UNIVERSITY OF LEEDS

This is a repository copy of *Can tribology be a tool to help tailor food for elderly population?*.

White Rose Research Online URL for this paper:
https://eprints.whiterose.ac.uk/193892/

Version: Accepted Version

Article:

Araiza-Calahorra, A, Mackie, AR orcid.org/0000-0002-5681-0593, Ferron, G et al. (1 more author) (Cover date: February 2023) Can tribology be a tool to help tailor food for elderly population? Current Opinion in Food Science, 49. 100968. ISSN 2214-7993

https://doi.org/10.1016/j.cofs.2022.100968

Reuse
This article is distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs (CC BY-NC-ND) licence. This licence only allows you to download this work and share it with others as long as you credit the authors, but you can't change the article in any way or use it commercially. More information and the full terms of the licence here: https://creativecommons.org/licenses/

Takedown
If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

White Rose
university consortium
Universities of Leeds, Sheffield & York

eprints@whiterose.ac.uk
https://eprints.whiterose.ac.uk/

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

Andrea Araiza-Calahorra[1], Alan R. Mackie[1] , Gilles Ferron[2] and Anwesha Sarkar[1*]

[1]Food Colloids and Processing Group, School of Food Science and Nutrition, University of Leeds, Leeds, LS2 9JT, UK

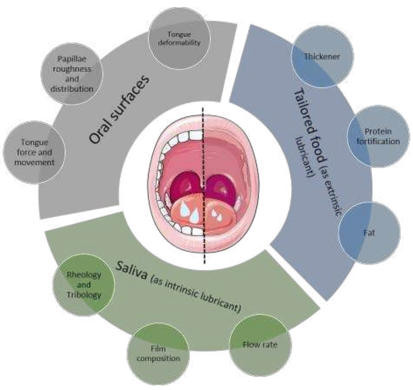
[2]Centre des Sciences du Goût et de l'Alimentation, CNRS, INRAE, Institut Agro, Université de Bourgogne Franche-Comté, F-21000 Dijon, France.

Corresponding author:
Food Colloids and Processing Group,
School of Food Science and Nutrition,
University of Leeds, Leeds LS2 9JT, UK.
*Email: A.Sarkar@leeds.ac.uk

Highlights

- Improving lubricity of food is important for designing food for older adults
- Current data on tribology of thickeners serves as a baseline for food design
- Lack of *in vivo* data from elder oral conditions limits surface design for tribology
- Influence of saliva in oral tribological studies is often overlooked
- Microgels serve as a promising template for formulating food for this demographics

Graphical Abstract



Abstract

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 allow 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 characterization of oral conditions of the elderly population is a necessary undertaking to fabricate tribology apparatus that better emulate *in vivo* conditions, to allow rational design of food products for this growing population.

Keywords

Lubrication; ageing; dysphagia; saliva; texture-modified; rheology

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 (WHO), 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 textured-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 *i.e.* 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 though 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 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-customized 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 aging 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 is out of scope for this review.

