Oral processing and dynamics of texture perception in commercial gluten-free breads

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Abstract

There is an increasing demand for gluten-free products, with the texture being a critical aspect. The aim of this work was to study the food bolus properties of gluten-free breads in relation to the dynamics of sensations perceived during its consumption. In this study, five-commercial gluten-free breads and two regular breads were analysed for their texture, crumb structure, and moisture content. Bread bolus particle size after three chews, bolus characteristics at the swallowing point, and oral activity were determined. The dynamics of textural sensations during bread consumption was evaluated using the temporal dominance of sensations (TDS) technique. Texture and structure properties vary among gluten-free breads being some of them close to regular breads (crumb with more and smaller cells that shows low hardness and high springiness) that lead to different in-mouth breakdown and TDS patterns. At the beginning, harder breads with low springiness values resulted in hard dominant sensations, in contrast, breads with low hardness and high springiness values were perceived soft and spongy. Breads that fragmented into a greater number of small size particles created crumbly and sandy sensations, characteristic of gluten-free breads with large air cell sizes. Compact sensation appeared in breads with low saliva uptake during bolus formation, while pasty and sticky sensations were related to a cohesive and adhesive bolus, respectively. Not only structure and mechanical properties, but also its oral behaviour in terms of fragmentation and bolus formation can fully explain the dynamics of texture perception of gluten-free breads.

Keywords: Gluten-free bread; Texture; Bolus properties; Dynamic sensations

Highlights

- Commercial gluten-free breads differed in mechanical properties and oral behaviour.
- Breads with low hardness and high springiness were perceived soft and spongy.
- Crumbly and sandy sensations were related to bolus with small particles.
- Low saliva uptake resulted in a compact dominant sensation.
- Pasty and sticky dominant sensations were related with cohesive and adhesive bolus.

1. Introduction

Over the last decade, there has been a growing demand for commercial gluten-free products, resulting from the increase in the detection of different gluten-related disorders including coeliac disease, wheat allergy, non-coeliac gluten sensitivity (Henggeler, Veríssimo, & Ramos, 2017; Sapone et al., 2012), and the wrongful conviction that a gluten-free diet is healthy (Christoph, Larson, Hootman, Miller, & Neumark-Sztainer, 2018; Gaesser & Angadi, 2012). Gluten present in wheat, rye, spelt, triticale, kamut, and some oat varieties, is the main structure-forming protein complex of dough and bread, providing characteristic viscoelastic properties of bread and bakery goods. The absence of gluten has a key impact on bread organoleptic characteristics, leading to poor mouthfeel and flavour (Lazaridou, Duta, Papageorgiou, Belc, & Biliaderis, 2007; Matos & Rosell, 2014; Molina-Rosell, 2013; Naqash, Gani, Gani, & Masoodi, 2017; Tsatsaragkou, Protonotariou, & Mandala, 2016). Therefore, studies have achieved products that resemble their gluten-containing counterparts by incorporating functional ingredients such as starches, hydrocolloids, proteins, and fibres, while also applying different technological processes (Capriles & Arêas, 2014; Diowks, Sucharzewska, & Ambroziak, 2009; Houben, Höchstätter, & Becker, 2012; Korus, Witczak, Ziobro, & Juszczak, 2009; Martínez, Díaz, & Gómez, 2014).

Strategies to modify or improve texture attributes has focused on the product characteristics (structural or instrumental texture); however, a recent approach, based on the knowledge of product behaviour in the mouth (oral processing) to better understand the mechanisms of texture perception, is gaining interest from new food products developers and researchers. During oral processing, food structures are broken down to form a bolus suitable for swallowing. Fragmentation, agglomeration, hydration, and lubrication take place (De Wijk, Engelen, Prinz, & Weenen, 2003; Hoebler et al., 1998; Lucas, Prinz, Agrawal, & Bruce, 2002; Witt & Stokes, 2015) and contribute to the sensory sensations perceived in the mouth; like texture perception, a complex and dynamic process (Devezeaux de Lavergne, van de Velde, & Stieger, 2017; Hutchings & Lillford, 1988).

Authors have developed methods for evaluating the various aspects involved in food oral processing (fragmentation, oral activity, bolus composition, and bolus mechanical properties). These approaches are different depending on the food properties (Tournier et al., 2017) and some have been developed or adapted for bread. To measure oral bread fragmentation, bolus particle size distribution has been analysed using image analysis or laser diffraction techniques (Gao, Wong, Lim, Henry, & Zhou, 2015; Hoebler et al., 1998;

Jourdren, Panouillé, et al., 2016; Jourden, Saint-Eve, et al., 2016; Le Bleis, Chaunier, Della Valle, Panouillé, & Réguerre, 2013). To evaluate the bolus mechanical properties, different rheological techniques (capillary rheology, and viscoelasticity) and empirical methods like double compression or penetration tests, have been proposed (Assad-Bustillos, Tournier, Septier, Della Valle, & Feron, 2019; Gao et al., 2015; Jourden, Panouillé, et al., 2016; Le Bleis et al., 2013; Panouillé, Saint-Eve, Déléris, Le Bleis, & Souchon, 2014, Peyron et al., 2011; Young et al. 2013). This wide variety of small and large deformation measurements shows how difficult it is to characterise the breads' bolus. Furthermore, previous authors have measured the moisture and saliva incorporation during consumption of breads from expectorated bolus (Gao, Tay, Koh, & Zhou, 2018; Gao et al., 2015; Le Bleis, Chaunier, Montigaud, & Della Valle, 2016; Motoi, Morgenstern, Hedderley, Wilson, & Balita, 2013; Panouillé et al., 2014; Tournier, Grass, Septier, Bertrand, & Salles, 2014).

