Oral processing of hydrogels: influence of food material properties versus individuals' eating capability

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This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1111/jtxs.12478

Abstract

Food material properties play an important role in the sensory perception and consumer acceptance of foods. However, the actual oral processing behaviour may depend on both the material properties of the food that is being consumed as well as individuals' oral capabilities. This study aimed to examine the relationships between intrinsic (oral capabilities of healthy participants), as well as extrinsic (food material properties of a set of hydrogels) variables to the real oral processing behaviour. Three κ-carrageenan hydrogels (κC), differing in fracture mechanics and oral tribology properties, were prepared: native κC, κC with added Na-alginate and a κC matrix with added Ca-alginate beads of 300 μm. A composite score of eating capability (EC) was measured with non-invasive techniques (maximum bite force and tongue pressure) using a panel of 28 untrained consumers. The oral processing behaviour (number of chews, oral residence time and chewing rate) was analysed with the same participants using frame-by-frame video analysis. It was found that the EC scores did not correlate with any of the oral processing behaviours. The number of chews and oral residence time showed a strong correlation to the fracture force and friction force at orally relevant speeds (10-100 mm/s), whereas chewing rate did not vary with these properties. The results from this study indicate that oral processing in healthy adults seems mainly motivated by food material properties, and the chewing rate seems to relate more to individual differences and EC than to food properties.

Practical applications

Understanding the interplay between food material properties, consumers' eating capability and oral processing behaviour is important to advance knowledge and to translate this to applications for the food industry, such as designing foods with improved textural properties. We employed a combination of eating capability measurements, texture analysis, oral

tribology as well oral processing video analysis as a feasible approach to understand the importance of intrinsic eating capability versus extrinsic food material properties on oral processing behaviour. Insights from this study, using model hydrogels, have helped to promote knowledge on oral processing behaviour in healthy individuals, could bridge the gap between consumer science, psychology and food science, and may be of interest to product developers in designing foods with pleasant texture properties.

Keywords

Oral processing; eating capability; hydrogels; texture analysis; tribology; video analysis

Introduction

As global obesity rates increase, there have been intensified efforts to design satiety-enhancing foods that can decrease appetite and thus reduce food intake in the longer term. Previous studies have demonstrated the role of oral processing on satiety (Miquel-Kergoat et al., 2015), and in a recent systematic review and meta-analysis it was found that "oral processing" leads to a significant reduction in food intake (-0.28 effect size, 95% CI: -0.36, -0.19) (Krop et al., 2018). Here, the term "oral processing" incorporated a variety of strategies, such as increased number of chews, eating rate or bite size, extended oro-sensory exposure time and/or introducing harder textures as compared to a softer/liquid variant. However, the effects of salivation and food/saliva interactions were not considered in the retrieved studies (Krop et al., 2018).

Previous evidence revealed that the actual oral processing strategy is adapted to the extrinsic material properties of the food that is being consumed (Koç et al., 2014; Le Révérend et al., 2016), but also varies between individuals according to their intrinsic oral capabilities (Wilkinson et al., 2000; Peyron et al., 2011). During oral processing, the food's physical properties are continuously manipulated with the food structure being broken down and mixed with saliva and fluid released from the food matrix to form a cohesive bolus (Chen, 2009). Therefore, both texture properties and the degree of moisture of the initial food structure contribute significantly to oral processing (Hutchings and Lillford, 1988). The central nervous system uses sensory feedback from the changing physical properties during oral processing to update the oral processing strategy, from visual cues before ingestion, to first bite until swallowing (van der Bilt et al., 1995; de Wijk et al., 2003; Koç et al., 2014).

Research on chewing has primarily focussed on solid foods, using various techniques to quantify chewing behaviour. In a study by Hiiemae et al. (1996), it was found that the number of chews and oral residence time increased for foods with a more complex initial structure, with banana requiring less chewing than biscuits. In another study by Forde et al. (2013), the number of chews related to the number of bites for 50 g food sample, and the eating rate was inversely related to the number of chews. Previous studies have also made the link between commercial food products like cheese, peanuts and carrots, where harder and drier foods required more chewing (Fontijn-Tekamp et al., 2004; Engelen et al., 2005). In addition, Engelen et al. (2005) found that quantity of saliva and maximum bite force were only weakly correlated with chewing characteristics, accounting for less than 10% of the variance in the number of chews. However, these products are highly familiar with learned expectancies for processing and satiety.

Hydrocolloids have been used in research to make model foods to study texture and oral processing behaviour without invoking an emotional response and expectancies built up from prior experience with real life products (Nishinari, 2004; Funami, 2011; Funami et al., 2012; Hayakawa et al., 2014; Funami et al., 2016; Laguna and Sarkar, 2016; Larsen et al., 2016). Previous studies observed a relationship between food hardness and chewing behaviour, where fracture stress from instrumental texture analyses was correlated to higher number of chews and increased oral residence time (Devezeaux de Lavergne et al., 2016; Funami et al., 2016; Laguna and Sarkar, 2016). Moreover, from bolus particle analysis it was found that harder and more complex model gels break down into significantly higher number of particles that are smaller in size (Devezeaux de Lavergne et al., 2016; Larsen et al., 2016).

Aside from fracture properties, the effects of food structure on oral lubrication (both internal and external) have gained increased research attention. Human saliva binds particulated food into a cohesive bolus that can be easily swallowed (Pedersen et al., 2002; Carpenter, 2012). In addition, the moisture content in foods (providing external oral lubrication) has been linked to the used oral processing strategy (Hutchings and Lillford, 1988). A dry solid food (e.g. biscuits) will generally require a large quantity of saliva in order to form a swallowable bolus, whereas more moist solid foods, such as fruits and vegetables, already contain a large quantity of moisture that is released during oral processing (Chen and Rosenthal, 2015). However, due to the continuously changing nature of the food structure during oral processing, the effects of external lubrication by food on oral processing behaviour remains a challenging research topic (Chen, 2009).