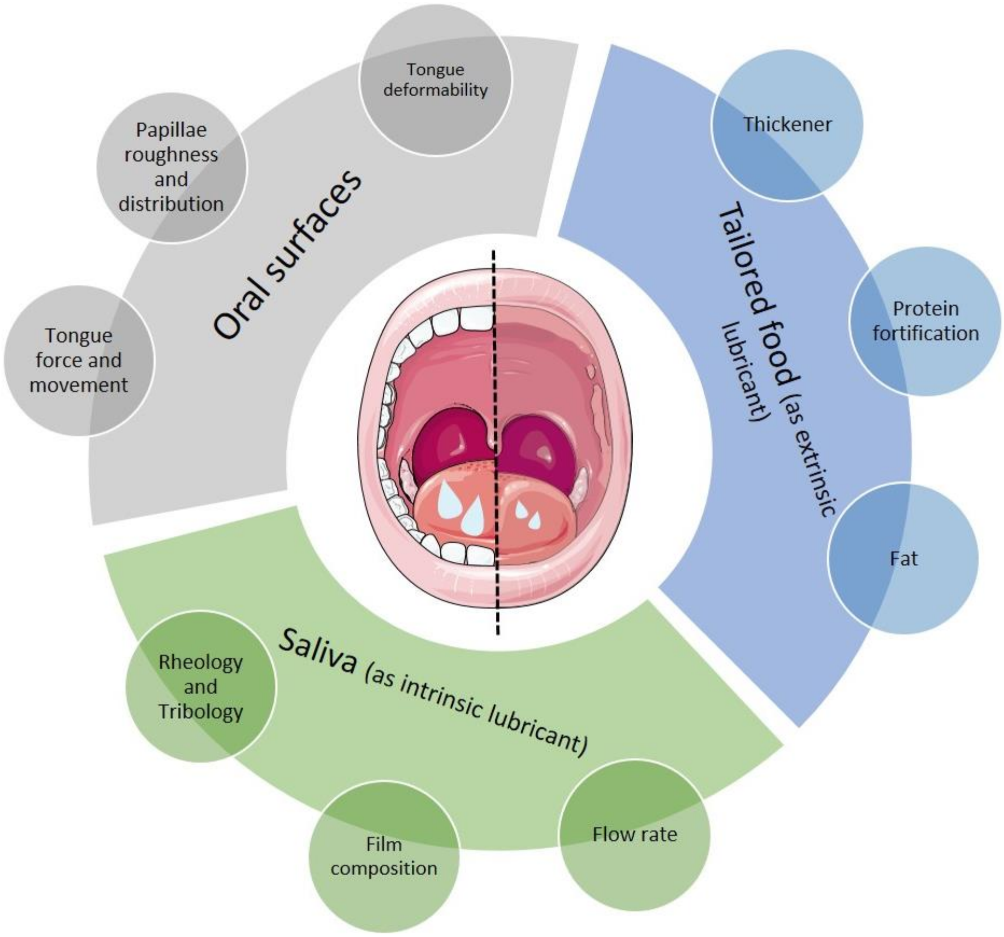


Figure 1. Factors that are expected to affect tribological properties of food designed for elderly population.

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 characterization 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 (NDD) Standard [49]. Nevertheless, most research on texture modified foods and thickened fluids for elderly population and dysphagia patients tend to study apparent viscosity at shear rates around 50 s^{-1} at 25 ºC [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.

Table 1. Recent studies in food and model systems for elderly population and/or dysphagia patients where textural characterization 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 / polydimethylsiloxane (PDMS), 0.01 – 1,000, 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) addition)	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]
Thickeners (gellan gum, modified starch and xanthan gum) solutions	0.01 – 1000, 37	PDMS / PDMS, 1 – 2000, 2.0, 37	-	[23]
Thickeners (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]
Thickeners (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]

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 has 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 *i.e.* 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.

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 Carragenan	✓	✓	-	[51, 53, 56, 58]
Gellan	✕	✓	-	[23, 53]
Guar gum	✕	✕	-	[51, 55]
Starch	✓	✓	-	[58]
Arabic gum	✓	-	-	[56]
Scleroglucan	✓	✓	-	[51]

