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Oral Textural Properties of Easy-to-Swallow Foods

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This study is part of a broader project aimed at designing foods tailored to specific populations, such as easy-to-swallow products for individuals with dysphagia, emphasizing the need for a deeper understanding into oral processing and its physiological interactions with food. The lack of objective datasets further complicates this effort. This research focused on data collection from commercial ready-to-eat foods designed for dysphagia. The products analyzed spanned various categories, all classified as soft-solids with expected distinct flow behaviors during oral mixing and swallowing. Measurements included the assessment of the flow behavior, of mucoadhesion on porcine tissue, and of texture-cohesiveness properties relevant to in-mouth behavior. Flow curves were modelled using the Herschel-Bulkley equation. Moreover, the oral-relevant viscosities were measured for the in-mouth mixing, the pharyngeal swallowing, and to assign foods to their respective IDDSI levels. Texture properties were assessed via back-extrusion tests, while mucoadhesion was evaluated in compression mode on porcine tongue. Key findings showed that fruit-based preparations exhibited the highest yield stress, while the other products had very low yield stress. It can be concluded that products within the same viscosity class exhibited significant variations in-mouth texture and rheology, including mucoadhesion. These results highlight the importance of considering properties beyond viscosity, such as cohesiveness and mucoadhesion, when designing dysphagia-oriented foods to ensure safe and comfortable swallowing.

1. Introduction

The design of foods tailored to the specific needs of people with swallowing difficulties, such as dysphagia, is a critical area of research in food science and nutrition. Dysphagia, a condition characterized by swallowing impairment, affects a significant proportion of the world's population (8%) and not only impacts nutritional intake, but also poses the risk of aspiration and choking, thus affecting the quality of life and health outcomes (Gallegos et al., 2017). The management of dysphagia through texture-modified foods is essential to reduce chewing difficulties, while thickened liquids are used to slow down the swallowing process, improving its safety and efficiency (Giura et al., 2021). The complexity in developing dysphagia-oriented foods lies in understanding and controlling the main physical parameters that influence oral processing and swallowing. Traditional approaches to food formulation have frequently focused on viscosity as the key determinant of swallowability. However, viscosity alone seems to be insufficient to describe the in-mouth behavior and swallowing dynamics of food. Therefore, the interactions between the food and the oral cavity during oral processing need to be investigated.

2. Materials and Methods

2.1 Materials

Five dysphagia-oriented ready-to-eat foods (DRFs) belonging to different food categories (namely, carbohydrate-rich foods, protein-rich foods, fruits and vegetables, desserts, thickened waters) were evaluated. Specifically, the selected products included: pasta-based puree, chicken-based puree, apple-based puree, vanilla-flavored pudding, and orange-flavored thickened water, providing a representative sampling of commercially available products (Ascrizzi et al., 2024).
All dysphagia oriented-products were purchased from a local pharmacy (Milan, Italy). Porcine tongues used in the mucoadhesion test were obtained from a local swine slaughterhouse (Lodi, Italy).

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2.2 Flow behavior assessment

A combined motor transducer rheometer (DHR-2, TA Instruments, USA), equipped with a 40 mm diameter cone-plate geometry was used. Tests temperature was kept constant at 25 ± 0.1 °C and a solvent trap was used to prevent loss of solvent. Shear flow tests were run in the range 0.01-1,000 s^{-1}. Data were modelled using Herschel-Bulkley Eq(1) to quantify the shear-thinning behavior:

$$\sigma = \sigma_0 + k \cdot \dot{\gamma}^{n} \quad \textbf{(1)}$$

where σ is the shear stress (Pa), σ_0 is the yield stress (Pa), k is the consistency index ($Pa \cdot s^n$), $\dot{\gamma}$ is the shear rate (s^{-1}) and n is the flow behavior index.
Oral-relevant viscosities (η) ascribed to the in-mouth mixing (10 s^{-1}) (Ross et al., 2019), to the pharyngeal swallowing (300 s^{-1}) (Bolivar-Prados et al., 2022) and used to assign foods to the viscosity levels of the International Dysphagia Diet Standardisation Initiative (IDDSI) (50 s^{-1}) framework were extrapolated from the flow curves.