Sensations perceived during food consumption vary continuously because of the breakdown of food structure and the progressive changes in bolus characteristics, releasing stimuli of different sensations. To capture the sensations along the mastication process, different dynamic sensory methodologies have been used, such as Time Intensity (TI), Progressive Profiling (PP), and TDS. The latter is the only method that registers the sensations that dominate during eating (Di Monaco, Su, Masi, & Cavella, 2014; Pineau et al., 2009; Wang & Chen, 2017).

TDS has been widely used to assess the temporality of sensations perceived in bread consumption (Gao, Ong, Henry, & Zhou, 2017; Gao et al., 2018; Jourden, Panouillé, et al., 2016; Jourden, Saint-Eve, et al., 2016; Panouillé et al., 2014). Authors have evaluated how bread properties affect bolus formation in mouth and the sensations perceived during mastication. Panouillé et al. (2014), found that with the same salt content, different crumb density (obtained by lowering the time of kneading and baking) resulted in a different sensory perception sequence (lighter crumb: chewy and aerated; denser crumb: dense and soft), different mastication time (denser crumbs: less time), and saltiness perception (denser crumbs: less saltiness perceived). Gao et al. (2017) studied how, in breads with different crust hardness and crumb structure (western baked bread, oriental steamed bread, and French baguette), oral processing performance (muscle activity and chewing rhythm), and texture perception were affected. The authors found that in breads with a hard crust, chewing effort increased and had a different sensations sequence than those with soft crusts. At the beginning of oral processing, the dominant attributes of breads with hard crusts were crunchy and chewy while steamed breads' initial dominant attribute

was stickier. It should be noticed that these conclusions are valid when serving volume is kept constant across samples but not for experiments where mass is kept constant and volume varies (Tournier et al., 2014).

To the best of the authors' knowledge here, this approach has not been applied to gluten-free breads. Therefore, the present study aims to describe the oral trajectory (fragmentation and bolus properties) of gluten-free commercial breads in relation to the dynamics of sensations perceived during its consumption, to better understand the factors involved in the perception of different texture sensations.

2. Materials and methods

2.1. Bread samples

Seven commercial sliced bread samples were selected. Five of them were gluten-free breads (A, B, C, D, and E) and the other two were regular breads, containing gluten (G1 and G2). Breads were purchased at the same time in a local supermarket and stored at -20 °C. The day before analysis, the breads were thawed to 4 °C and tempered to ~25 °C prior to the tests. Table 1 shows the ingredients and nutrition facts of each bread.

2.2. Bread characterisation

2.2.1. Internal structure of bread crumb

The internal crumb structure of commercial breads was studied by digital image analysis. Bread slices were digitised in TIF format at 600 ppi on a scanner (Canon MP270 model K.10339, NY., USA) using a black background. Images of the bread slices were analysed using Nis-Elements® BR 3.2 software (Nikon, Tokyo, Japan). The image was first binarised from a 5 x 5 cm² square at the centre of slice, defined as the region of interest; three parameters were measured: cell density, cell size, and crumb air area fraction. Cell density corresponded to the number of air cells per cm² of crumb. Cell size corresponded to the mean of air cells areas (mm²). Air area fraction (%) corresponded to the percentage of crumb area occupied by air cells. For each bread, six replicates were performed. Crumb density was calculated from the volume and weight of the serving sample.

2.2.2. Instrumental texture of bread crumb

Bread crumb hardness and springiness were determined using a TA-Xt plus Texture Analyser equipped with Exponent software v.6 (Stable Micro Systems Ltd, Godalming, UK), using an aluminium cylindrical probe with a 35mm diameter.

Two slices of bread were subjected to a double compress test with a 2 s waiting time between the two cycles, performing a 40% compression at 1 mm/s with a trigger force of 0.196 N. Hardness of the bread samples was determined at 5 mm of distance during the first compression. Springiness was obtained by calculating the ratio between the distance to the maximum peak force of the second compression and the distance to the maximum peak force of the first compression. The analyses were performed in triplicate for each bread.

2.2.3. Moisture of bread crumb

Moisture content of the breads was determined by a gravimetric method. Approximately 4 g of crumb were weighed, thoroughly mixed with 8 g of sand, which facilitated the even evaporation of moisture, and dried to a constant weight in an oven at 105 °C. Moisture content was expressed as g of water/100 g of bread crumb (wet basis). The analyses were performed in triplicate for each bread.

2.3. Bolus collection

2.3.1. Served samples

Cylinders from the central part of the bread slices were obtained with a metallic puncher ($d=3.2$ cm). Samples served to participants comprised two stacked cylinders, resembling the consumption of a sandwich, with a total height of 2.4 ± 0.1 cm. Sample sizes had been previously established to allow consumption in one bite. Because of differences among bread densities, the weights varied from 2.9 ± 0.1 to 5.1 ± 0.4 g.