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 offer 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 bio-relevant 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, PDMS *etc.*, normal forces (1-3 N) and temperature conditions (25-37 ºC) have been used to measure tribological performance (**Table 1**), which makes it challenging to compare. Of more importance, none of the aforementioned studies used bio-relevant surfaces, forces, oral speeds and salivary composition that are tailored to ageing conditions. The first challenge in doing bio-relevant oral tribological testing is scarcity of *in vivo* data from elder oral conditions such as oral motor function, tongue topography, saliva composition etc. [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 2,000 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 0.01–270 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 to 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 to 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 to 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 needs 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 5 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 mimicked using polyvinyl alcohol (PVA) [76], whilst hydrophilicity close to the human oral mucosa has also been achieved by changing the wettability of PDMS surfaces by using surfactant (**Table 3**). These advancements in current surface development offers a promising strategy to adapt the surfaces to resemble more closely the aging 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 to 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, specially 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 lack the lubricious proteins due to them suffering from dry mouth conditions due to polypharmacy and 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, aging 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 to 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 aging, 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, phosphorous, uric acid, amylase, IgA and secretory IgA), where mean values were found to be significantly higher for older adults compared to young adults. More recently, age-dependent analysis of the salivary proteome has identified proteins that varied significantly between young adult and elderlies 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 influence tribological performance, but remains to be studied.

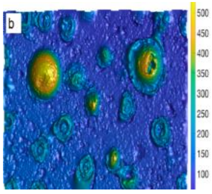
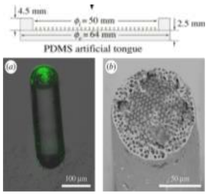
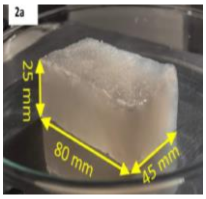
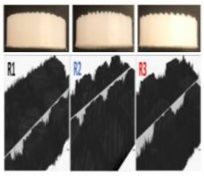
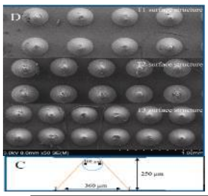
Image of the surface	Materials	Young's Modulus (kPa)	Roughness (µm)	Density (cm^2)	Contact Angle (°)	References
	Ecoflex™ 00-30 Silicone	120 - 2,400	111-529	13.5 and 160 for fungiform and filiform	63.0 ± 0.2	[75]
	PDMS	800 ± 160	435 ± 7	10	-	[78]
	Polyvinyl alcohol (PVA)	50.17 ± 1.46 and 100.78 ± 2.12	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]

Table 3. Recently developed synthetic tongue-like surface for oral tribological experiments.

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 ration design of texture-modified foods. For example, customization 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 don't 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.

Acknowledgements

The work was funded by the EAT4AGE project which received funding from [Medical Research Council (MRC), UK] under the umbrella of the European Joint Programming Initiative "A Healthy Diet for a Healthy Life" (JPI HDHL) and of the ERA-NET Cofund ERA-HDHL (GA N°696295 of the EU Horizon 2020 Research and Innovation Programme)."

References

Special interest (•) or Outstanding interest (••)

[1] Ageing and health. World Health Organization; 2021.
[2] Kirkwood TBL. Understanding the Odd Science of Aging. Cell. 2005;120:437-47.
[3] Harada CN, Natelson Love MC, Triebel KL. Normal Cognitive Aging. Clinics in Geriatric Medicine. 2013;29:737-52.
[4] Sarkar A. Oral processing in elderly: understanding eating capability to drive future food texture modifications. Proceedings of the Nutrition Society. 2019;78:329-39.

(•) This is an important review on characterisation of capabilities of elderly individuals in food handling and oral processing.

[5] Song X, Giacalone D, Bølling Johansen SM, Frøst MB, Bredie WLP. Changes in orosensory perception related to aging and strategies for counteracting its influence on food preferences among older adults. Trends in Food Science & Technology. 2016;53:49-59.

(•) This is a comprehensive review summarizing the causes of orosensory changes with aging and the compensatory strategies for counteracting age-related orosensory changes.

