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Can tribology be a tool to help tailor food for elderly population?

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The rapidly ageing population requires food products that meet their specific physiological needs and have pleasurable sensory characteristics. Conventionally, rheology is used as a food formulation design tool that allows food bolus to be swallowed safely. Nevertheless, in the last few decades, there has been increased understanding of soft tribology of thickeners and fabrication of biologically relevant tribological set-ups. We discuss how this knowledge can offer a solid baseline to employ tribology as a design tool to tailor foods for the elderly population with various oral insufficiencies. In-depth characterisation of oral conditions of the elderly population is a necessary undertaking to fabricate tribology apparatus that better emulates *in vivo* conditions, to allow rational design of food products for this growing population.

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Introduction

People are generally living longer today than in the past and the elderly represent the world's fastest-growing demographic group. According to the World Health Organization, it is estimated that by 2050, the proportion of the world's population aged over 60 years will nearly double to 22% [1]. Recognising that the increase in the elderly population is a leading demographic trend globally, the United Nations has declared 2020–2030 the 'Decade of Healthy Ageing' [1]. For the food industry, this demographic shift suggests that a special taskforce is needed to design safe, pleasurable and nutritious food products that will nourish this growing population and improve their quality of life. This represents a major technological challenge, as ageing not only results in gradual impairment and/or decline in repair functions of physical, physiological, cognitive and cellular processes, but is also accompanied by the occurrence of multiple life-threatening health conditions [2–4]. From a food ingestion perspective, ageing involves issues with eating capability, salivation, oro-sensory perception, swallowing and digesting, all affecting the overall nutrient intake [5,6]. So far, the two most commonly used food design strategies for older adults are 1) fortification of foods with calories or bioactive compounds to improve nutrient intake [7–11] and 2) development of texture-modified foods or thickened liquids [12–14] focusing mainly on *rheology* as a design tool to cater the lack of dentition, hyposalivation and swallowing disorders (Table 1). Tackling oropharyngeal dysphagia has also emerged as an important research theme, as swallowing disorders are common conditions affecting the health of older adults [15–27].

Oral processing of food is a complex dynamic process covering several length and time scales where food is transformed dramatically from being rheology-dominant to tribology, that is, friction and lubrication-dominant [28–30]. However, while the use of apparent viscosity measurements has been extensively used to design relevant texture-modified foods with 'swallow-safe bolus' performance, the use of tribology as a tool taking account of food–oral surface interaction affecting mouthfeel and safe swallowing has not received much attention in food design for older adults [14,21,23,25,27]. For example, 'ease of swallowing', a term that is commonly used as an attribute in the sensory evaluation of food texture, has been recently reported to be dependent on the degree of lubrication of the food bolus [31]. Additionally, 'oral comfort' of a food when eating, obtained through developed and validated questionnaires, has also been reported to be dependent on 'easiness to humidify' among other oral properties of food [32]. More precisely, on cereal products, such as sponge cake enriched with

Table 1

Recent studies in food and model systems for elderly population and/or dysphagia patients where textural characterisation is used.