2.3.2. Procedure

Six subjects (four females and two males) from the 19, participating in the sensory evaluation, were recruited for this part of the study. Bread boluses were collected, after three chewing cycles, for particle size analysis and at swallowing point, for moisture and mechanical properties measurement.

Each participant was asked to eat the bread sample as usual and then spit the bolus out into a plastic cup, either after three chewing cycles or after full mastication, when they felt the need to swallow. Bread samples were presented monadically following William's design in a different order across participants, on plastic plates labelled with three-digit codes.

For each subject, one bolus per sample was collected in each session. Boluses for the three tests (particle size analysis, moisture, and mechanical properties) were obtained considering three replicates over nine separate sessions.

2.4. Particle size analysis of bolus after three chewing cycles

Each bolus collected after three chewing cycles was spread out on a transparent glass surface (30 x 21 cm). Particles were carefully and manually separated from each another with thin wooden sticks and digitised in TIF format at 600 pixels per inch (42.33 microns) on a scanner (Canon MP270 model K.10339, NY., USA), using a black background. Images obtained from bolus particles were analysed using Nis-Elements® BR 3.2 software (Nikon, Tokyo, Japan) and binarised using a histogram-based segmentation process, according to the pre-defined intensity threshold values. Particle size distribution and the number of particles were obtained for each bread and subject. The median particle area (a50), which is the particle area corresponding to 50% of total area occupied by particles, was calculated. For each subject, three boluses of each sample were collected over three different sessions.

2.5. Bolus characterisation at swallowing point

2.5.1. Moisture

Moisture content of each bolus at the swallowing point was gravimetrically determined. Approximately 5 g of bolus was weighed, thoroughly mixed with 10 g of sand, which facilitated the even evaporation of moisture, and dried to a constant weight in an oven at 105 °C. The moisture content was expressed as g of water/100g bolus.

The saliva uptake was calculated as the difference between the water content of the bread samples (%) and the water content from the expectorated bolus (%). For each participant, three boluses of each sample were collected over three different sessions.

2.5.2. Mechanical properties

Consistency and adhesiveness of boluses obtained at swallowing point were determined using a TA.XT plus Texture Analyser (Stable Micro System, UK), fitted with a TTC Spreadability Rig containing a male cone (90° and 40 mm diameter) that matches a glass containing the female cone fixed in an HDP/90 platform. The bolus was placed into the female cone and carefully levelled. The force when penetrating the sample with the male cone at a constant rate of 2 mm/s until a depth of 28 mm was recorded.

From the force-displacement curves, consistency values corresponded to the maximum peak force during the downstroke (N.s). Adhesiveness value (N.s) corresponded to the area under the curve during rising the probe (negative area). For each subject, three boluses of each sample were collected over three different sessions. Measurements were performed at room temperature.

2.6. Sensory evaluation

Nineteen participants performed the sensory evaluation of the bread samples. Sensations perceived during consumption were assessed using the TDS method, focusing only on texture sensations.

Three preliminary sessions were conducted. In the first session, assessors generated, individually, a list of texture attributes based on the comparisons among the bread samples. In the second session, terms and descriptions of the sensations were discussed among assessors. A final list of nine attributes and definitions obtained by consensus is shown in Table 2. Furthermore, assessors were introduced to the notion of the TDS technique and the concept of the dominant sensation as the most salient or the attribute that captures their attention. In the third session, assessors evaluated samples of bread (not included in the study) to familiarise themselves with the TDS test.

For the evaluation sessions, samples were served as described in Section 2.3. Each participant was asked to introduce the whole sample into the mouth and click the “start” button on the screen at the same time they started chewing. During sample consumption, participants had to select the dominant sensation at each moment from a list of nine attributes. They were instructed to stop the test when they did not perceive any further sensation in the mouth. The order of attributes on the list varied (randomly) among assessors, but for each assessor the same order was kept across the different samples. Bread samples were presented monadically following the William’s design but in a different order across participants, on plastic plates labelled with three-digit codes. A dummy sample was always served first, to eliminate first-position bias. In all the experiments, participants could rest between samples and were provided with still mineral water for rinsing. For each sample, participants performed three replicates of the TDS test in three separate sessions. The assessments took place in a temperature-controlled room under white light and in standard sensory booths, designed according to ISO 8589 (ISO, 2007). Data were collected by using Compusense Cloud (Compusense Inc., Guelph, Canada).

2.7. Chewing and swallowing events

The same 19 participants took part in the chewing and swallowing events assessment. Sample presentation was performed as described in Section 2.3.1. Participants were instructed to eat the bread sample, while at the same time indicate when each swallow occurred and the end of chewing happened using a temporal question with Compusense Cloud software (Compusense Inc., Guelph, Canada). From the data the number of swallows, first swallow, and chewing times were obtained. For accuracy of the chewing and swallowing time, participants were instructed to place the entire sample in the mouth and click the software “start” button at the same time they started chewing. Three replicate assessments were performed over three separate sessions.

2.8. Statistical analysis

For moisture content, the internal structure, and instrumental texture parameters of breads one-way analysis of variance (ANOVA) was applied. Fisher’s least significant difference (LSD) was calculated to assess significant differences among samples ($\alpha < 0.05$).

For parameters of bolus characterisation, chewing and swallowing activity mixed ANOVAs with the bread as a fixed factor and the participant as a random factor were applied. Fisher’s LSD was calculated to assess significant differences among breads ($\alpha < 0.05$).