2.3 Textural properties

Back extrusion tests were performed using a TA-XT2 texture analyzer (Stable MicroSystems Ltd, Godalming, UK) equipped with a 50 Kg load cell and a specific geometry (A/BE) with a cup and a 40-mm diameter Plexiglas disk probe. Test speed was equal to 2 mm/s and 10 mm/s, for the compression and the return of the cross-head. The product was extruded upwards and around the edge of the disk when the samples were compressed to a 50% depth. Mechanical data were recorded using Texture Exponent v32 (Stable MicroSystems Ltd). Samples were analyzed in quadruplicate at room temperature and the following parameters, expressed as mean ± standard deviation, were evaluated: Maximum positive force (N), Positive area (N·mm), Maximum negative force (N), Negative area (N·mm).

2.4 Mucoadhesion evaluation

To evaluate the adhesion of foods to the tongue during oral processing, an ex-vivo assessment of mucoadhesion was performed on a porcine tongue. Each dysphagia-oriented food was subjected to a mucoadhesion test using a TA-XT2 texture Analyzer equipped with 50 Kg load cell and fitted with a specific geometry for assessing mucoadhesion (Rig A/MUC) (Tobyn et al., 1994), with the porcine tongue attached to the geometry's tissue holder. The test speed was equal to 0.5 mm/s and contact with the tongue was realized under a force of 1.0 N. After compression, the probe was withdrawn from the mucosal tissue and the adhesive properties were measured. Samples were analyzed at room temperature in quintuple and data expressed as mean ± standard deviation. The mucoadhesion parameters recorded were the Peak value (N) and the total Work of adhesion (W_{ADH}, N·mm) (Bassi da Silva et al., 2017).

2.5 Statistical analysis

Data were analyzed using JMP Pro version 17.0 (SAS Institute, Cary, NC, USA) and OriginPro version 9.0 (Stat-Ease Company, Northampton, MA, USA). Data were subjected to one-way analysis of variance ($p<0.05$) and the means were compared using Tukey-Kramer test to examine if differences between samples were significant.

3. Results and Discussion

3.1 Flow behavior

The viscosity of dysphagia-oriented foods was assessed up to 1,000 s^{-1}, allowing for the evaluation of the different shear rates that occur during the whole oral processing and swallowing. All the products showed a non-Newtonian shear-thinning behavior, as shown in Figure 1.
The data were then modelled using the Herschel-Bulkley Eq(1), which describes the flow behavior of non-Newtonian fluids and was used to calculate the yield stress of the samples, as shown in Table 1.

Table 1: Rheological parameter obtained from the Herschel-Bulkley model

DRFs	σ_0	k	n	R^2
Pasta puree	1.21	48.23	0.313	0.99
Chicken puree	1.93	68.87	0.247	0.99
Apple puree	9.01	70.88	0.134	0.99
Vanilla pudding	5.42	29.80	0.307	0.99
Thickened water	1.29	10.05	0.297	0.99

σ_0: yield stress (Pa); *k*: consistency index (Pa·s^n); *n*: flow behavior index (dimensionless). DRFs: Dysphagia-oriented Ready-to-eat Foods.

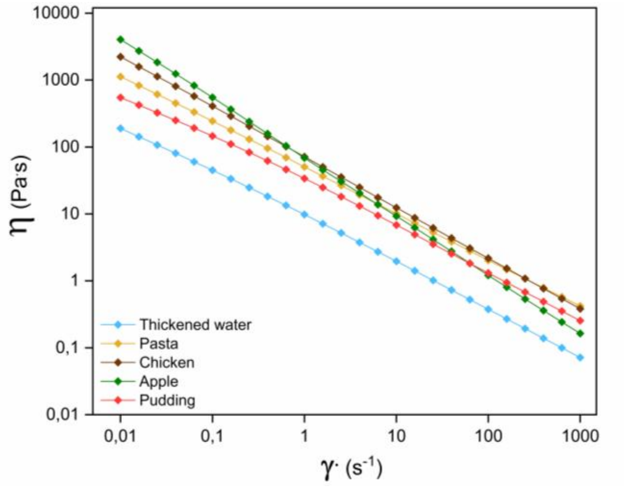

Figure 1: Flow curves in the range 0.01-1,000 s^{-1}.