[6] Laguna L, Sarkar A, Chen J. Chapter 10 - Eating Capability Assessments in Elderly Populations. In: Watson RR, editor. Nutrition and Functional Foods for Healthy Aging: Academic Press; 2017. p. 83-98.
[7] Dinkar DK, Mishra S. Preparation of Biscuits by Using Lotus Seed, Pearl Millets and Multigrain Wheat for Elderly People. International Journal of Research in Engineering, Science and Management. 2020;3:413-5.
[8] García J, Méndez D, Álvarez M, Sanmartin B, Vázquez R, Regueiro L, et al. Design of novel functional food products enriched with bioactive extracts from holothurians for meeting the nutritional needs of the elderly. Lwt. 2019;109:55-62.
[9] Keršienė M, Jasutienė I, Eisinaitė V, Pukalskienė M, Venskutonis PR, Damulevičienė G, et al. Development of a high-protein yoghurt-type product enriched with bioactive compounds for the elderly. Lwt. 2020;131.
[10] Kersiene M, Jasutiene I, Eisinaite V, Venskutonis PR, Leskauskaite D. Designing multiple bioactives loaded emulsions for the formulations for diets of elderly. Food Funct. 2020;11:2195-207.
[11] Spence C, Navarra J, Youssef J. Using ice-cream as an effective vehicle for energy/nutrient delivery in the elderly. International Journal of Gastronomy and Food Science. 2019;16.
[12] Eom SH, Chun YG, Park CE, Kim BK, Lee SH, Park DJ. Application of freeze-thaw enzyme impregnation to produce softened root vegetable foods for elderly consumers. J Texture Stud. 2018.
[13] Vandenberghe-Descamps M, Sulmont-Rosse C, Septier C, Follot C, Feron G, Laboure H. Impact of blade tenderization, marinade and cooking temperature on oral comfort when eating meat in an elderly population. Meat Sci. 2018;145:86-93.
[14] Aussanasuwannakul A, Puntaburt K, Treesuwan W. Rheological, Tribological, and Sensory Analysis of Coconut-Oil-Modified Coconut Milk Kefir. Current Research in Nutrition and Food Science Journal. 2020:496-503.
[15] Dick A, Bhandari B, Dong X, Prakash S. Feasibility study of hydrocolloid incorporated 3D printed pork as dysphagia food. Food Hydrocolloids. 2020;107.
[16] Kongjaroen A, Methacanon P, Gamonpilas C. On the assessment of shear and extensional rheology of thickened liquids from commercial gum-based thickeners used in dysphagia management. Journal of Food Engineering. 2022;316.
[17] Lee AY, Pant A, Pojchanun K, Lee CP, An J, Hashimoto M, et al. Three-Dimensional Printing of Food Foams Stabilized by Hydrocolloids for Hydration in Dysphagia. Int J Bioprint. 2021;7:393.
[18] Martínez O, Vicente MS, De Vega MC, Salmerón J. Sensory perception and flow properties of dysphagia thickening formulas with different composition. Food Hydrocolloids. 2019;90:508-14.

[19] Pematilleke N, Kaur M, Rai Wai CT, Adhikari B, Torley PJ. Effect of the addition of hydrocolloids on beef texture: Targeted to the needs of people with dysphagia. Food Hydrocolloids. 2021;113.
[20] Reyes-Torres CA, Castillo-Martinez L, Reyes-Guerrero R, Ramos-Vazquez AG, Zavala-Solares M, Cassis-Nosthas L, et al. Design and implementation of modified-texture diet in older adults with oropharyngeal dysphagia: a randomized controlled trial. Eur J Clin Nutr. 2019;73:989-96.
[21] Sharma M, Pondicherry KS, Duizer L. Understanding relations between rheology, tribology, and sensory perception of modified texture foods. J Texture Stud. 2021.

(•) This is a systematic study drawing important correlations between rheology, tribology and sensory attributes in pureed carrot matrices designed for dysphagia patients using saliva (ex vivo).

[22] Streimikyte P, Kersiene M, Eisinaite V, Jasutiene I, Lesauskaite V, Damuleviciene G, et al. Formulating protein-based beverages for the dysphagia diets of the elderly: viscosity, protein quality, in vitro digestion, and consumers acceptability. J Sci Food Agric. 2020;100:3895-901.
[23] Torres O, Yamada A, Rigby NM, Hanawa T, Kawano Y, Sarkar A. Gellan gum: A new member in the dysphagia thickener family. Biotribology. 2019;17:8-18.