Besides the extrinsic food properties, oral processing also depends on intrinsic individual differences in oral physiology, from the size of the oral cavity to the strength of the oro-facial muscles (Engelen et al., 2005; Alsanei and Chen, 2014). Several studies have mentioned that chewing patterns vary not only between individuals but also within the same person. In a study by Lassauzay et al. (2000) the number of chews for gelatine based model foods in male individuals varied from 19 to 57, with a similar variability found for the different test foods. Another study by Brown et al. (1994) using healthy subjects also reported large variations between subjects for the tested foods, such as apple, salami and toast, with raw carrot showing particularly big differences in number of chews and oral residence time, ranging from 20 to 190 chews and 15 to 125 s, respectively. Furthermore, the effects of gender and age on masticatory ability have been reported in literature. Males have a bigger bite size, faster eating rate and a higher EMG muscle activity than females (Peyron et al., 2004; Park and Shin, 2015), whereas females chewed more and for a longer time than males ($p < 0.05$) (Park and Shin, 2015). Also, due to the decrease of masticatory muscle mass and maximum bite force with age (Bakke et al., 1990), the number of chews and EMG activity increased in older participants who still had complete healthy dentition compared to younger adults (Kohyama et al., 2002; Peyron et al., 2004). At the same time, salivary secretion, saliva viscosity, and its protein content varies widely between individuals, as well as within the same individual at different times of the day (Carpenter, 2012), and would therefore be expected to influence oral processing.

Thus, understanding the relationship between oral processing behaviour, food material properties (determined both instrumentally and sensorially) and individuals' eating capabilities is important in determining what drives the consumer experience of eating a food and what leads to consumer acceptance and preference. To date, no studies have looked at the oral processing behaviour of hydrogels in young individuals, examining both the food material properties as well as the participants' individual eating capability. Therefore, the aim of this study was to investigate the oral processing response and their potential relationships with 1) the extrinsic food material properties of different hydrogels (i.e. fracture behaviour and oral lubrication) and 2) the intrinsic eating capability of a group of young healthy consumers.

Materials and methods

Materials

Food grade-quality κ-carrageenan (κC) and sodium alginate (NaA) were purchased from Special Ingredients Ltd (Chesterfield, UK). Green food colouring was obtained from AmeriColor (Placentia, USA) and American peppermint extract was purchased at a local supermarket (Leeds, UK). Potassium chloride (KCl) was purchased from Minerals Water Ltd (Purfleet, UK) and calcium chloride (CaCl) from VWR International (Leuven, Belgium). All materials were used without further purification. Demineralised water was used in preparation for all hydrogels.

Hydrogels

Based on a previous study by Krop et al. (2019), three model hydrogels (that did not contain any fat) were selected that had different chewing and oral lubrication properties as determined by instrumental and sensory texture analysis. The hydrogels consisted of varying concentrations of κC alone or with the addition of NaA or calcium alginate (CaA) beads of 300 μm diameter. The selected model gels were 3κC (3 wt% κC), 1.5κC0.5NaA (1.5 wt% κC and 0.5 wt% NaA) and 2.4κC0.2CaA$_{300}$ (2.4 wt% κC and 0.2 wt% CaA beads of 300 μm). The hydrogels were unsweetened, but flavoured with peppermint aroma and coloured with green food colouring to increase acceptability. Further details on the preparation method, as well as instrumental and sensory characterisation of the hydrogels have been published elsewhere (Krop et al., 2019). The samples were presented in bite-size round pieces (diameter 25 mm, height 10 mm) in small, shot-glass type plastic cups.

Puncture test (texture analysis)

The mechanical properties of the hydrogels were determined using uniaxial puncture test with a Texture Analyzer (TA-TX2, Stable Micro Systems Ltd., Surrey, UK) , with a 30 kg load cell. The fracture mechanics were measured using a 10 mm Volodkevitch bite jaw probe to simulate a first bite with human incisor teeth. Tests were carried out at 22 °C, at a constant speed of 2 mm/s and the deformation level was set at 80 % strain. Six replicates were measured for each hydrogel on at least four different preparation days. The software Exponent (TEE32, v6.1.9.0, Stable Micro Systems Ltd., Surrey, UK) was used to plot the force-distance curve and the Young's modulus was determined from the slope of the curve.

Tribological measurements

The oral lubrication properties of the hydrogels after simulated oral processing were determined with a Mini Traction Machine (MTM2, PCS Instruments, London, UK), based on a method developed by Krop et al. (2019). Briefly, the hydrogels were broken down in presence of artificial saliva containing mucin at pH 6.8 (Sarkar et al., 2009) with a mechanical blender (final sample to saliva ration 4:3 w/w). The larger gel particles (> 500 μm) were filtered out, and the friction behaviour of the bolus filtrate was determined. Commercially available polydimethylsiloxane (PDMS) ball (diameter of 19 mm) and disc (diameter of 46 mm, thickness of 4 mm) were obtained from PCS Instruments (MTM ball and disc, Sylgard 184, 50 Duro, London, UK), with the surface roughness of the PDMS tribopairs, $R_a < 50$ nm. The friction force in the mixed lubrication regime was determined as a function of the applied entrainment speed, ranging from 10 to 100 mm/s, with an applied load of 2N, slide-to-roll ratio (SRR) of 50 % at 37 °C. Measurements were performed in triplicate and then averaged to obtain the Stribeck curves.

Participants

Twenty-eight healthy participants with natural, intact dentition were recruited to participate in this study and gave written informed consent before the start of the study. The study was reviewed and approved by the Faculty Research Ethics Committee at the University of Leeds (reference number MEEC 16-006). Participants were aged between 22 and 52 years old (mean 28.5 ± SD 6.2, 9 male and 19 female). Participants with any allergies/intolerances to the gel ingredients were excluded, as well as those who suffered from any condition hampering normal chewing or swallowing. All participants received a financial compensation.

Study procedure

Test sessions were conducted in sensory booths at the School of Food Science and Nutrition, University of Leeds. Prior to the start of the study, participants were instructed that they would be video recorded while eating the three model foods and that afterwards eating capability measures (bite force and tongue pressure) would be taken. Participants were given the opportunity to ask questions in case anything was unclear, after which they provided written, informed consent form. Samples were provided to the panellists in randomised order, and a practice sample was provided to familiarise the panellists with the type of test samples and the eating instructions.

Video analysis of oral processing characteristics

To analyse the oral processing behaviour, participants were video recorded while eating the model foods. A digital camera (Panasonic SDR-H90) was positioned in front of the participant on a tripod, and participants were instructed to look straight into the camera while eating the hydrogels. Participants were aware that their oral processing behaviour would be analysed, such as number of chews and eating rate, and were given the option to swallow the samples or indicate the moment they felt the urge to swallow by raising their hand and expectorate the sample in provided containers. Videos were analysed frame-by-frame using Observer XT 12 software (v 12.5, Noldus Information Technology, The Netherlands). A coding scheme was created to identify the first bite, number of chews and point of swallowing, as adapted from previous studies (Forde et al., 2013; Lasschuijt et al., 2017). A chew was defined as the point in time when the jaw was at the lowest position during a masticatory cycle (closing action). From these behaviours, the eating duration was determined as the time between first bite and swallowing, identified as the first main swallow at the end of the rhythmic rotary chewing movements. The chewing frequency was calculated by dividing the number of chews for each sample by the total eating duration of this hydrogel (Chen and Lolivret, 2011; Forde et al., 2013; Laguna et al., 2016b; Laguna and Sarkar, 2016).