Yield stress, which represents the stress required to initiate flow and is associated with internal bond strength and structural organization, is a critical parameter in assessing the suitability of foods for individuals with dysphagia, as it is linked to the ease of swallowing (Tobin et al., 2020). Fruit puree showed the highest yield stress (9.01 Pa), indicating a more cohesive structure among tested samples. While this higher structure may improve bolus formation, it could pose a challenge for dysphagia patients, as the higher yield stress requires more force to initiate flow during oral processing and swallowing. This highlights the need for careful optimization of these products to achieve a balance between cohesion and ease of swallowing.
Following, the flow curves of each dysphagia-oriented ready-to-eat food (DRF) were analyzed to determine the apparent viscosity at the different shear rates of oral processing-relevant viscosities. In-mouth mixing (10 s^{-1}) and pharyngeal swallowing (300 s^{-1}) were calculated, and the viscosities at the 50 s^{-1} value were used to assign each food to the appropriate IDDSI level, as reported in Table 2.

Table 2: Calculated oral-relevant apparent viscosities (η, in Pa·s) and retrieved IDDSI level

DRFs	η (10 s^{-1})	η (50 s^{-1})	η (300 s^{-1})	IDDSI Level †
Pasta puree	10.12	3.28	0.95	4
Chicken puree	12.38	3.67	0.95	4
Apple puree	9.26	2.25	0.46	4
Vanilla pudding	6.38	2.16	0.60	4
Thickened water	1.96	0.62	0.17	3

† Level *3*: Moderately thick (IDDSI) - Viscosity reference range (NDD): 351-1,750 mPa·s.
† Level *4*: Extremely thick (IDDSI) - Viscosity reference range (NDD): >1,750 mPa·s.

The viscosity values at 10 s^{-1}, representing in-mouth mixing conditions, showed significant differences between products. The pasta, chicken and fruit purées exhibited the highest viscosities, suggesting these products may require more oral manipulation effort at the beginning of the oral processing. In contrast, thickened water showed markedly lower viscosity, suggesting easier oral processing. At 50 s^{-1}, the reference shear rate for IDDSI classification, most products fell into Level 4 (Extremely thick) with viscosities above 1,750 mPa·s. Only thickened water was classified as Level 3 (Moderately thick), which corresponds to its intended use as a modified beverage rather than a food product. However, it should be noted that the products identified as Level 4 exhibited different viscosities (ranging from 2,160 to 3,280 mPa·s). The viscosity values at 300 s^{-1}, representative of pharyngeal swallowing conditions, demonstrated significant shear-thinning behavior across all products. Overall, the viscosity reduction from 50 to 300 s^{-1} ranged from 71-80%, indicating favorable flow properties during swallowing in pharyngeal phase (Bolivar-Prados et al., 2022). Results for the shear-thinning behavior suggest these products can maintain adequate cohesiveness during oral processing while flowing more easily during swallowing.

3.2 In-mouth texture properties

The back extrusion test on these samples is an efficient method for obtaining detailed information on deformation resistance and structural properties of the ready-to-eat meals under study. Since in-mouth texture plays a critical role in both meal processing and bolus formation, ensuring a pleasant texture is essential, especially for patients with specific swallowing difficulties. The results are presented in Figure 2 and Table 3.