(••) This is an important study on measuring tribological properties of commercial dysphagia thickeners.

[24] Vieira JM, Andrade CCP, Santos TP, Okuro PK, Garcia ST, Rodrigues MI, et al. Flaxseed gum-biopolymers interactions driving rheological behaviour of oropharyngeal dysphagia-oriented products. Food Hydrocolloids. 2021;111.
[25] Vieira JM, Oliveira FD, Jr., Salvaro DB, Maffezzolli GP, de Mello JDB, Vicente AA, et al. Rheology and soft tribology of thickened dispersions aiming the development of oropharyngeal dysphagia-oriented products. Curr Res Food Sci. 2020;3:19-29.
[26] Wei Y, Guo Y, Li R, Ma A, Zhang H. Rheological characterization of polysaccharide thickeners oriented for dysphagia management: Carboxymethylated curdlan, konjac glucomannan and their mixtures compared to xanthan gum. Food Hydrocolloids. 2021;110.
[27] Funami T, Nakauma M. Correlation of human perception in swallowing with extension rheological and tribological characteristics in comparison with shear rheology. Journal of Textural Studies. 2021:60–71.
[28] Stokes JR, Boehm MW, Baier SK. Oral processing, texture and mouthfeel: From rheology to tribology and beyond. Current Opinion in Colloid & Interface Science. 2013;18:349-59.
[29] Chen J, Stokes JR. Rheology and tribology: Two distinctive regimes of food texture sensation. Trends in Food Science & Technology. 2012;25:4-12.
[30] Sarkar A, Andablo-Reyes E, Bryant M, Dowson D, Neville A. Lubrication of soft oral surfaces. Current Opinion in Colloid & Interface Science. 2019;39:61-75.
[31] de Lavergne MD, van de Velde F, Stieger MJF, Function. Bolus matters: The influence of food oral breakdown on dynamic texture perception. 2017;8:464-80.
[32] Vandenberghe-Descamps M, Labouré H, Septier C, Feron G, Sulmont-Rossé C. Oral comfort: A new concept to understand elderly people’s expectations in terms of food sensory characteristics. Food Quality and Preference. 2018;70:57-67.
[33] Assad-Bustillos M, Tournier C, Palier J, Septier C, Feron G, Della Valle G. Oral processing and comfort perception of soft cereal foods fortified with pulse proteins in the elderly with different oral health status. Food Funct. 2020;11:4535-47.
[34] Assad-Bustillos M, Tournier C, Septier C, Della Valle G, Feron G. Relationships of oral comfort perception and bolus properties in the elderly with salivary flow rate and oral health status for two soft cereal foods. Food Research International. 2019;118:13-21.