All videos were coded by a trained researcher, with a second observer analysing at least 15 % of the videos in parallel to assess the accuracy of the coding scheme and the performance of the coders. The performance of the researchers assessing the videos was validated using a reliability analysis, showing at least 85 % agreement.

Eating capability measurements

Tongue pressure was measured using the Iowa Oral Performance Instrument (IOPI®, Medical LLC, Redmond, Washington, USA (Ono et al., 2009; Laguna et al., 2015). Participants were instructed to place the plastic bulb sensor in the centre of the oral cavity between their tongue and the hard upper palate, and press these surfaces together with their maximum strength. The maximum tongue-palate pressure was recorded in kPa.

The maximum biting force was measured using force sensors and a multimeter connected through a bread board, a device previously used by Flanagan et al. (2012). The force sensor was sandwiched between two adhesive silicone disks (diameter 1.5 cm, thickness 0.3 cm), which in turn were wrapped in wrapping foil for hygienic reasons. Participants were instructed to bite down separately on the sensor for a couple of seconds using their front incisors, left molars and then their right molars. The minimum resistance was independently recorded by the multimeter for the front incisors, left molars and right molars and subsequently converted into N (Flanagan et al., 2012; Laguna et al., 2015). Both measures of tongue pressure and bite force were measured in triplicate for each participant.

Eating capability (EC) has been defined as "the physical, physiological and cognitive capabilities of an individual consuming food" (Laguna et al., 2016b). In previous studies, a composite EC score was used that consisted of grip strength, manual dexterity, and oro-facial muscular capability (tongue pressure and bite force) (Laguna et al., 2015; Laguna et al., 2016b). It was determined that the most important factors in determining the EC score were related to the oro-facial muscular capabilities, therefore for this study only tongue pressure and bite force were included. The EC composite score was calculated using the following equation:

$$EC = \left(\frac{TP}{TP_{max}}\right) + \left(\frac{\frac{BF_L}{BF_{L,max}} + \frac{BF_F}{BF_{F,max}} + \frac{BF_R}{BF_{R,max}}}{3}\right) \quad (1)$$

where, TP represents the tongue pressure and BF the biting force measured for each participant. The subscript max indicates the highest value measured in the strongest participant for that particular variable, L is the bite force from the left side molars, F from the front incisors and R from the right side molars. Thus, the maximum EC score that could be obtained was 2-points.

Statistical analysis

All statistical analyses were performed using SPSS (IBM® SPSS® Statistics, v24, SPSS Inc, Chicago, USA). Results are presented as mean ± standard deviation (SD) and alpha was set at $p < 0.05$, unless stated otherwise. Analysis of variance (ANOVA) was applied to determine statistically significant differences between samples for the fracture mechanics and eating behaviour, and between participants for the bite force parameters. Least significant differences were calculated by Bonferroni's post-hoc test. Pearson's correlations were calculated to study the relationships between food material properties, oral processing behaviour and participants' eating capabilities.

Results and discussion

Fracture properties

The force-distance curves of the three hydrogels upon puncturing with a Volodkevitch bite jaw probe can be seen in **Figure 1**. It shows the typical penetration curves, with the increasing deformation of the sample upon increased applied load up to the point of fracture as the probe penetrates and ruptures the sample. The hydrogel 3*κ*C required an applied force of 8.29 ± 0.96 N, whereas the sample containing alginate beads, 2.4*κ*C0.2CaA$_{300}$, required only half that to rupture (3.67 ± 0.88 N). Interestingly, the sample containing alginate, 1.5*κ*C0.5NaA, was structurally weaker and required a force of an order of magnitude lower than the native κC hydrogel to puncture the gel (0.57 ± 0.14 N). The fracture forces for the three hydrogels were determined to be significantly different ($p < 0.05$).

This indicates that κC formed a strong continuous network, whereas the CaA beads disrupted this network indicating they were not inherently connected to the κC matrix. The presence of NaA weakened the κC network even further, causing disruption of the strong κC matrix. This weakening of κC gels in presence of alginates as measured with puncture tests was in agreement with results from the same gels during compression tests (previously studied by Krop et al. (2019) and Laguna and Sarkar (2016)).

Lubrication properties

Figure 2 shows the friction force as a function of entrainment speed for the bolus filtrate of the three hydrogels. From previous studies it was determined that the relevant oral processing speeds, such as the speed of the tongue, ranged from 20-50 mm/s (Steele and Van Lieshout, 2009; Krop et al., 2019). Therefore, we have focussed here on the mixed lubrication regime. The hydrogel bolus samples were prepared using artificial saliva, and therefore the friction force of the artificial saliva was used as a control. It can be seen that the friction force curve of the simulated bolus filtrate of the 3κC hydrogel is similar to that of artificial saliva ($p > 0.05$, except at μ = 70, 90, 100 mm/s), whereas the 1.5κC0.5NaA and 2.4κC0.2CaA$_{300}$ samples had a significantly lower friction force as compared to artificial saliva ($p < 0.001$). It is worth pointing out here that the larger gel particles were removed by filtration before the oral tribology measurements. The 3κC hydrogel broke down into significantly larger particles than the other two after simulated oral processing (> 500 μm), and thus were most likely removed during the filtration process resulting in friction forces more similar to those of artificial saliva. Interestingly, the 1.5κC0.5NaA and 2.4κC0.2CaA$_{300}$ hydrogel boli did not have a significant difference in friction force over the measured entrainments speeds in the mixed regime ($p < 0.001$). The reduced friction force of 1.5κC0.5NaA and 2.4κC0.2CaA$_{300}$, compared to 3κC, could be explained by the entrainment of a viscous layer of the alginate-based systems (hydrogel bolus filtrates with artificial saliva) between the PDMS contact surfaces due to the smaller broken down hydrogel particles (Gong and Osada, 2001; Krop et al., 2019). For 2.4κC0.2CaA$_{300}$, as theoretically predicted by Hertz theory in our previous study (Krop et al., 2019), the alginate beads will most likely be deformed during entrainment due to the high pressures generated in the PDMS-PDMS contact zone. Therefore, the lubrication was attributed to the entrainment of the alginate polymer in continuum rather than the intact beads, as well as leaching out of a layer of water from these beads that might act as a surface separator, reducing the friction values.