Food/model food	Viscosity Shear rate (s^{-1}), Temp. (°C)	Tribology Surface, speed (mm/s), normal force (N), Temp. (°C)	Sensory Test type, N (mean age, years old)	Reference
Elderly population				
Kefir (Fortification with coconut oil)	0–1000, 25	Glass/PDMS, 0.01–1000, 1.0, 37	Quantitative descriptive analysis (QDA®), 6 (60–70)	[14]
High-protein yoghurt (fortification with berry polyphenols, vitamins A, D, C, B9 and B12)	1–500, 23	–	Food comfortability questionnaire, 20 (78)	[9]
Canned mackerel pâté and frozen ready-made meal (salmon with spinach sauce) (fortification with bioactive extracts from sea cucumber)	–	–	Ranking test and sensorial analysis based on quantitative scales according to standards UNE-ISO 8587:2010 and UNE-ISO 4121:2006, 10.	[8]
Dysphagia patients				
Cooked pork paste (thickened with xanthan gum and guar gum)	0.1–200, 23	–	–	[15]
Thickened foams (egg white, foam magic (maltodextrin, methylcellulose and xanthan gum) and Methocel F50 (food-grade hydroxyl propyl methylcellulose)	0.001–100	–	–	[17]
Pureed carrot (thickened with starch, xanthan gum or starch–xanthan blends)	10, 37	Glass/PDMS, 10^{-5}–1000, 3.0, 37	Temporal dominance of sensations (TDS), 16.	[21]
Model foods				
Orange-flavoured soy juice and skim milk (thickened with flaxseed gum, xanthan gum and modified starch)	0–400, 25	Steel/PDMS, 40, 5.0, 25	–	[25]
Thickener (gellan gum, modified starch and xanthan gum) solutions	0.01–1000, 37	PDMS PDMS, 1–2000, 2.0, 37	–	[23]
Thickener (flaxseed gum, modified starch and xanthan gum) solutions	0–400, 25	–	–	[24]
Thickeners (Resource Thickenup® clear™ (TUC) by Nestle; Thick-It Clear Advantage® (TIC) by Kent Precision Foods Group; Quik Thik (QT) by Dr. MacLeod's Medical food; Supercol™ (SP) by Supercol Australia; Purathick™ (PT) by Parapharma Tech) solutions	0.1–500, 25	–	–	[16]
Thickener (Resource® (Nestle Health Science, Spain) and VISCO® instant (Smoothfood, Spain)) solutions	50	–	Duo-Trio, ranking and sensory discriminant tests, 23 (45).	[18]
Thickeners (xanthan gum and locust bean gum solutions)	0.1–100, 25	Steel/steel, 10^{-3}–1000, 0.3, 25	Visual Analogue Scale (VAS) for cohesiveness, spinnability and sliminess, 12 (32.3 ± 5.4)	[27]
Oil-in-water emulsions (thickened with starch and xanthan gum)	1–200, 37	–	–	[50]
Model emulsion (thickened with carboxymethylated curdlan, konjac glucomannan and xanthan gum)	0.1–1, 000	–	–	[26]

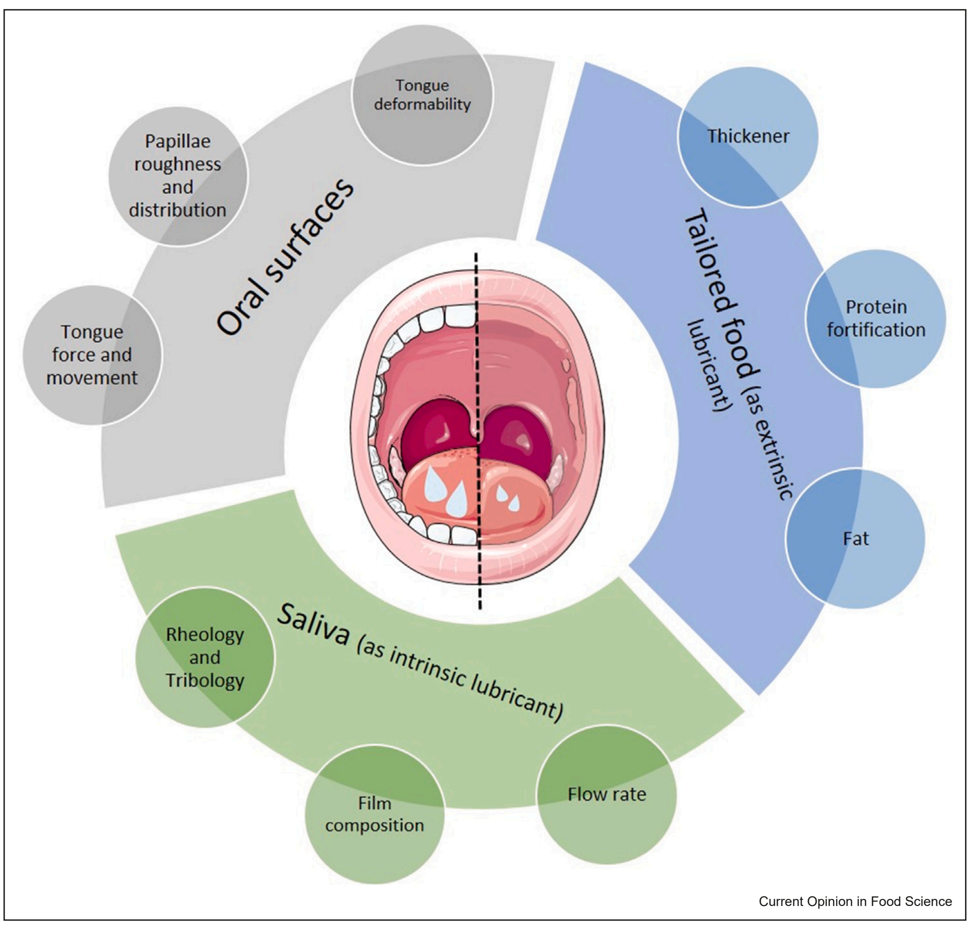
protein or not, oral comfort was associated with the viscosity of the food bolus produced, which was directly dependent on product salivary moistening and salivary flow of the elderly subjects [33,34].