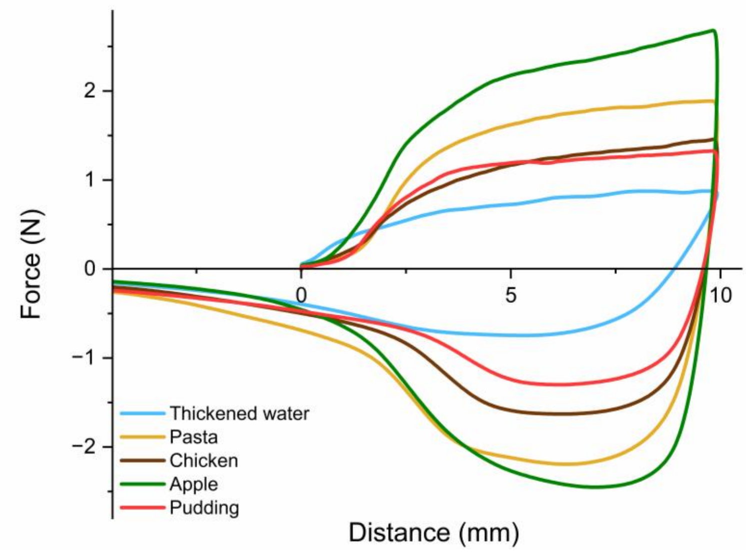

Figure 2: Back extrusion test expressed as Force vs Space.

Table 3: Back extrusion retrieved value for each DRFs

DRFs	Positive peak (N)	Positive area (N·mm)	Negative peak (N)	Negative area (N·mm)
Pasta puree	1.95 ± 0.15 b	12.27 ± 1.11 b	-2.19 ± 0.11 b	13.34 ± 1.53 b
Chicken puree	1.43 ± 0.04 c	9.86 ± 0.23 c	-1.59 ± 0.05 c	11.08 ± 0.56 c
Apple puree	2.69 ± 0.09 a	17.09 ± 1.19 a	-2.49 ± 0.10 a	16.74 ± 1.06 a
Vanilla pudding	1.32 ± 0.03 c	9.31 ± 0.83 c	-1.29 ± 0.04 d	8.57 ± 0.37 d
Thickened water	0.93 ± 0.07 d	6.62 ± 0.50 d	-0.73 ± 0.05 e	5.32 ± 0.31 e

For each column, different lowercase letters (a, b, c, d, e) indicate significant differences (*p<0.05*).

The fruit-based puree exhibited the highest extrusion force, indicating greater resistance to deformation and structural integrity. This aligns with its higher yield stress values observed in flow measurements, suggesting a more structured material requiring greater force for oral manipulation. The positive area values, representing mechanical cohesiveness and work required for deformation, showed significant variations among samples. The fruit puree demonstrated the highest cohesive strength, while thickened water showed the lowest. This correlation between yield stress and cohesiveness has already been suggested by for thickened fluids (Ross et al., 2019). The negative area values, representing adhesive properties, followed a similar pattern to cohesiveness. The fruit puree exhibited the highest adhesiveness, while thickened water showed the lowest. Finally, the negative peak values, representing the resistance during probe separation, provided more insights into adhesive properties during oral processing. The fruit puree exhibited the highest negative peak force, and this aligns with the adhesiveness data suggesting that products with higher negative peak forces may require greater effort for bolus clearance during the oral phase. The significantly higher mechanical parameters of the fruit puree may pose challenges for individuals with limited oral strength. The combination of high cohesiveness, resistance to deformation and adhesiveness could increase the risk of fatigue during oral processing and potentially lead to incomplete bolus clearance and complications during swallowing.

3.3 Mucoadhesion assessment

The mucoadhesive test used is a common methodology to evaluate allows a quantitative assessment of the adhesion strength of food formulations on mucosal tissues (Cook et al., 2017). The mucoadhesive capacity, is critical for dysphagic patients as excessive adhesion can hinder swallowing, while insufficient adhesion may lead to laryngeal penetration. Results are shown in Figure 3 (here displayed as force-vs-time for a better visualization) and Table 4.