Eating capability

The EC values of tongue pressure and the different measurement locations of bite force for all participants is shown in **Table 1**. The measured tongue pressure values were in line with the results from previous studies on young healthy participants (Alsanei and Chen, 2014; Alsanei et al., 2015; Laguna et al., 2016a). The bite force values were comparable to studies on healthy participants by Fernandes et al. (2003) and Laguna et al. (2016a) who used a similar measurement device. However, on average the values were slightly higher in the current study, possibly due to the positioning of the test sensors or the interpretation of the instructions by the participants. Interestingly, there was no correlation between tongue pressure and any of the bite force measurements, with $p > 0.1$ (see **Table 2a**). This is in line with the study by Laguna et al. (2016a) on participants from a similar age group, highlighting that such correlations between oro-facial muscle forces only exist in older adults with limited overall oral capabilities (Laguna et al., 2015).

To group the panellists according to their overall eating capability (tongue pressure and bite force), the EC composite scores were calculated using eq. (1). **Figure 3** shows the histogram of the distribution of the EC scores of all participants. Based on the plot, two groups of panellists can be identified on the extreme ends of the plot, with eighteen observations in each group: a low EC group (< 1.0) and a high EC group (> 1.3). The age distribution was similar in both groups, and both groups consisted of male and female participants. The remaining 48 values in the middle had an EC score between 1.0 and 1.3 ($1.0 \leq$ EC score ≤ 1.3). From an eating capability perspective, the participants in this study were however rather homogeneous.

Oral processing behaviours

Figure 4 shows the oral processing characteristics, such as number of chews, oral residence time and chewing rate, that were derived from frame-by-frame video analysis of participants eating the hydrogels. The sample 3κC had a significantly higher number of chews and oral residence time compared to the 1.5κC0.5NaA and 2.4κC0.2CaA$_{300}$ hydrogels ($p < 0.05$). The chewing rate did not show a significant difference between the presented samples, suggesting that chewing rate was subject to individual differences rather than the food material properties (Hiiemae et al., 1996).

The correlations between the chewing behaviours were analysed for the combined data set (see **Table 2b**). The number of chews and the oral residence time were strongly correlated ($p < 0.01$), meaning that food that is kept in the mouth for a longer amount of time is also chewed more. This was in line with findings from previous studies (Engelen et al., 2005; Laguna et al., 2016a). The number of chews also correlated with chewing rate ($p < 0.01$), but the chewing rate was not related to oral residence time ($p > 0.1$).

Correlations between food material properties, EC parameters and oral processing behaviours

The food material properties and EC parameters were examined for relationships (if any) with the oral processing behaviours to check whether it was the intrinsic capability or extrinsic food design factors that could best explain the oral processing strategy used for the hydrogels (**Table 3a** and **b**, respectively). As can be seen in **Table 3a**, the puncture force showed a strong correlation with the oral processing characteristics, i.e. number of chews and oral residence time ($p < 0.001$). This confirms the data from previous researchers using real food systems, where they made similar conclusions for banana, apple, biscuits (Hiiemae et al., 1996) and products like cheese, peanuts and carrots (Engelen et al., 2005). The friction force measurements showed a good correlation to the number of chews ($p < 0.01$ to $p < 0.05$), and the oral residence time ($p < 0.05$ to $p < 0.1$), depending on the entrainment speed. At the orally relevant speeds, 20-50 mm/s, the correlations seemed to be weaker ($p < 0.01$) however than at higher speeds ($p < 0.05$), suggesting that slightly higher entrainments speeds might relate better to the number of chews and oral residence time. Therefore, we propose that for the hydrogel bolus filtrates, number of chews and oral residence time are better explained by frictional properties in the mixed lubrication regime at speeds ≥ 80 mm/s, where the boli form a film separating the two PDMS surfaces (i.e. separating tongue and palate during in vivo oral processing). Additionally, we do not expect to see any correlations of the friction force in the boundary regime (speeds < 10 mm/s) to the oral residence time due to the absence of any adsorption of the hydrophilic hydrogel bolus particles to the hydrophobic tribo-surfaces (de Vicente et al., 2006; Krop et al., 2019; Sarkar et al., 2019). The chewing rate did not correlate with any of the food material properties ($p > 0.1$), suggesting that it is a more inherent property linked to each individual. In addition, it is worth pointing out that while the number of chews and oral residence time showed a strong correlation (see **Table 2b**), and are more product specific (**Figure 4**), the more inherent chewing rate still increased with the number of chews as indicated by the correlation between the two. This effect was not found for the oral residence time (no correlation to chewing rate), suggesting that where chewing rate and number of chews have a link to the individual, the oral residence time does not and is mostly linked to the type of food structure being consumed.

The individual EC measures did not correlate with the oral processing behaviours, nor did the EC composite scores ($p > 0.1$), see **Table 3b**. Together, these results suggest that the food material properties dictated the oral processing behaviour of hydrogels with different textural properties in young individuals rather than their individual EC. However, it should be noted that EC was not a limiting factor in the oral processing of the model gels used in these participants. The strength of these model gels was considerably lower than the maximum bite force and tongue pressure measured in current individuals, 8.29 ± 0.96 N or 10.83 ± 1.18 kPa for the hardest hydrogel (3κC) compared to the mean 50.6 ± 15.5 kPa for tongue pressure and 154.8 ± 68.8 N for bite force.

Additionally, the effect of EC level was checked by analysing the correlations between ECs and oral processing behaviours for the selected low EC and high EC groups separately. For the participants with an EC score < 1.0, the bite force for the front incisors and left side molars correlated with the number of chews and oral residence time ($p < 0.05$). On the other hand, the high EC group (score > 1.3) only showed correlations of the chewing rate with the bite force of the front incisors and EC ($p < 0.05$). This would suggest that participants with a low EC score compensated for this by increasing the number of chews and oral residence time, while for people with a higher EC score, and thus a combination of higher maximum bite force and higher maximum tongue pressure, the chewing rate increased.