Although general aspects of the lubrication mechanisms can be deduced from recent published studies on food [35–39] and well-defined model food systems, such as emulsions and dysphagia thickeners [39–48], fundamental understanding of tribological performance of the bolus in age-customised oral surfaces appears to be a missing link when designing texture-modified food with tailored mouthfeel properties for elderly population. In this mini-review, we discuss the current understanding of soft tribology measurements in the context of texture-modified foods bringing the current learning from model food to real foods. We consider food as an extrinsic lubricant. We also examine how material property of saliva (an intrinsic lubricant) is an important undertaking when designing tribological experiments for elderly population who might have limiting salivary flow and/or quality. We finally examine the adaptability of current tools and mechanisms to cater to the oral surfaces of elderly population. Finally, we outline perspectives for future research for unlocking the full potential of tribology as a test kit for tailoring foods for the ageing population. Figure 1 illustrates the scope of this review. The areas of work involving fortification of food for nutritional enhancement without any contribution to textural medication are out of scope for this review.

Using lubrication principles to design texture-modified food (extrinsic lubricants)

While there has been much research that seeks to link rheology to sensory data, tribological analysis to predict more complex sensory and swallowing sensations has been rarely investigated (Table 1). From the rheological characterisation perspective, it is worth noting that there is no clear consensus about the shear rate value of the swallowing process, as indicated by the American National Dysphagia Diet Standard [49]. Nevertheless, most research on texture-modified foods and thickened fluids for elderly population and dysphagia patients tends to

Figure 1



Factors that are expected to affect tribological properties of food designed for elderly population.

Table 2

Literature on lubrication performance and sensory perception of thickeners.

Polysaccharide	Contribution to boundary lubrication	Contribution to fluid film lubrication (friction scaled to viscosity)	Key sensory perception	References
Xanthan	✖	✓	Slimy, slippery	[23,53–56]
Pectin	✓	✓	Slimy, film forming, sticky	[53,54]
Locus bean gum	✖	✓	Slimy, film forming, sticky	[53,54,57]
λ/κ Carrageenan	✓	✓	–	[51,53,56,58]
Gellan	✖	✓	–	[23,53]
Guar gum	✖	✖	–	[51,55]
Starch	✓	✓	–	[58]
Arabic gum	✓	–	–	[56]
SCL	✓	✓	–	[51]

study apparent viscosity at shear rates around 50 s^{-1} at 25°C [16,18,21,24,26,50]. The products are hence classified for their 'ease of swallow' based on the viscosity values at this specific shear rate and temperature. Classifying the safeness of products/boli based on a unique shear rate is oversimplified. For instance, more complex undesirable surface-related sensations such as stickiness and graininess may associate with swallowing issues and risk of choking, which cannot be quantified using viscosity measurements at single shear rates. However, quantitative sensory studies when designing food for the ageing population and dysphagia population are also limited to date.