For the TDS data, the percentage of participants who selected one attribute as dominant at a specific time, was calculated per attribute for each product and time. The TDS curves representing the dominance rate for each of the sensations at different points of the chewing time, for a sample across participants, were obtained. According to Pineau et al. (2009), two limits can be included on graphs, representing the variations of the dominance rate with time. The chance limit represented the dominance rate that an attribute can be obtained by chance. The significance limit expressed the smallest value of the proportion being significantly higher ($p < 0.05$) than the chance level, based on a binomial test. The data from TDS evaluation was normalised according to individual evaluation time on a scale from 0 (beginning of consumption) to 100% (end of perception), according to the method described by Lenfant, Loret, Pineau, Hartmann, & Martin (2009). For each sample, the dominance area was calculated as the area under the curve of dominance rate versus time.

Multi-factor analysis was applied to the matrix containing each sample (rows) and the dominance area value for the different attributes (columns); three supplementary tables

containing bread characteristics, bolus properties, and chewing activity were also included.

Statistical analyses were performed with XLSTAT statistical software (version 2017.6, Microsoft Excel[®], Addinsoft, Paris, France).

3. Results and discussion

3.1. Structure, moisture, and instrumental texture of breads

Cell density, cell size, and air area fraction were obtained from 2D scanned images to compare the internal structure of the bread crumb and are presented in Table 3. ANOVA results show that the three parameters significantly vary among bread samples ($p < 0.001$). Although both cell density and size vary among gluten-free breads, in general all of them show a lower number of air cells but larger than in regular breads (Table 3).

Air area fraction varies less among samples, with two exceptions; gluten-free bread A, with a higher proportion of air in the crumb than the rest of samples, and the regular bread G1, with a lower proportion of air than the rest of samples. However, the air area fraction calculated here is probably lower than the real air area fraction. As described by previous authors (Zghal et al. 1999, Pa 2013), cell size observed at the surface (2D technique) is always smaller than the diameter of the real cell, and in addition, the intra-mural air of cells walls has not been considered.

Among all breads studied, G1 is the bread with the lowest density values and D, the highest. Regarding gluten-free breads, A is the least dense, and the density of the other breads (G2, B, C, and E) does not differ.

Both hardness and springiness values vary significantly among bread samples (Table 3). Regular breads (G1 and G2) are less hard than gluten-free samples. Within gluten-free samples, C and D are harder than A, B, and E. Regarding springiness, G1, B, and E are the springiest, while gluten-free samples A and C show the lowest levels. These results are comparable to previously reported values for homemade gluten-free breads with rice flour (springiness values ranging from 0.77 to 0.94) and commercial gluten breads (0.87 to 0.95) (Marco & Rosell, 2008). In bread, springiness was associated with freshness (Matos & Rosell, 2012). In contrast, breads with low springiness were related with crumb brittleness (McCarthy, Gallagher, Gormley, Schober, & Arendt, 2005).

Moisture content significantly varies among samples ($p < 0.001$) regardless of the bread type. The highest value of moisture content is for gluten-free bread D, and the least is for the regular bread sample G1.

In this study, bread characteristics (structure, texture, and moisture) varied between regular and gluten-free breads and among samples in each group. Establishing solid relationships between texture and structure characteristics is difficult here, because of using commercial samples (different formulations and processing conditions). According to Zghal et al., (2002) mechanical properties of these solid foams depends on density, cellular structure, and the intrinsic properties of the cell wall. As bread has a porous structure; the compression during instrumental texture, is dependent on the resistance exerted by the three dimensional structure of the solid foam created (Jekle, Fuchs, & Becker, 2018). In experimental breads, when only one ingredient is changed, greater crumb density is translated to more solid material, requiring more force to compress (Collar, Bollaín, & Angioloni, 2005). In this study, harder breads (C and D) are the denser, however breads with lower hardness do not have low density. For instance, G2 is the softest bread but had medium density value. However, those breads with low hardness (regular breads: G1 and G2) have a greater number of smaller cells showing different cell wall properties than gluten-free breads. Previous studies have shown the relevant contribution of cell wall thickness to the mechanical response of breads (Zghal et al., 1999). In this study, cell wall thickness was not determined, which could have provided a better understanding of texture from structure.

3.2. Bolus characterisation

3.2.1. Particle size distribution after three chewing cycles

To study fragmentation of breads during mastication, the particle size distribution of the bread after being chewed (three strokes) were analysed from the scanned image of boluses (examples of each bread can be found in Figure 1).

Figure 2 shows, for each bread sample, the percentage of area occupied by small (0.3 - 10 mm²), medium-sized (10 - 100 mm²), and large particles (> 100 mm²). For regular bread samples (G1 and G2), almost the totality of the area (> 97.5%) is occupied by large particles >100 mm². The same is seen for two gluten-free breads (B and E) where large particles account for the 93.5 and 97.6% of the total area, respectively. In these four breads, the small and medium particles are sparse. For breads A, C, and D, small and medium-sized particles occupy a greater area percentage, indicating a higher degree of fragmentation. For sample A, small and medium-sized particles represent 8.5 and 26.9% of the area. For samples C and D, fragmentation is higher, with small particles representing 23.4 and 16.9% of the area and medium particles representing 40.1 and 35.3% of the area.