Conclusions

Both the extrinsic food material properties and the intrinsic eating capability of the consumer are hypothesized to have an influence on oral processing behaviour. Food material properties can be quantified by the use of instrumental as well as sensory techniques. Characteristics of an individual including age, gender and their oro-facial muscular capabilities may also affect oral processing behaviour. In this study, a panel of relatively young, healthy participants, consisting of both males and females, was recruited to investigate the importance of their eating capabilities, such as maximum bite force and tongue pressure, versus the food material properties on the oral processing strategy of three hydrogels with different textural properties and bolus tribology. It was found that the oral processing behaviour was dominated by both the instrumental fracture properties of the hydrogels and lubrication properties of the hydrogel boli. Whilst the fracture properties of the gels and the friction force of the boli in the mixed lubrication regime correlated well with number of chews and oral residence time, they did not relate to the chewing rate. Therefore, we suggest that chewing rate for hydrogels is more subject to individual differences than their physical properties. Interestingly, the number of chews and oral residence time were greater in participants with a low EC compared to high EC score, whereas individuals with a higher EC score had a higher chewing rate. In the future, this study should be replicated with different hydrogels, as well as other types of food to confirm the current findings. Also, it might be interesting to investigate relationships between oral physiological parameters specific to each individual, such as the effects of consumers' habitual salivary flow on oral processing strategy, as well as their preferred oral processing style/chewing type and their favoured type of food materials to eat (Wilson et al., 2018).

Acknowledgements

This work was supported by the University of Leeds 110 Anniversary Research Scholarship with matched support from Mars Wrigley Confectionery, awarded to EK for her PhD studies. We would like to thank Hannah Clark for her assistance with the frame-by-frame analysis of the video recordings as a second observer.

Ethical Statements

Conflict of Interest: The authors declare that they do not have any conflict of interest

Ethical Review: This study was reviewed and approved by the Faculty Research Ethics Committee at the University of Leeds (reference number MEEC 16-006).

Informed Consent: Written informed consent was obtained from all study participants before the start of the study.

Author Contributions

The authors' responsibilities were as follows —AS: designed the research; EK: developed the experimental design, conducted all the experiments and analysed the data; EK: wrote the manuscript; AS, SM and MMH: contributed to revisions of the manuscript; AS: had primary responsibility for final content; and all authors: read, edited and approved the final manuscript.

References

ALSANEI, W.A., and CHEN, J. 2014. Studies of the oral capabilities in relation to bolus manipulations and the ease of initiating bolus flow. Journal of Texture Studies 45, 1-12.

ALSANEI, W.A., CHEN, J., and DING, R. 2015. Food oral breaking and the determining role of tongue muscle strength. Food Research International 67, 331-337.

BAKKE, M., HOLM, B., JENSEN, B.L., MICHLER, L., and MOLLER, E. 1990. Unilateral, isometric bite force in 8-68-year-old women and men related to occlusal factors. Scandinavian journal of dental research 98, 149-158.

BROWN, W.E., LANGLEY, K.R., MARTIN, A., and MACFIE, H.J.H. 1994. Characterisation of patterns of chewing behaviour in human subjects and their influence on texture perception. Journal of Texture Studies 25, 455-468.

CARPENTER, G. 2012. Role of saliva in the oral processing of food. In Food Oral Processing: Fundamentals of Eating and Sensory Perception. J. Chen and L. Engelen, eds.

CHEN, J. 2009. Food oral processing - A review. Food Hydrocolloids 23, 1-25.

CHEN, J., and LOLIVRET, L. 2011. The determining role of bolus rheology in triggering a swallowing. Food Hydrocolloids 25, 325-332.

CHEN, J., and ROSENTHAL, A. 2015. Food texture and structure. In Modifying Food Texture. J. Chen and A. Rosenthal, eds. Woodhead Publishing, pp. 3-24.

VAN DER BILT, A., WEIJNEN, F.G., OTTENHOFF, F.A.M., VAN DER GLAS, H.W., and BOSMAN, F. 1995. The role of sensory information in the control of rhythmic open-close movements in humans. Journal of Dental Research 74, 1658-1664.

DEVEZEAUX DE LAVERGNE, M., TOURNIER, C., BERTRAND, D., SALLES, C., VAN DE VELDE, F., and STIEGER, M. 2016. Dynamic texture perception, oral processing behaviour and bolus properties of emulsion-filled gels with and without contrasting mechanical properties. Food Hydrocolloids 52, 648-660.

ENGELEN, L., FONTIJN-TEKAMP, A., and VAN DER BILT, A. 2005. The influence of product and oral characteristics on swallowing. Archives of Oral Biology 50, 739-746.

FERNANDES, C.P., GLANTZ, P.-O.J., SVENSSON, S.A., and BERGMARK, A. 2003. A novel sensor for bite force determinations. Dental Materials 19, 118-126.

FLANAGAN, D., ILIES, H., O'BRIEN, B., MCMANUS, A., and LARROW, B. 2012. Jaw bite force measurement device. The Journal of oral implantology 38, 361-364.

FONTIJN-TEKAMP, F.A., VAN DER BILT, A., ABBINK, J.H., and BOSMAN, F. 2004. Swallowing threshold and masticatory performance in dentate adults. Physiol Behav 83, 431-436.

FORDE, C.G., KUIJK, N., THALER, T., DE GRAAF, C., and MARTIN, N. 2013. Oral processing characteristics of solid savoury meal components, and relationship with food composition, sensory attributes and expected satiation. Appetite 60, 208-219.

FUNAMI, T. 2011. Next target for food hydrocolloid studies: Texture design of foods using hydrocolloid technology. Food Hydrocolloids 25, 1904-1914.

FUNAMI, T., ISHIHARA, S., NAKAUMA, M., KOHYAMA, K., and NISHINARI, K. 2012. Texture design for products using food hydrocolloids. Food Hydrocolloids 26, 412-420.

FUNAMI, T., NAKAO, S., ISONO, M., ISHIHARA, S., and NAKAUMA, M. 2016. Effects of food consistency on perceived intensity and eating behavior using soft gels with varying aroma inhomogeneity. Food Hydrocolloids 52, 896-905.

GONG, J., and OSADA, Y. 2001. Surface friction of polymer gels. Progress in Polymer Science 27, 3-38.

HAYAKAWA, F., KAZAMI, Y., ISHIHARA, S., NAKAO, S., NAKAUMA, M., FUNAMI, T., NISHINARI, K., and KOHYAMA, K. 2014. Characterization of eating difficulty by sensory evaluation of hydrocolloid gels. Food Hydrocolloids 38, 95-103.