Although tribological studies on foods tailored for older adults are currently limited (Table 1), significant progress has been made in understanding the lubrication properties of hydrocolloid solutions that are widely used to design texture-modified foods (Table 2). From these studies, it appears that hydrocolloids with high molecular weights and expanded chains such as λ-carrageenan (λ-C) and scleroglucan (SCL) show good lubrication performance [51]. In particular, in most studies, friction data have been scaled to viscosity and demonstrate that viscous lubrication definitely serves as a key mechanism separating the tribo-contact surfaces for hydrocolloids, which is not surprising (Table 2).

Good lubrication performance, specifically friction-reducing property in the boundary regime where oral surfaces, that is, tongue and palate are in close contact, could be particularly important for older adults, as many older adults lack saliva, the key intrinsic lubricant [52]. For example, λ-C, SCL and pectin have been found to provide a bound hydration layer, which contributes significantly to the reduction of friction in the boundary regime (Table 2). Whether such improved boundary lubrication performance results in 'ease of swallow' remains to be elucidated, which is crucial for designing food and drinks for the elderly and for dysphagia management.

Some desired sensations such as fattiness and creaminess, have also been correlated with reduced friction due to coalescence of fat globules forming a fatty layer between the contact surfaces [9]. However, reduction of fats, particularly from animal origin, which tend to have high levels of unsaturation, has to be a key part of the food formulation strategy for the elderly due to food-linked diseases such as obesity, coronary heart disease, among others. Today, at the forefront of the low-fat colloidal strategies are microgels made of thermal-sensitive hydrogels, starch, whey protein, as well as non-starch polysaccharides such as alginate, agarose and κ-carrageenan [47,59–64]. These microgels, which are essentially largely structured hydrogel particles, have gained significant popularity as fat replacers due to their ultra-high lubricating performance attributed to their 'surface separators' properties in a possible combination with a roll-bearing mechanism, the latter has not yet been fully quantified and understood [65–67]. However, their use for formulation of textured-modified or thickened liquids to target the elderly population or patients with dysphagia is a principally unexplored research area, which needs future investigation. In summary, a significant body of literature on model foods such as thickeners, emulsions and microgels offers a promising springboard to start exploring possibilities to use this knowledge to design texture-modified food and compare the tribological data with sensory attributes with older adults. However, in order to have correlations, one should also question whether or not the tribological conditions emulate the real *in vivo* mouth conditions of older adults, which is examined in the next section.

Mimicking *in-mouth* conditions for biorelevant tribological testing for elderly population

Having reviewed the tribological principles of foods and model foods, it is important to highlight that the instrumentation and conditions used to perform the tribological testing suffer from serious limitations. These need to be rectified if such knowledge is to be used for food design for elderly population. For instance, a variety of surfaces such as glass, steel, polydimethylsiloxane (PDMS) and so on, normal forces (1–3 N) and temperature conditions (25–37°C) have been used to measure tribological performance (Table 1), which makes it challenging to compare. Of more importance, none of the aforementioned studies used biorelevant surfaces, forces, oral speeds and salivary composition that are tailored to ageing conditions. The first challenge in doing biorelevant oral tribological testing is scarcity of *in vivo* data from elder oral conditions such as oral motor function, tongue topography, saliva composition and so on [68–71]. In the following sections, we highlight some of the several challenges that need to be addressed to mimic more closely the *in vivo* elderly physiological conditions, in order to consequently use the frictional data for food design for elderly population.

Tongue speed and force

The choice of speeds and forces during tribological measurements is expected to influence friction data for relating such outputs to desired sensory properties of food. Classic food tribological studies tend to go to speeds up to 2000 mm/s [14,21,23,27,36,40,48], which raises critical questions regarding the biological relevance to any human oral condition. In fact, few tribological tests have been performed at relatively low speeds between 0.01 and 270 mm/s, which cover indeed the estimated speeds of the oral conditions of an average adult (5–200 mm/s) [68]. Although, to the best of our knowledge, no literature was found on the average oral speed for elderly people, a study on masticatory performance observed a decreased speed of tongue movement and/or tongue muscle force for elderly as compared with young adults (~6.3 ± 0.9 and 1.5 syllables/s, respectively) [68,69]. This might serve as an indicator that, to bring food tribology closer to the *in vivo* elderly conditions, *bespoke* equipment [44] could be adapted in the future. Customised equipment has been observed to work at speed ranges of 0.1–40 mm/s, with clear differentiation of the boundary and mixed regimes [25,37].