The mean area and number of the particles in boluses are obtained from the images (Figure 1), both parameters show significant differences among breads (Table 4). Boluses of regular breads G1 and G2 and gluten-free samples B and E have few particles (2.1 - 7.1) while for samples A, C, and D, the number of particles was much higher. Among these, the sample with the lowest number of particles was sample A (112.8), while sample D has the highest particle number (769.9). Mean area values also varied among samples, being significantly higher for bread samples G1, G2, and gluten-free E than for the rest of samples; while significantly lower for samples A, C, and D.

This study shows different bread boluses after three chewing strokes. Gluten-free bread samples show high fragmentation, while sample group G1, G2, and E present boluses with two or three large particles. Previous authors, indicated that once fragile or soft solid foods are wetted for the saliva action and along mastication, the particle size distribution of boluses can reflect fragmentation and / or aggregation phenomena (Assad-Bustillos et al., 2019; Tournier et al., 2014; Yven, Guessasma, Chaunier, Della Valle, & Salles, 2010). Using two alveolar structures (sponge cake and brioche), Assad-Bustillo et al. (2019) showed that the breakdown pattern was different for sponge cake, showing fragmentation, while brioche showed fragmentation and agglomeration. Therefore, boluses formed by few and large particles result from either a low fragmentation or a quick agglomeration of bread particles, that is the case of bread A, C and D. However, for the breads E, G1, G2, and to a lesser extent bread B, the bread material is maintained in mouth as a cohesive bolus and does not undergo a fragmentation status. It is possible, that in the gluten-free breads, A, C and D, the lack of gluten, that provides structure-building properties, made the structure of these breads crumblier (Gallagher, Gormley, & Arendt, 2004), as observed in the Table 4.

3.2.2. Bolus at the swallowing point

Bolus properties at the swallowing point were studied by evaluating moisture content, hardness, and adhesiveness of the boluses of six subjects.

Bolus moisture content values significantly vary among the bread samples ($p < 0.001$, (Table 5)). The moisture content ranges from 52.9% for boluses of bread G2 to 58.7% for boluses of bread B. The range of variation in moisture content among bread boluses at the swallowing point is lower (4.8%) than the variation in moisture content among breads (12.5%), indicating that during oral processing, the amount of saliva incorporated compensates, in part, the initial differences in moisture among breads. This confirms that,

to trigger the swallowing action, a bolus must have similar moisture content, independently from the initial product characteristics (Panouillé et al., 2014).

The amount of saliva incorporated was calculated as the difference between the water content (%) of boluses at swallowing point and the water content (%) of the bread sample (Table 5). The amount of saliva incorporated varies according to the initial moisture content of the product. Bread sample G2, with higher moisture content, incorporated less saliva in the bolus during mastication than the rest. Samples G1, D, and A, with low initial moisture, incorporate a higher amount of saliva during mastication. Previous research has shown comparable results of bolus moisture at swallowing point (Le Bleis et al., 2016; Panouillé et al., 2014). This confirms, during mastication, saliva is incorporated to the bolus, reaching a critical moisture level, needed for a suitable swallowable bolus, not only for bread, but for most food products (Loret et al., 2011).

Consistency and adhesiveness values of bolus also significantly varies among bread samples ($p = 0.006$ and $p < 0.001$, respectively). Bolus of the regular bread G1 is less consistent, while bolus of gluten-free bread C is the most consistent. Consistency of bread bolus (Table 5) is not related to initial bread hardness (Table 3). Previous authors explained that bread bolus' mechanical properties are governed by their initial water content and initial water absorbing capacity (Jourden, Panouillé, et al., 2016). Evidently, the boluses with higher moisture content requires less force to be compressed. However, this pattern is not observed for all the samples of this study: the bolus of sample D presented low moisture content and has a lower hardness value than other samples, probably due to the presence of different hydrocolloids in each recipe. The variation in adhesiveness of bolus also relates to the initial water content. The regular bread G2 and gluten-free bread E, with higher moisture content than the rest, results in the most adhesive bolus, while gluten-free breads C and D, with lower moisture content, results in the least adhesive bolus.

3.2.3. Oral activity

The number of swallows, the time of the first swallow, and the total chewing time of subjects when eating the bread sample (Table 6) vary significantly among samples ($p = 0.009$, $p < 0.001$, and $p < 0.001$, respectively). These parameters vary depending on the bread. Overall, the number of swallowing events is smaller for regular bread A than gluten-free breads A, C, and D. For gluten-free breads, the first swallowing event occurs later and chewing time is longer than for the regular breads. Gluten-free breads require more time to be processed because, as previously reported, harder products usually

require more chewing time to be broken and form, with the help of the saliva, a cohesive bolus (Engelen, Fontijn-Tekamp, & Van Der Bilt, 2005; Tournier et al., 2014).

Besides the initial hardness of product there are other reported factors that influence the oral activity. Swallowing triggers when the bolus is safe and comfortable and this is usually related to its moisture level and hardness. In this study, bolus moisture content and consistency seem to explain the differences in chewing time among samples in each group of breads. For example, bread D has a high hardness value among gluten-free breads but the time of chewing is lower than the breads because it has a high saliva uptake, leading to a bolus of low consistency attained sooner in mouth that is perceived soft enough and needs no further chewing. Likewise, in sample G1, that had similar hardness values to sample G2, but the time of chewing was shorter. The amount of saliva incorporated in the bread was higher in G1, making the bolus softer and ready to swallow sooner than for sample G2.

