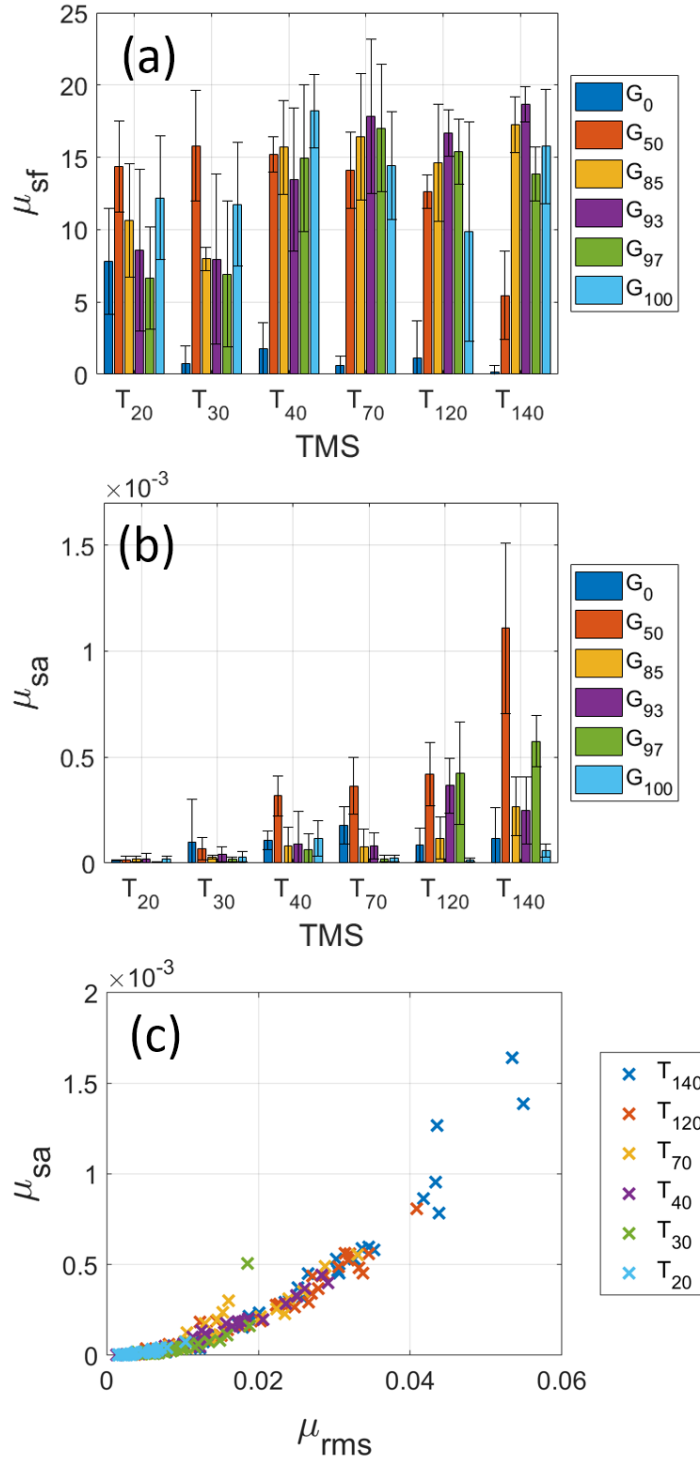
669 **Figure 10.** (a) Average and standard deviation values of the root mean square μ_{rms} of F_T/F_N
 670 during the 0.3 s before shear motions end. (b) μ_{rms} and μ_d values plotted against each other
 671 for each test performed, with points of the same color corresponding to tests carried out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

673

674 Figures 11 (a) and (b) describe the mean and standard deviation values of the frequency
 675 (μ_{sf}) and the amplitude (μ_{sa}) associated with the peak of the frequency spectrum of F_T/F_N signals
 676 (taken from the 0.3 s before shear motions end) on all I_1 and I_3 intervals. The results show that
 677 μ_{sf} (frequency at which the spectrum peak amplitude occurs) does not vary significantly
 678 between the different roughness conditions. Except for the results obtained on G₀ (lowest
 679 viscosity) which show lower frequencies, the average frequencies ranged between 10 and 20
 680 Hz, without clear trends or statistical differences between the different roughness and
 681 lubrication conditions. A relationship between this frequency μ_{sf} and the characteristic width of

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

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



699

700 **Figure 11.** Average and standard deviation values of the spectrum frequency μ_{sf} (in a), and of
 701 the spectrum amplitude μ_{sa} (in b) of F_T/F_N during the 0.3 s before shear motions end. (c) μ_{sa}
 702 and μ_{rms} values plotted against each other for each test performed, with points of the same
 703 color corresponding to tests carried out with the same TMS (all lubrication conditions
 704 combined).

705 4. Conclusion

706 The artificial tongues made from PVA implemented on this custom-built tribometer
707 confer the originality of being able to study the role of the roughness of the tongue by
708 considering a tribopair with a physiologically relevant contact surface. Furthermore, the
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
712 steps were found to increase when (i) the roughness of the TMSs increased and when (ii) the
713 viscosity of glycerol solutions decreased. These trends could be consistent with mixed
714 lubrication. The decrease of friction level during rest steps showed a potential to monitor
715 mechanical relaxation in the bulk of the TMSs. Finally, the fluctuations of friction level during
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
720 restricted, the study shows that deeper analyses of the signal of the friction level may therefore
721 provide additional knowledge, that could contribute to a better understanding of the
722 mechanisms of texture perception.

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

728 As food oral processing cannot be represented just by pure shear back-and-forth motions
729 as considered here for validation purposes, future work will require the usage of the full capacity
730 of the custom-built tribometer. Complex sequences of motions combining compression and
731 shear can indeed be imposed, and the behavior of normal and tangential forces will be
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
735 to semi-solid products, with various degrees of heterogeneity. The validation of this newly
736 designed system may thus open up many opportunities for aiding in the development of novel
737 food products adapted to the physiology of specific populations.

738

739 5. Credit author statement

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751

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755

756 7. Declaration of interest

757 The authors have no conflicting financial or any other interests to declare.

758

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761 9. References

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