Tribological research for elderly could also greatly benefit by matching the contact pressures more closely to the oral-palate contact of the elderly as it has been reported to be in a lower range (19–36 kPa) as compared with younger adults (15–60 kPa) [69,72]. Currently, using PDMS surfaces [30], which is a generalised practice to perform tribological test at a normal load of 2 N, the maximum contact pressure is ~200–300 kPa [30], which is an order of magnitude higher as compared with the oral-palate contact of healthy older adult [73,74]. Besides using materials with low elastic modulus to closely resemble real deformable oral surfaces, one can also employ lower loads of ~0.1 N to reduce the contact pressure. To the best of our knowledge, the lowest load reported in the literature has been of 0.3 N [27] (Table 1), suggesting that tribological set-up conditions with biological relevance need to be considered.

Surface topography

As frictional measurements are surface-dependent, the topography of the adult human tongue has been extensively studied in the last five years and multiple synthetic tongues have been developed to emulate the topography and viscoelastic properties of the human tongue [36,75–78] (Table 3). For example, silicone (Dragon Skin™ 10 Fast' Silicone and EcoFlex 00–30™) synthetic tongues with papillae height and density closer to human conditions have been recently developed [36,77]. Furthermore, stiffness closer to the human tongue (~50 kPa) has also been recently developed using polyvinyl alcohol [76], whilst the hydrophilicity has been maintained close to the human oral mucosa by changing the wettability of PDMS surfaces using a surfactant (Table 3). These advancements in current surface development offer a promising strategy to adapt the surfaces to resemble more closely the ageing conditions.

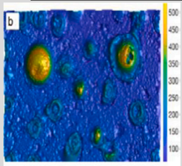
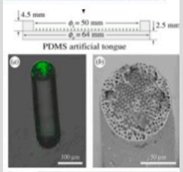
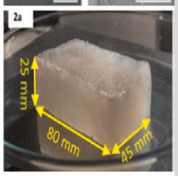
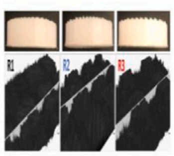
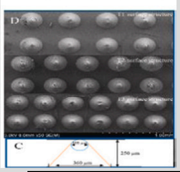
The most recent study on the roughness of the elderly tongue performed in 2012 [79], suggests that a surface with an increased roughness might have to be developed to resemble the topographic characteristic of the elderly tongue. In the latter, the average tongue roughness for the elderly was found to be significantly different compared with young adults (R_a: 94.1 ± 29 and 65.0 ± 36.4 μm, respectively), which might influence the lubrication behaviour and sensory perception of food products. Positive significant correlation between roughness and friction has been observed in various fluids and full-fat lubricated systems. This indicates that highly textured surfaces with increased surface roughness might affect the formation and thus the effectiveness of the lubricating film between the roughness peaks of the tongue and the palate, especially at low speeds, which might sensorially appear dry and astringent, presumably would be the case for elderly people [80,81]. Nevertheless, the lack of *in vivo* data and lack of recent studies on the topography and viscoelastic properties of the elderly oral surfaces currently limits the future development of elderly-relevant tribological surfaces.

Saliva (intrinsic lubricant)

Even though saliva has a key role in making food cohesive to allow the bolus to be safely swallowed, the influence of saliva has been overlooked in the current tribological studies of real and model food systems that have surfaced in the last five years [42–44,82], which can be an important direction for future tribology work. This is particularly important for older adults who have limited salivary flow. In addition, the saliva of older adults often lacks the lubricious proteins due to them suffering from dry mouth conditions due to polypharmacy and

Table 3

Recently developed synthetic tongue-like surface for oral tribological experiments.