3.3. Sensory sensations perceived during bread consumption

3.3.1. Temporal dominance of sensations

TDS curves showing the dominance rate (agreement among assessors) of each sensation during eating time were obtained for gluten-free and regular breads (Figure 3). Standardised time was divided into three periods: initial (0 - 33%), intermediate (33 - 66%), and final (66 - 100%).

Regular breads G1 and G2 display a similar sequence of dominant texture sensations along the consumption of breads in the following order: soft and spongy at the initial period, with an intermediate compact, then the final pasty and sticky sensations. Some differences are seen among the two breads, especially in the first period. The dominance rates for soft and spongy are higher with the sensation lasting longer in bread G1 than in G2, thus, a higher dominance rate for the compact sensation becomes dominant sooner and endures for longer.

Gluten-free breads show different TDS curves that can be summarised in three different patterns. The first, for gluten-free breads C and D at the beginning, hard and dry are the dominant sensations, then crumbly during the intermediate period, and finally sandy; pasty; and sticky. The second, for bread A, dry and crumbly are the dominant sensations up to the intermediate period. Then, the sandy sensation is significantly dominant from the beginning of the intermediate period and reaches its maximum value during the final period, together with sticky sensation. The third pattern, in gluten-free breads B and E, soft and spongy are dominant during the first and intermediate periods, the pasty during

intermediate and final periods, and sticky sensation emerges at the end. The main differences among these breads (B and E) is the compact sensation was dominant in bread E (initial and intermediate periods) but not in bread B, thus, a higher dominance rate of spongy and soft sensations endured over time.

According to TDS plots, commercial gluten-free breads differ in the sensations that are elicited at different periods of consumption. Hard and soft sensations are mainly relevant for the initial period; while spongy, crumbly, dry, and compact are relevant during both the initial and intermediate periods. Sandy and pasty are sensations relevant during the intermediate and final periods, and the sticky sensation is relevant only during the final period. Two gluten-free breads (B and E) present a profile that was like regular breads (G1 and G2), with a higher dominance of soft and spongy sensations at the beginning, with pasty and adhesive sensations at the intermediate and final periods. However, the other gluten-free breads present very different profiles from regular breads (A, C, and D) with a higher dominance rate of hard or dry sensations at the beginning, crumbly at the intermediate period, and sandy at the end.

To understand the dynamic sensory perception of breads, TDS have been previously used with different breads types (Gao et al., 2017; Panouillé et al., 2014). Differences in bread properties provided different perceived sensations and different generated attributes for performing TDS. In breads with hard crust (baguette and baked bread), first sensations were associated with an initial perception of crunchy, while those without crust, initial sensations were associated with aerated, soft, and chewy (Gao et al., 2017). The intermediate sensations were related to crumb properties and moisture content, while the dominant attributes were dry, chewy, and dense, with sticky and hydrated appearing in all samples (Gao et al., 2017). In bread crumb with different fat content and processing time (kneading, fermentation, and baking), elicited sensations also differed, with more fat and aerated breads perceived with a similar pattern of the attributes dry, aerated, crumbly, and hydrated (Panouillé et al. 2014). In the present study, TDS technique has revealed differences among commercial gluten free breads and compared to regular breads. Critical texture sensations on gluten-free breads have been identified such as hardness, dryness, crumbliness and sandiness sensations but also the lack of sponginess and pastiness.

3.3.2. Relationship between texture sensations, bolus properties, and oral activity during bread consumption

Differences in the dominance of texture sensations perceived among breads during the consumption and their relationship with the initial texture and structure of breads, the breakage pattern, and bolus characteristics were found via a multi-factorial analysis (MFA). Figure 4 shows the MFA plot where bread samples are distributed according to texture sensations (dominance area in TDS plot), bread characteristics, and oral trajectory parameters.

The first MFA dimension separated gluten-free samples A, C, and D (on the right) with a higher dominance of crumbly sensation, related to the number of particles generated during the first three chewing cycles. Among these samples, C and D are separated on the top with higher dominance of the hard sensation that was positively correlated with bread hardness, while sample A (at the bottom) was differentiated for the higher dominance of dry and sandy sensations, positively related to bread air cell size, yet negatively related to the size of particles in bolus. In contrast, in the other extreme of the first dimension, regular breads (G1 and G2) are found and the gluten-free samples B and E are close to them. These samples show higher dominance for sticky and pasty sensations than the rest of samples and sensations related to the size of bolus particles and adhesiveness. As it was observed in Section 3.3.1, the breakdown pattern (particle area and particle number) of these breads is similar, inducing similar sensations. Among these four samples, the second dimension separated samples G2 and E on the top, because of the higher dominance of compact sensation, that is inversely related to saliva uptake. While samples G1 and B (on the bottom) show a higher dominance for spongy and soft sensations, they are positively related with bread springiness and negatively related to bread hardness. Bread hardness and oral activity (total chewing time, first swallow time, and number of swallows) are related with samples C and D. Previous authors have proven that bread, perceived sensory characteristics are related to the structure fragmentation of bread and its breakage pattern and bolus formation (Jourdren, Saint-Eve, et al., 2016).