HIIEMAE, K., HEATH, M.R., HEATH, G., KAZAZOGLU, E., MURRAY, J., SAPPER, D., and HAMBLETT, K. 1996. Natural bites, food consistency and feeding behaviour in man. Archives of Oral Biology 41, 175-189.

HUTCHINGS, J.B., and LILLFORD, P.J. 1988. The perception of food texture - the philosophy of the breakdown path. Journal of Texture Studies 19, 103-115.

KOÇ, H., ÇAKIR, E., VINYARD, C.J., ESSICK, G., DAUBERT, C.R., DRAKE, M.A., OSBORNE, J., and FOEGEDING, E.A. 2014. Adaptation of oral processing to the fracture properties of soft solids. Journal of Texture Studies 45, 47-61.

KOHYAMA, K., MIOCHE, L., and MARTIN, J.-F. 2002. Chewing patterns of various texture foods studied by electromyography in young and elderly populations. Journal of Texture Studies 33, 269-283.

KROP, E.M., HETHERINGTON, M.M., HOLMES, M., MIQUEL, S., and SARKAR, A. 2019. On relating rheology and oral tribology to sensory properties in hydrogels. Food Hydrocolloids 88, 101-113.

KROP, E.M., HETHERINGTON, M.M., NEKITSING, C., MIQUEL, S., POSTELNICU, L., and SARKAR, A. 2018. Influence of oral processing on appetite and food intake – A systematic review and meta-analysis. Appetite 125, 253-269.

LAGUNA, L., BARROWCLOUGH, R.A., CHEN, J., and SARKAR, A. 2016a. New approach to food difficulty perception: food structure, food oral processing and individual's physical strength. Journal of Texture Studies 47, 413-422.

LAGUNA, L., HETHERINGTON, M.M., CHEN, J., ARTIGAS, G., and SARKAR, A. 2016b. Measuring eating capability, liking and difficulty perception of older adults: A textural consideration. Food Quality and Preference 53, 47-56.

LAGUNA, L., and SARKAR, A. 2016. Influence of mixed gel structuring with different degrees of matrix inhomogeneity on oral residence time. Food Hydrocolloids 61, 286-299.

LAGUNA, L., SARKAR, A., ARTIGAS, G., and CHEN, J. 2015. A quantitative assessment of the eating capability in the elderly individuals. Physiology & Behavior 147, 274-281.

LARSEN, D.S., TANG, J., FERGUSON, L.R., MORGENSTERN, M.P., and JAMES, B.J. 2016. Oral breakdown of texturally complex gel-based model food. Journal of Texture Studies.

LASSAUZAY, C., PEYRON, M.-A., ALBUISSON, E., DRANSFIELD, E., and WODA, A. 2000. Variability of the masticatory process during chewing of elastic model foods. European journal of oral sciences 108, 484-492.

LASSCHUIJT, M.P., MARS, M., STIEGER, M., MIQUEL-KERGOAT, S., DE GRAAF, C., and SMEETS, P.A.M. 2017. Comparison of oro-sensory exposure duration and intensity manipulations on satiation. Physiology & Behavior.

LE RÉVÉREND, B., SAUCY, F., MOSER, M., and LORET, C. 2016. Adaptation of mastication mechanics and eating behaviour to small differences in food texture. Physiology & Behavior 165, 136-145.

MIQUEL-KERGOAT, S., AZAIS-BRAESCO, V., BURTON-FREEMAN, B., and HETHERINGTON, M.M. 2015. Effects of chewing on appetite, food intake and gut hormones: a systematic review and meta-analysis. Physiology and Behavior 151, 88-96.

NISHINARI, K. 2004. Rheology, food texture and mastication. Journal of Texture Studies 35, 113-124.

ONO, T., HORI, K., TAMINE, K.-I., and MAEDA, Y. 2009. Evaluation of tongue motor biomechanics during swallowing—From oral feeding models to quantitative sensing methods. Japanese Dental Science Review 45, 65-74.

PARK, S., and SHIN, W.-S. 2015. Differences in eating behaviors and masticatory performances by gender and obesity status. Physiology & Behavior 138, 69-74.

PEDERSEN, A., BARDOW, A., JENSEN, S.B., and NAUNTOFTE, B. 2002. Saliva and gastrointestinal functions of taste, mastication, swallowing and digestion. Oral Diseases 8, 117-129.

PEYRON, M.A., BLANC, O., LUND, J.P., and WODA, A. 2004. Influence of age on adaptability of human mastication. J Neurophysiol 92, 773-779.

PEYRON, M.A., GIERCZYNSKI, I., HARTMANN, C., LORET, C., DARDEVET, D., MARTIN, N., and WODA, A. 2011. Role of physical bolus properties as sensory inputs in the trigger of swallowing. PloS one 6, e21167.

SARKAR, A., ANDABLO-REYES, E., BRYANT, M., DOWSON, D., and NEVILLE, A. 2019. Lubrication of soft oral surfaces. Current Opinion in Colloid & Interface Science 39, 61-75.

SARKAR, A., GOH, K.K.T., and SINGH, H. 2009. Colloidal stability and interactions of milk-protein-stabilized emulsions in an artificial saliva. Food Hydrocolloids 23, 1270-1278.

STEELE, C.M., and VAN LIESHOUT, P. 2009. Tongue movements during water swallowing in healthy young and older adults. Journal of speech, language, and hearing research : JSLHR 52, 1255-1267.

DE VICENTE, J., STOKES, J.R., and SPIKES, H.A. 2006. Soft lubrication of model hydrocolloids. Food Hydrocolloids 20, 483-491.

DE WIJK, R.A., ENGELEN, L., and PRINZ, J.F. 2003. The role of intra-oral manipulation in the perception of sensory attributes. Appetite 40, 1-7.

WILKINSON, C., DIJKSTERHUIS, G.B., and MINEKUS, M. 2000. From food structure to texture. Trends in Food Science & Technology 11, 442-450.

WILSON, A., JELTEMA, M., MORGENSTERN, M.P., MOTOI, L., KIM, E., and HEDDERLEY, D. 2018. Comparison of physical chewing measures to consumer typed Mouth Behavior. Journal of Texture Studies 49, 262-273.

Tables

Table 1. Eating capability measures of the 28 included participants.