Image of the surface	Materials	Young's Modulus (kPa)	Roughness (μm)	Density (cm^2)	Contact Angle (°)	References
	Ecoflex™ 00-30 Silicone	120 - 2,400	111-529	13.5 and 160 for fungiform and filiform	63.0 ± 0.2	[75]
	PDMS	800 ± 160	435 ± 7	10	-	[78]
	Polyvinyl alcohol (PVA)	50.17 ± 1.46 and 100.78 ± 2.12	425	-	-	[76]
	Dragon Skin™ 10 Fast' Silicone and Silicone Thinner™	83.02 ± 0.55 - 168.86 ± 1.46	200 and 600	9 and 16	104.8 ± 1.1 - 106.2 ± 0.7	[36]
	PDMS	820 ± 280	96.60 ± 0.68 - 103.52 ± 0.4	280 - 530	-	[77]

multiple comorbidities [52,83]. Few studies on real food and model food systems have determined the tribological properties when mixed with simulated or *ex vivo* human saliva. For example, when emulsions are mixed with simulated saliva, the friction coefficient is significantly lowered as saliva acts as a biolubricant [44]. However, in other studies involving saliva, it has been observed that the frictional behaviour was dependent on the structure and properties of the system rather than the lubricating properties of the saliva [42,43].

Currently, it is known that, like many biological functions, ageing affects the salivary glands decreasing significantly the average salivary flow at both stimulated and resting conditions (1.52 ± 0.73 (range 0.11–4.01) and 0.31 ± 0.19 (range 0.03–0.86) mL/min, respectively) compared with younger adults (2.47 ± 1.06 (range 0.70–5.45) and 0.50 ± 0.23 (range 0.05–1.19) mL/min, respectively) [84]. Furthermore, mucin concentration has been observed to decrease with ageing, and an age-related increase in salivary viscoelasticity in relation to its protein concentration has also been reported [83,85–87]. However, no recent studies have characterised the specific protein composition, rheological and lubrication behaviour of elderly saliva, and will therefore be an important direction of future tribological work. The most recent studies on elderly saliva focusing on specific composition are from Nagler and Hershkovich [88,89] and can be reviewed to extract relevant information such as salivary composition (potassium, calcium, phosphorus, uric acid, amylase, IgA and secretory IgA), where mean values were found to be significantly higher for older adults compared with young adults. More recently, age-dependent analysis of the salivary proteome has identified proteins that varied significantly between young adults and elderly and that are related to immune response, oral cavity protection, buffering capacity and normal physiological processes. However, the direction of change (increase or decrease) depends on the type of protein [90,91]. Such observation points towards the relevance of understanding the mechanism of elder saliva lubrication, not only for the design of artificial saliva that mimics more closely *in vivo* elderly conditions, but also for the design of products with good *in-mouth* lubrication properties for targeted populations with other conditions such as xerostomia, commonly found in geriatric patients. Mixing food samples with fresh *ex vivo* elderly saliva might be an interesting starting point to understand how saliva influences tribological performance, but remains to be studied.

Outlook and recommended considerations

Oral tribology can serve as a unique tool to offer new correlations between friction coefficients and sensory properties of food designed for older adults and eventually can add a new dimension to safe swallowing. Although researchers have made great effort to mimic *in vivo* conditions, there are many aspects that could be taken into consideration to bring food tribology closer to the *in vivo* characteristics of the elderly oral conditions and make meaningful contributions for rational design of texture-modified foods. For example, customisation of surfaces closely resembling the deformability, wettability and roughness (papillae height and density) of tongue surface of older adults could greatly benefit the tribological research. Further avenues for improvement could lie in saliva incorporation. Either model or *ex vivo* saliva could provide insights on the relevance of saliva-mediated lubrication, which is particularly crucial to understand for older adults. This might lead to design of new foods that do not need saliva incorporation, and thus can offer a new product line for dry mouth patients who suffer from lack of saliva. Finally, we also recommend greater efforts to publish fundamental studies on characterising oral surfaces of the elder population. With the advent of 3D printing, the translation of *in vivo* knowledge into fabricating synthetic surfaces is expected to be much faster. With these considerations in mind, we believe that the field of oral tribology will undoubtedly enable rational design of tailored foods for ageing populations with/without age-related health conditions. This should be possible whilst maintaining ease of eating and swallowing and the sensory pleasure without being detrimental to nutritional qualities, which is one of the key overlooked feature and needs to be addressed to increase nutrient intake and tackle malnutrition issues in elderly population.

Conflict of interest statement

None.

Data Availability

No data were used for the research described in the article.

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