A limitation of this study, samples were commercial, and although they provide a realistic picture of breads (gluten-free and regular), factors such as formulation and processing conditions could impact results, as they are not controlled. Therefore, further studies including experimentally designed samples with controlled variability are needed. From a mechanical point of view, future studies including bread characterisation in 3D, cell wall thickness measurement, and microscopic disposition might also contribute to the structural understanding. For instance, X-ray computed tomography has been proposed as a non-destructive technique to studied the bread dough and baked bread (Schoeman, Williams, du Plessis, & Manley, 2016). This will allow validation of the proposed

mechanisms of bread texture perception and determination of which formulation and bread-making factors are key for producing gluten-free breads with tailored texture characteristics.

Bread is a solid foam structure with two phases, air and cell wall material. The present study shows that in commercial breads, with and without gluten, there is a wide variation in bread structure. As it was briefly explained in the introduction, gluten is capable of retaining the air created during fermentation and baking, that also confers elastic and extensible properties to the bread (Khatkar et al., 1995). Our results show that bread structure and texture in regular breads (G1 and G2) is different, with lots of smaller cells and softer crumb, to gluten-free breads which contains fewer cells of bigger size, providing a harder structure. However, at mouth, these differences change, and regular breads G1 and G2, have similar bolus properties and provoke the same sensations than gluten-free breads B and E. This means that gluten-free breads B and E, despite having a different structure, have managed to mimic the oral behaviour of regular breads.

4. Conclusions

Commercial gluten-free breads with different structures and mechanical properties presented different oral trajectories (fragmentation, bolus formation, and oral activity) during its consumption. The sequence of texture sensations experienced during bread consumption also varied among commercial gluten-free breads. Sensations perceived at the beginning of bread consumption (hard, soft, spongy, and dry) were related to its structure and mechanical properties; however, the remaining sensations were mostly explained by oral trajectory features. Crumbly and sandy sensations were related to bread fragmentation in mouth, the compact sensation to the amount of saliva uptake, pasty sensation to a cohesive bolus (none fragmented), and sticky sensation to a bolus with high dominance of adhesiveness at the end of consumption.

In summary, this paper shows that when reformulating or improving gluten free breads, strategies should take into account in-mouth behaviour of product, as its breakage pattern in presence of saliva and oral movements is crucial to modulate texture sensations. In the present work some of gluten-free breads showed similar behaviour to regular breads that seems to be achieved through including many different emulsifiers, thickeners and fat as the long list of ingredients for these breads. The challenge for the future is then to find alternatives (for example changing baking conditions) that allow obtaining breads with an in-mouth behaviour and texture sensations similar to gluten-containing breads.

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Table 1. Ingredients and nutritional facts of the commercial bread samples in the study according to the information on the label / package.

Bread	Ingredients	Energy (kcal)	Total fat (g)	Saturated fat (g)	Total carbohydrate (g)	Fibre (g)	Protein (g)
A	Water, sourdough (rice flour, water), corn starch, rice syrup, high oleic sunflower oil, rice starch, tapioca starch, vegetable fibres (psyllium, bamboo), potato protein, thickener (hydroxypropylmethyl cellulose), sugar, yeast, salt, preservatives (sorbic acid, calcium propionate).	267	5.3	0.6	60.0	N/A	3.1
B	Water, potato starch, corn starch, refined sunflower oil, tapioca starch, egg white powder, rice bran, sugar, stabilizers (E-466, E-464, E-422, E-415), yeast, thickener (cellulose), salt, wine vinegar, preservatives (E-200, E-202, E-282), aroma	272	11.0	1.1	28.0	11.5	5.0
C	Corn starch, water, sugar, pasteurised liquid egg, margarine, yeast, thickener (xanthan gum), emulsifier (monoacetyl and diacetyl tartaric esters of monoglycerides and diglycerides of fatty acids), salt, preservative (sodium propionate), antioxidant (ascorbic acid), gasifiers (diphosphate disodium, sodium bicarbonate)	283	5.9	3.2	53.0	5.4	1.7
D	Water, corn starch, margarine, sugar, tapioca starch, rice flour, yeast, thickener (xanthan gum), emulsifier (monoacetyl and diacetyl tartaric esters of monoglycerides and fatty acid diglycerides), rice fibre, salt, preservative (sodium propionate), gasifiers (disodium diphosphate, sodium bicarbonate), antioxidant (ascorbic acid)	295	9.9	4.9	47.0	5.5	1.6
E	Corn starch, water, sourdough (rice flour, water), rice starch, rice syrup, vegetable fibre (psyllium), sunflower oil, millet flour, soy protein, flour quinoa, thickener, yeast, salt, honey	239	3.4	0.5	45.0	7.3	3.5
G1	Wheat flour, water, yeast, sugar, sunflower oil, salt, vinegar, bean flour, emulsifiers (E-472e, E-471), acidity corrector (E-341iii), antioxidant (E-300), preservatives (E-282, E-202).	255	2.2	0.5	48.0	3.5	9.0
G2	Wheat flour, water, yeast, vegetable oil (sunflower), conservative salts (E-282, E-200), emulsifiers (E-481, E-471), wine, vinegar, corn treatment agent for the flour (E-300, E-341)	252	1.9	0.5	49.0	2.9	9.4

N/A: data not available.