Gender	**Age**	**Tongue Pressure (kPa)**		**Bite Force (N) Left Side Molars**		**Bite Force (N) Front Incisors**		**Bite Force (N) Right Side Molars**	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Female	24	12.3	1.2	85.1	2.2	79.4	5.7	62.8	1.4
Female	32	10.0	1.0	164.2	17.4	142.3	11.8	124.7	27.8
Female	34	27.7	1.5	89.9	2.2	58.2	1.6	104.0	15.1
Female	22	42.0	3.0	73.8	5.2	62.3	0.0	63.0	19.1
Female	27	47.0	4.4	91.7	10.9	78.9	13.4	91.3	7.6
Male	25	54.3	7.5	106.9	15.8	61.0	4.1	98.4	7.9
Female	26	44.3	3.8	148.9	18.3	108.7	29.5	174.1	20.7
Male	28	61.0	1.0	121.0	4.5	85.5	8.5	105.2	12.5
Female	36	64.0	4.6	83.7	6.4	76.4	12.2	116.0	11.3
Female	31	37.3	7.5	198.7	15.1	151.6	5.3	230.7	7.5
Male	31	57.0	1.7	180.0	7.3	75.9	3.2	126.7	23.9
Female	27	47.3	8.3	196.1	3.5	127.9	10.8	186.4	10.3
Female	25	53.7	6.7	164.9	3.4	138.9	5.1	172.2	9.6
Male	52	63.0	1.7	147.0	5.2	103.9	8.5	143.7	8.3
Male	36	62.7	2.1	165.8	19.8	123.3	8.0	122.1	3.3
Female	25	51.7	7.0	247.8	3.1	110.8	24.6	191.4	44.2
Female	31	59.3	2.3	244.8	14.6	121.4	8.6	117.6	12.6
Female	24	53.0	10.1	198.9	3.1	144.5	7.6	210.0	14.6
Female	29	40.0	3.6	286.4	7.8	154.9	9.3	272.8	13.3
Male	24	56.0	8.5	106.9	1.7	160.5	4.2	256.7	5.3
Female	23	60.7	5.5	207.7	14.4	73.0	19.7	227.5	5.8
Female	23	65.3	2.9	148.8	19.2	132.9	2.5	172.0	12.7
Female	32	60.0	1.0	230.3	45.7	99.9	12.2	206.4	12.0
Male	28	52.3	5.8	237.9	11.8	151.7	27.6	236.8	16.4
Female	26	81.3	2.9	123.4	2.7	79.5	31.8	108.7	25.7
Female	22	52.3	1.5	273.6	4.4	147.6	25.3	268.6	12.9
Male	23	53.7	1.5	297.2	3.3	166.7	17.8	272.6	10.7
Male	33	46.0	2.6	336.0	9.0	284.6	5.7	280.6	16.1
Panel Mean		50.6	15.5	177.1	72.2	117.9	48.1	169.4	68.5

Table 2. Correlation matrix of the eating capability measurements (a) and oral processing behaviours (b) for the 28 participants with 3 replicates (n= 85), and significant values indicated in green: $p < 0.01$.

(a)	**Tongue pressure**	**Bite force, left side molars**	**Bite force, front incisors**	**Bite force, right side molars**
Tongue pressure	1			
Bite force, left side molars	0.07	1		
Bite force, front incisors	-0.08	0.69	1	
Bite force, right side molars	0.11	0.77	0.71	1

(b)	**Number of chews**	**Oral residence time**	**Chewing rate**
Number of chews	1		
Oral residence time	0.94	1	
Chewing rate	0.35	0.07	1

Table 3. Correlation matrix of food material properties related to oral processing behaviour (a) and eating capabilities related to oral processing behaviour (b), with the levels of significance indicated in different shades of green: $p \geq 0.1$, $p < 0.1$, $p < 0.05$ and $p < 0.01$. Since the number of measurements for the food material properties and the oral processing characteristics (a) was not the same, no exact correlation values are displayed but an overall impression of the data is shown based on multiple variations of correlation analyses between the two data sets.

(a)	**Number of chews**	**Oral residence time**	**Chewing rate**
Puncture force			
Friction force 100 mm/s			
Friction force 90 mm/s			
Friction force 80 mm/s			
Friction force 70 mm/s			
Friction force 60 mm/s			
Friction force 50 mm/s			
Friction force 40 mm/s			
Friction force 30 mm/s			
Friction force 20 mm/s			
Friction force 10 mm/s			

(b)	**Number of chews**	**Oral residence time**	**Chewing rate**
Tongue pressure	0.09	0.04	0.02
Bite force left molars	0.13	0.07	0.09
Bite force front incisors	0.14	0.04	0.21
Bite force right molars	0.08	0.00	0.11
EC score	0.15	0.06	0.11

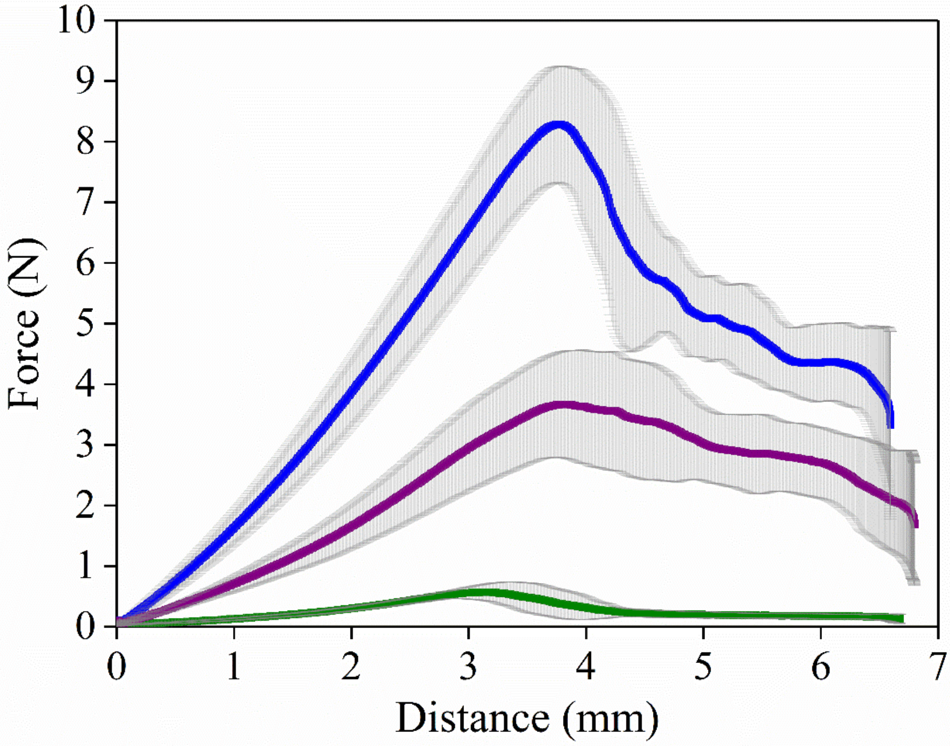
Captions for Figures

Figure 1. Mean (± SD) force over distance curve of the hydrogels obtained from puncture tests with a Volodkevitch bite probe (first bite), with 3κC (▲), 1.5κC0.5NaA (◆) and 2.4κC0.2CaA$_{300}$ (⬡).