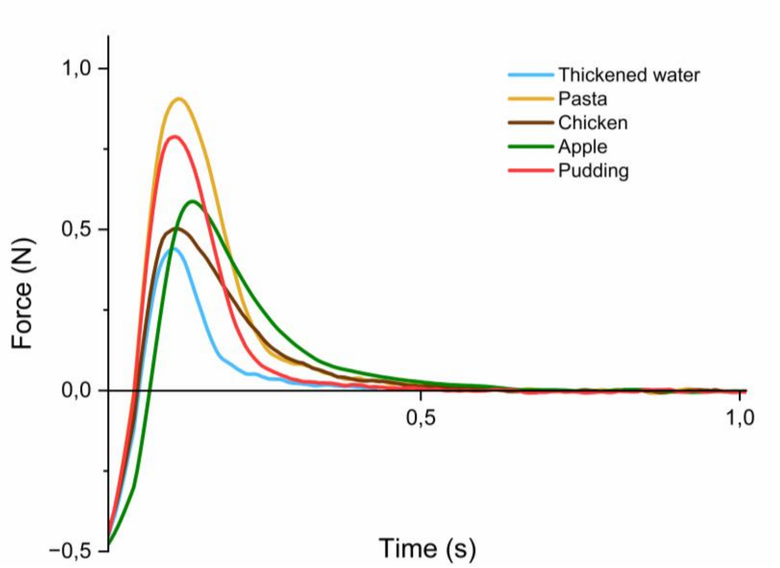

Figure 3: Mucoadhesion test expressed as Force vs Time.

Table 4: Mucoadhesion value for each DRFs

DRFs	Peak value (N)	W_{ADH} (N·mm)
Pasta puree	0.85 ± 0.05 a	1.09 ± 0.12 a
Chicken puree	0.48 ± 0.03 d	0.84 ± 0.07 b
Apple puree	0.59 ± 0.01 c	0.97 ± 0.02 a;b
Vanilla pudding	0.74 ± 0.05 b	0.89 ± 0.10 b
Thickened water	0.45 ± 0.02 d	0.52 ± 0.05 d

For each column, different lowercase letters (a, b, c, d) indicate significant differences ($p<0.05$).

The test results revealed important variations in the adhesive properties of the different dysphagia-oriented foods, providing insights into their potential behavior during oral processing and swallowing. The pasta-based product demonstrated the highest detachment force, significantly different from other samples, indicating stronger mucoadhesive properties, while the fruit and pudding samples showed intermediate values. The W_{ADH} values followed a similar pattern, with pasta and fruit-based puree showing the higher energy requirement for food-mucosae bond breakage. In particular, the W_{ADH} provides a better measure of the tenacity of the mucoadhesive bond, representing an index of the adhesive strength of the product.

It must be noted that for products intended for dysphagic patients, there are no reference mucoadhesion levels, as this parameter can vary depending on the type of product, its formulation, and the specific needs of the patient. The significant variations in mucoadhesive properties among the meals under study highlight the importance of careful product selection based on individual patient needs. Products with excessive mucoadhesion may require additional consideration for patients with reduced oral clearance capabilities, while those with very low adhesion might pose risks for bolus control during oral processing.

4. Conclusions

The findings of this study highlight the significant variability in texture and adhesive properties among foods classified within the same IDDSI level, thus confirming that viscosity alone is not sufficient to fully characterize a product intended for dysphagic nutrition. These results highlight the importance of properties beyond viscosity, such as cohesiveness and mucoadhesion, for ensuring safe and comfortable swallowing. Despite being categorized as similar according to the IDDSI viscosity-based classification, these products demonstrated distinct performances in back-extrusion and mucoadhesion tests, revealing differences in their structure and interaction with the oral cavity and pharynx. Together with viscosity, cohesiveness and mucoadhesion data could help in the development of AI-driven simulators that can improve the design of personalized food solutions for people with swallowing impairments.

It is clear that healthcare providers may not yet be familiar with the new indices introduced in this study. Further fundamental research is required to align these indices with IDDSI standards. Choosing foods and drinks at specific IDDSI levels can help alleviate symptoms for individuals with swallowing difficulties. Collaborating with healthcare professionals trained in IDDSI and dysphagia management is a key objective of this research.

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