[35] Agyei-Amponsah J, Macakova L, DeKock HL, Emmambux MN. Effect of Substituting Sunflower Oil with Starch-Based Fat Replacers on Sensory Profile, Tribology, and Rheology of Reduced-Fat Mayonnaise-Type Emulsions. Starch - Stärke. 2020;73.
[36] Fan J, Annamalai PK, Prakash S. 3D enabled facile fabrication of substrates with human tongue characteristics for analysing the tribological behaviour of food emulsions. Innovative Food Science & Emerging Technologies. 2021;73.
[37] Kim MS, Walters N, Martini A, Joyner HS, Duizer LM, Grygorczyk A. Adapting tribology for use in sensory studies on hard food: The case of texture perception in apples. Food Quality and Preference. 2020;86.
[38] Liu Y, Qu F, Luo L, Xu W, Zhong M. Detection of rice syrup from acacia honey based on lubrication properties measured by tribology technique. Tribology International. 2019;129:239-45.
[39] Ruan Q, Yang X, Zeng L, Qi J. Physical and tribological properties of high internal phase emulsions based on citrus fibers and corn peptides. Food Hydrocolloids. 2019;95:53-61.
[40] Anvari M, Joyner HS. Effect of fish gelatin and gum arabic interactions on concentrated emulsion large amplitude oscillatory shear behavior and tribological properties. Food Hydrocolloids. 2018;79:518-25.
[41] Huang T, Tu Z, Zou Z, Shangguan X, Wang H, Bansal N. Glycosylated fish gelatin emulsion: Rheological, tribological properties and its application as model coffee creamers. Food Hydrocolloids. 2020;102.
[42] Fuhrmann PL, Kalisvaart LCM, Sala G, Scholten E, Stieger M. Clustering of oil droplets in o/w emulsions enhances perception of oil-related sensory attributes. Food Hydrocolloids. 2019;97.
[43] Fuhrmann PL, Sala G, Scholten E, Stieger M. Influence of clustering of protein-stabilised oil droplets with proanthocyanidins on mechanical, tribological and sensory properties of o/w emulsions and emulsion-filled gels. Food Hydrocolloids. 2020;105.
[44] Upadhyay R, Chen J. Smoothness as a tactile percept: Correlating 'oral' tribology with sensory measurements. Food Hydrocolloids. 2019;87:38-47.
[45] Pang Z, Luo Y, Li B, Zhang M, Liu X. Effect of different hydrocolloids on tribological and rheological behaviors of soymilk gels. Food Hydrocolloids. 2020;101.
[46] Pang Z, Xu R, Zhu Y, Li H, Bansal N, Liu X. Comparison of rheological, tribological, and microstructural properties of soymilk gels acidified with glucono-delta-lactone or culture. Food Res Int. 2019;121:798-805.
[47] Torres O, Andablo-Reyes E, Murray BS, Sarkar A. Emulsion Microgel Particles as High-Performance Bio-Lubricants. ACS Appl Mater Interfaces. 2018;10:26893-905.
[48] Yang N, Feng Y, Su C, Wang Q, Zhang Y, Wei Y, et al. Structure and tribology of κ-carrageenan gels filled with natural oil bodies. Food Hydrocolloids. 2020;107.
[49] National Dysphagia Diet Task Force ADA. National dysphagia diet : standardization for optimal care. [Chicago, Ill.]: American Dietetic Association; 2002.
[50] Riquelme N, Robert P, Troncoso E, Arancibia C. Influence of the particle size and hydrocolloid type on lipid digestion of thickened emulsions. Food Funct. 2020;11:5955-64.
[51] Garrec DA, Norton IT. The influence of hydrocolloid hydrodynamics on lubrication. Food Hydrocolloids. 2012;26:389-97.
[52] Xu F, Laguna L, Sarkar A. Aging-related changes in quantity and quality of saliva: Where do we stand in our understanding? 2019;50:27-35.

(•) This is an important recent review on salivary changes during ageing.

[53] Stokes JR, Macakova L, Chojnicka-Paszun A, de Kruif CG, de Jongh HH. Lubrication, adsorption, and rheology of aqueous polysaccharide solutions. Langmuir. 2011;27:3474-84.

(••) This is a systematic study on characterising aqueous lubrication, viscosity and adsorption properties of polysaccharide solutions.