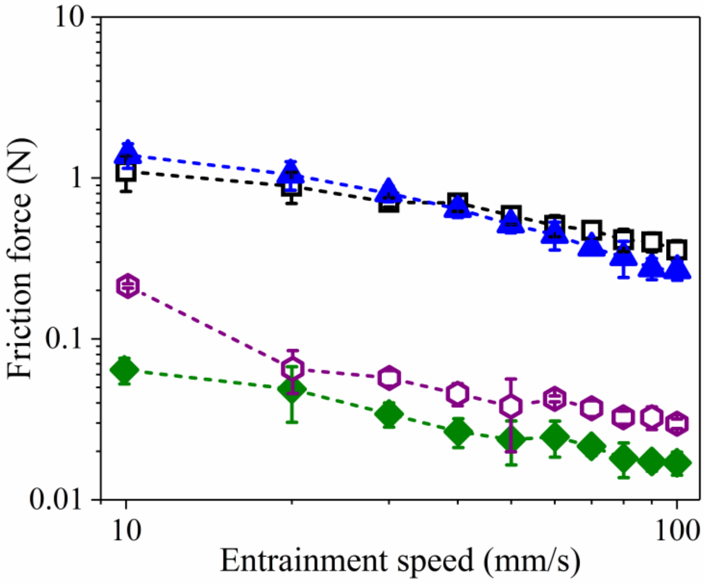
Figure 2. Mean friction force (± SD) of 3κC (▲), 1.5κC0.5NaA (◆) and 2.4κC0.2CaA$_{300}$ (⬡) gel bolus filtrates, after simulated oral processing with artificial saliva (□), at 37 °C as a function of entrainment speed in the mixed lubrication regime.

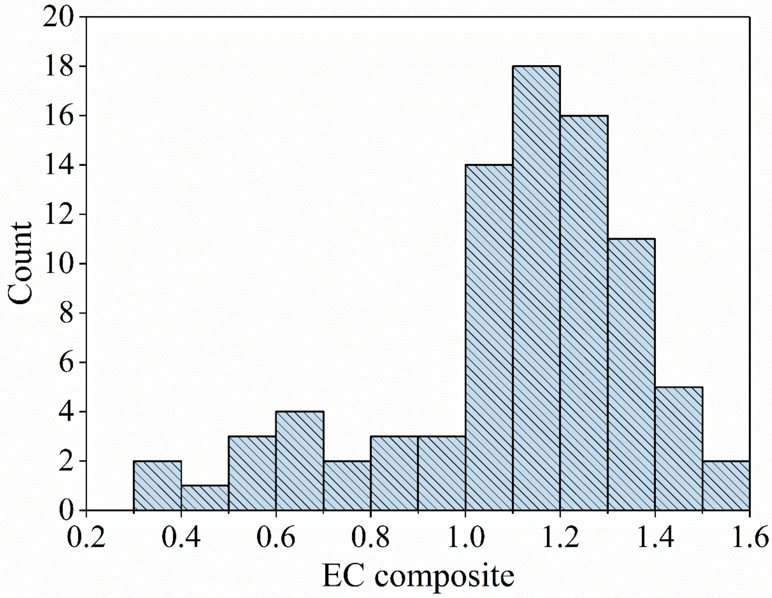
Figure 3. Histogram of the eating capability (EC) composite scores of the 28 participants with three replicates each (n = 84).

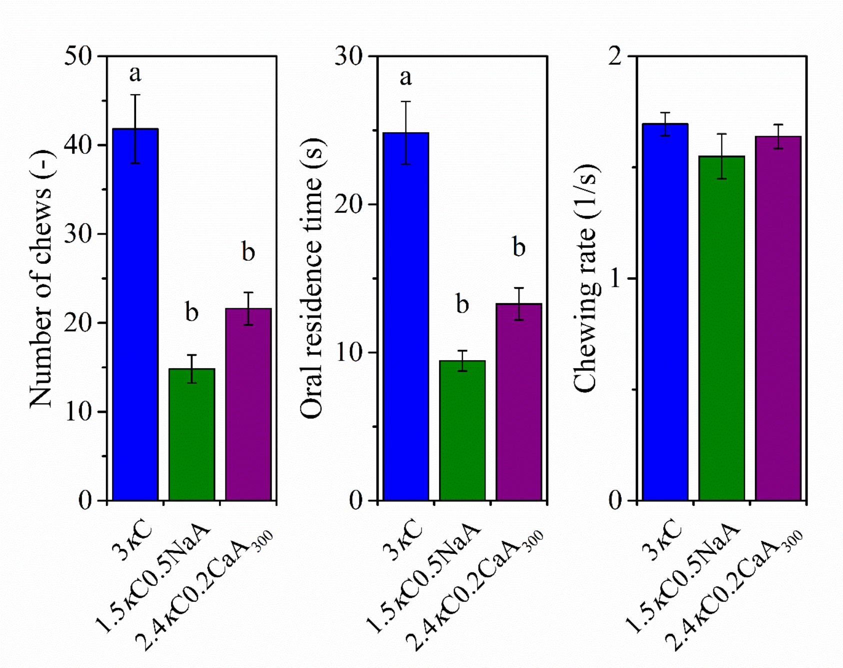
Figure 4. Mean values (± SEM) of the oral processing characteristics of the hydrogels obtained from video analysis (n = 28). From left to right: number of chews, oral residence time and chewing rate. Different lower case letters indicate statistically significant differences between conditions ($p < 0.05$).



Force (N)
0
1
2
3
4
5
6
7
8
9
10
Distance (mm)
0
1
2
3
4
5
6
7


10
1
0.1
0.01
Friction force (N)
10
100
Entrainment speed (mm/s)


Count
20
18
16
14
12
10
8
6
4
2
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
EC composite


Number of chews (-)
Oral residence time (s)
Chewing rate (1/s)
a
b
b
a
b
b
3κC
1.5κC0.5NaA
2.4κC0.2CaA300