Table 2. List of sensory attributes and definitions used for the TDS assessment of breads

Attribute	Definition
Hard	Sensation that describes the resistance to being deformed by teeth during chewing.
Compact	The bread has a tight or little porous structure.
Soft	The bread has a tender texture, easy to crush when chewing.
Crumbly	The bread is easy to disaggregate in crumbs and breaks down rapidly.
Pasty	Sensation that describes the formation of a dough of the bolus.
Dry	Sensation that describes the absence of moisture in mouth when chewing and the difficulty to moisturise the bread.
Spongy	The bread has a light and porous structure.
Sticky	Sensation that describes the adhesion of the bolus to teeth and oral cavity during chewing.
Sandy	Sensation that describes the presence of particles in oral cavity which tend to scratch the tongue and throat.

Table 3. Mean values of internal structure parameters, density, moisture content, mechanical texture parameters and weight and volume of serving samples of gluten-free breads (A - E) and regular breads (G1, G2).

Bread	Cell density (cells/cm ²)	Cell size (mm ²)	Air area fraction* (%)	Bread density (g/cm ³)	Hardness (N)	Springiness	Moisture content (gH ₂ O/100g bread)
A	10.0 d	4.7 a	45.3 a	0.21 ab	6.9 b	0.89 cd	35.1 d
B	13.5 c	3.1 d	41.0 b	0.27 c	5.6 b	0.96 ab	39.5 b
C	11.2 d	3.8 bc	41.7 b	0.27 c	20.9 c	0.86 d	36.5 c
D	10.7 d	3.9 b	40.9 b	0.33 d	23.4 c	0.90 c	32.2 e
E	12.9 c	3.2 cd	41.1 b	0.24 bc	5.9 b	0.96 ab	39.9 b
G1	22.0 a	1.7 e	36.5 c	0.16 a	1.8 a	0.97 a	34.9 d
G2	19.4 b	2.1 e	40.4 b	0.24 bc	1.3 a	0.93 bc	44.7 a

Letters indicate significant differences according to Fisher's LSD test ($\alpha = 0.05$). For each column, values not sharing a letter are different.

* It should be noticed that air area fraction calculated from 2D images can underestimate the air fraction as described by Zghal et al. 1999, Pa 2013.

Table 4. Mean values of the number and mean area of the particles in bolus obtained after three chewing cycles of gluten-free breads (A - E) and regular breads (G1, G2).

Bread	Particles area (mm ²)	Particles number
A	28.9 c	112.8 c
B	324.6 b	7.1 d
C	7.7 c	769.9 a
D	12.8 c	248.5 b
E	538.9 a	3.2 d
G1	562.6 a	2.1 d
G2	557.5 a	2.8 d

Letters indicate significant differences according to Fisher’s LSD test ($\alpha = 0.05$). For each column, values not sharing a letter are different.

Table 5. Mean values of moisture content and mechanical properties of the bolus obtained at swallowing point when eating gluten-free breads (A - E) and regular breads (G1, G2).

Bread	Bolus moisture content (g/100 g)	Saliva uptake (%)	Bolus consistency (N)	Bolus adhesiveness (N.s)
A	54.6 c	19.5 b	65.5 abcd	1.98 bc
B	58.7 a	19.2 b	52.4 cd	2.28 b
C	54.7 bc	18.1 b	85.3 a	1.68 c
D	53.7 cd	21.5 a	57.3 bcd	1.83 c
E	54.6 c	14.7 c	76.5 ab	2.81 a
G1	56.2 b	21.3 a	47.0 d	2.03 bc
G2	52.9 d	8.2 d	69.3 abc	3.19 a

Letters indicate significant differences according to Fisher’s LSD test ($\alpha = 0.05$). For each column, values not sharing a letter are different.

Table 6. Mean values of oral activity of participants when eating the gluten-free breads (A - E) and the regular breads (G1, G2).

Sample	Number of swallows	First swallow time (s)	Total chewing time (s)
A	3.1 a	22.7 ab	30.1 ab
B	2.8 ab	20.8 abc	28.9 ab
C	2.9 ab	23.1 ab	32.2 a
D	3.0 a	22.5 ab	29.9 a
E	2.9 ab	24.9 a	35.3 a
G1	2.5 b	17.3 c	23.6 b
G2	2.8 ab	20.2 bc	27.5 ab

Letters indicate significant differences according to Fisher’s LSD test ($\alpha = 0.05$). For each column, values not sharing a letter are different.

Figure 1. Example of particles obtained at three chewing cycles for each type of bread

Figure 2. Particle size distribution of bolus after three chewing cycles. Percentage of area occupied by particles of size 0.3 - 10 (white), 10 - 100 (grey), and > 100 mm² (black).

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Figure 3. Normalised dominance curves of attributes (soft, spongy, sticky, pasty, compact, sandy, hard, dry, crumbly) obtained by TDS during consumption of the breads.

(A)

(B)

Figure 4. Multiple factor Analysis of the dominance area value for the different attributes. Bread characteristics, bolus properties, and chewing activity were included as supplementary variables. (A) Map of attributes (in blue) with supplementary variables (represented by dotted lines): bread characteristics (in green), bolus properties (in red) and chewing activity (in pink). (B) Map of samples.