[54] Chojnicka-Paszun A, Doussinault S, de Jongh HHJ. Sensorial analysis of polysaccharide–gelled protein particle dispersions in relation to lubrication and viscosity properties. Food Research International. 2014;56:199-210.
[55] de Vicente J, Stokes JR, Spikes HA. Soft lubrication of model hydrocolloids. Food Hydrocolloids. 2006;20:483-91.
[56] Huang T, Tu Z, Shangguan X, Wang H, Zhang L, Bansal N. Characteristics of fish gelatin-anionic polysaccharide complexes and their applications in yoghurt: Rheology and tribology. Food Chem. 2021;343:128413.
[57] Zinoviadou KG, Janssen AM, de Jongh HH. Tribological properties of neutral polysaccharide solutions under simulated oral conditions. J Food Sci. 2008;73:E88-94.
[58] You KM, Murray BS, Sarkar A. Rheology and tribology of starch + kappa-carrageenan mixtures. J Texture Stud. 2021;52:16-24.
[59] Garrec DA, Norton IT. Kappa carrageenan fluid gel material properties. Part 2: Tribology. Food Hydrocolloids. 2013;33:160-7.
[60] Liu G, Wang X, Zhou F, Liu W. Tuning the tribological property with thermal sensitive microgels for aqueous lubrication. ACS Appl Mater Interfaces. 2013;5:10842-52.
[61] Sarkar A, Kanti F, Gulotta A, Murray BS, Zhang S. Aqueous Lubrication, Structure and Rheological Properties of Whey Protein Microgel Particles. Langmuir. 2017;33:14699-708.
[62] Olivares ML, Shahrivar K, de Vicente J. Soft lubrication characteristics of microparticulated whey proteins used as fat replacers in dairy systems. Journal of Food Engineering. 2019;245:157-65.
[63] Fernández Farrés I, Douaire M, Norton IT. Rheology and tribological properties of Ca-alginate fluid gels produced by diffusion-controlled method. Food Hydrocolloids. 2013;32:115-22.
[64] Gabriele A, Spyropoulos F, Norton IT. A conceptual model for fluid gel lubrication. Soft Matter. 2010;6:4205-13.

(•) This is an important study providing mechanistic information on lubrication performance of gel particles as a function of speed.

[65] Andablo-Reyes E, Yerani D, Fu M, Liamas E, Connell S, Torres O, et al. Microgels as viscosity modifiers influence lubrication performance of continuum. 2019;15:9614-24.
[66] Hu J, Andablo-Reyes E, Soltanahmadi S, Sarkar AJAml. Synergistic microgel-reinforced hydrogels as high-performance lubricants. 2020;9:1726-31.
[67] Torres O, Andablo-Reyes E, Murray BS, Sarkar A. Emulsion Microgel Particles as High-Performance Bio-Lubricants. ACS Applied Materials & Interfaces. 2018;10:26893-905.
[68] Sagawa K, Furuya H, Ohara Y, Yoshida M, Hirano H, Iijima K, et al. Tongue function is important for masticatory performance in the healthy elderly: a cross-sectional survey of community-dwelling elderly. J Prosthodont Res. 2019;63:31-4.
[69] Nakamori M, Imamura E, Fukuta M, Tachiyama K, Kamimura T, Hayashi Y, et al. Tongue thickness measured by ultrasonography is associated with tongue pressure in the Japanese elderly. PLoS One. 2020;15:e0230224.

(•) This study provides data on oral characteristics specific to elderly population.

[70] Pushpass R-AG, Daly B, Kelly C, Proctor G, Carpenter GHJFip. Altered salivary flow, protein composition, and rheology following taste and TRP stimulation in older adults. 2019:652.
[71] Buranarom N, Komin O, Matangkasombut OJPo. Hyposalivation, oral health, and Candida colonization in independent dentate elders. 2020;15:e0242832.
[72] Hori K, Murakami K, Fujiwara S, Funami T, Inoue M, T. O. Tongue pressure and hyoid movement by tongue squeezing. 4th Food Oral Processing Conference. Lausanne, Switzerland2016.

[73] Laguna L, Barrowclough RA, Chen J, Sarkar AJJoTS. New approach to food difficulty perception: Food structure, food oral processing and individual's physical strength. 2016;47:413-22.
[74] Laguna L, Sarkar A, Artigas G, Chen JJP, behavior. A quantitative assessment of the eating capability in the elderly individuals. 2015;147:274-81.
[75] Andablo-Reyes E, Bryant M, Neville A, Hyde P, Sarkar R, Francis M, et al. 3D Biomimetic Tongue-Emulating Surfaces for Tribological Applications. ACS Appl Mater Interfaces. 2020;12:49371-85.

(••) This is an important study on designing the first ever synthetic 3D tongue-like surface replicating the wettability, topography and deformability of a real human tongue .

[76] Srivastava R, Bosc V, Restagno F, Tournier C, Menut P, Souchon I, et al. A new biomimetic set-up to understand the role of the kinematic, mechanical, and surface characteristics of the tongue in food oral tribological studies. Food Hydrocolloids. 2021;115.
[77] Wang Q, Zhu Y, Chen J. Development of a simulated tongue substrate for in vitro soft "oral" tribology study. Food Hydrocolloids. 2021;120.
[78] Thomazo JB, Contreras Pastenes J, Pipe CJ, Le Reverend B, Wandersman E, Prevost AM. Probing in-mouth texture perception with a biomimetic tongue. J R Soc Interface. 2019;16:20190362.
[79] Uemori N, Kakinoki Y, Karaki J, Kakigawa H. New method for determining surface roughness of tongue. 2012;29:90-5.
[80] Wang X, Chen J, Wang X. In situ oral lubrication and smoothness sensory perception influenced by tongue surface roughness. Journal of the Science of Food and Agriculture. 2022;102:132-8.
[81] Krzeminski A, Wohlhüter S, Heyer P, Utz J, Hinrichs J. Measurement of lubricating properties in a tribosystem with different surface roughness. International Dairy Journal. 2012;26:23-30.
[82] Shahbazi M, Jäger H, Chen J, Ettelaie R. Construction of 3D printed reduced-fat meat analogue by emulsion gels. Part II: Printing performance, thermal, tribological, and dynamic sensory characterization of printed objects. Food Hydrocolloids. 2021;121.
[83] Hu J, Andablo-Reyes E, Mighell A, Pavitt S, Sarkar A. Dry mouth diagnosis and saliva substitutes—A review from a textural perspective. 2021;52:141-56.
[84] Vandenberghe-Descamps M, Labouré H, Prot A, Septier C, Tournier C, Feron G, et al. Salivary Flow Decreases in Healthy Elderly People Independently of Dental Status and Drug Intake. 2016;47:353-60.
[85] Kazakov VN, Udod AA, Zinkovych II, Fainerman VB, Miller R. Dynamic surface tension of saliva: General relationships and application in medical diagnostics. Colloids and Surfaces B: Biointerfaces. 2009;74:457-61.
[86] Zussman E, Yarin AL, Nagler RM. Age- and Flow-dependency of Salivary Viscoelasticity. Journal of Dental Research. 2007;86:281-5.
[87] Waterman HA, Blom C, Holterman HJ, s-Gravenmade EJ, Mellema J. Rheological properties of human saliva. Archives of Oral Biology. 1988;33:589-96.
[88] Nagler RM, Hershkovich O. Age-related changes in unstimulated salivary function and composition and its relations to medications and oral sensorial complaints. Aging Clinical and Experimental Research. 2004;17:358 - 66.

(••) This is an important study on measuring salivary flow rate and composition in older adults in relation to drug consumption and idiopathic oral sensorial complaints.

[89] Nagler RM, Hershkovich O. Relationships between age, drugs, oral sensorial complaints and salivary profile. Arch Oral Biol. 2005;50:7-16.
[90] Wang K, Wang X, Zheng S, Niu Y, Zheng W, Qin X, et al. iTRAQ-based quantitative analysis of age-specific variations in salivary proteome of caries-susceptible individuals. Journal of translational medicine. 2018;16:293.
[91] Fleissig Y, Reichenberg E, Redlich M, Zaks B, Deutsch O, Aframian DJ, et al. Comparative proteomic analysis of human oral fluids according to gender and age. Oral diseases. 2010;16:831-8.