Muscle activity during oral processing of sticky-cohesive foods

Seyed Mostafa Kazemeini\textsuperscript{a}, Daniel Prado Campos\textsuperscript{b}, Andrew J. Rosenthal\textsuperscript{c, c}

\textsuperscript{a} School of Biosciences, University of Nottingham, Sutton Bonington, LE12 5RD, UK
\textsuperscript{b} Universidade Tecnológica Federal do Paraná (UTFPR), Marcella Dias, 635, Postal Code 86812-460, Apucarana, PR, Brazil
\textsuperscript{c} Department of Biotechnology and Food Science, Norwegian University of Science and Technology (NTNU), Trondheim, 7491, Norway

\textbf{ARTICLE INFO}

\textbf{Keywords:}
Sticky-cohesive foods
Oral processing
Chew work
Electromyography (sEMG)
Trigger for swallowing

\textbf{ABSTRACT}

We investigated muscle activity during oral processing of sticky model foods. Chewing Time extracted from the EMG data distinguished the most sticky and least sticky model foods from the others, but was not a good discriminator between the other models. Mean chew work declined by 25.4%, while the median frequency shift (which is related to muscle fatigue) increased by 54.9% during oral processing for all the model foods, with the effect being greatest for the stickiest foods.

We conclude that the degree of stickiness is not a trigger for swallowing and changes in the other bolus properties, such as softness, may influence muscle activity to a level at which we can swallow.

1. Introduction

The oral trajectory of many foods leads towards a sticky-cohesive bolus, and these sensations remain dominant until the point of swallow for example wheat flake type breakfast cereals [38, 45], nut butters [22, 50], crackers and Melba toast [48], granola (with yoghurt) [57] and bread [26]. While a sticky-cohesive sensation may be dominant, their magnitude may well change and the purpose behind this study was to investigate whether there might be a threshold for swallowing based on the magnitude of sticky-cohesive sensations, above which we are unable to swallow.

Sticky-cohesive definitions are closely related to each other [10, 17, 43]. The association of sticky cohesive terms was highlighted by Rosenthal and Thompson [51] and they mentioned that many researchers linked these terms together. Chewing along with the incorporation of saliva are suggested as the main reasons for a cohesive bolus forming in low water, high carbohydrate content foods [22]. Cohesiveness and stickiness (adhesiveness) are features of bolus formation, the former referring to the tendency of a food material to stick to itself, while the latter refers to the material to sticking to external surfaces such as mouth [36].

Stickiness is a multi-dimensional textural attribute and its quantification is a dynamic mechanism and involves complicated processing [1, 2, 31]. Different parameters such as viscosity, water content, temperature and compression have been suggested to affect the perceived stickiness both sensorially and instrumentally [1, 2, 16, 17, 53, 56].

Sensory assessment of stickiness can be perceived either by finger touch or in the mouth [6, 12, 24, 42, 54].

Hutchings et al. [24], examined stickiness perception of nuts by using the Time Intensity method. Although, no reference samples were provided as anchor points, a high variation was reported between the assessors which was in accordance with other researchers who used such anchors. They suggested that other factors might be responsible for stickiness rankings by the assessors. Stickiness is largely influenced by the levels of low molecular sugar in food systems, e.g., caramel [1, 2, 3, 25, 39, 58]. Specifically, prolonged heating times lead to increased hydrolysis of sugars and subsequently higher amounts of low molecular sugars are produced [3]. Surface Electromyography (sEMG or EMG) is a non-invasive method for studying human muscle activity in which the electrical responses of active muscles are recorded. Surface electromyography provides an in vivo evaluation of chewing process and its relationship with food texture [11, 18, 28, 30]. sEMG signals are acquired from bipolar electrodes placed adjacent to the masticatory muscles and represents their electrical response during chewing. Studies show that some sEMG parameters can be related to food texture attributes, mainly to assess sensory characteristics [20]. Various studies have used sEMG features to extract quantifiers of the mastication behavior (such as number of chews, chewing frequency and muscle activity) and then correlate them with the texture of the food such as gum [47], meat [4, 14], bread [15, 19], biscuits [8], pasta [4] and potatoes [15].

* Corresponding author.

E-mail addresses: seyed.kazemeini@nottingham.ac.uk (S.M. Kazemeini), danielcampos@utfpr.edu.br (D.P. Campos), DocARosenthal@gmail.com (A.J. Rosenthal).

https://doi.org/10.1016/j.physbeh.2021.113580
Received 8 May 2021; Received in revised form 26 August 2021; Accepted 5 September 2021
Available online 7 September 2021
0031-9384/© 2021 The Authors. Published by Elsevier Inc. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).
Many different parameters can be extracted from the sEMG data to study the food mastication. Some of the most common sEMG parameters used in eating studies are chew rate, chew time, total number of chews, chew work, number of swallows, maximum voltage (peak-to-peak amplitude), mean voltage, the interval between single cycles and the clearance duration [7,9,32,41,47,52,55].

It is important to note that a large number of existing studies in the literature use a combination of parameters or modify some of the parameters. For example, some researchers undertook the summation of the muscle activity [21,33,44,52] while others divided the mastication process into defined segments such as the whole chewing sequence, the first chew, and the last five chews [34,35,55].

Increased understanding of the oral processing of sticky-cohesive food products and the parameters responsible for trigger of swallowing of such foods can help in formulating food products with specific textures and applications (e.g., dysphagic people).

2. Materials and methods

2.1. Model food preparation

All model foods included granulated white sugar beet (Sainsbury’s, UK), native wheat starch (Foo Lung Ching Kee, Hong Kong), citric acid (Sigma-Aldrich, Dorset, UK) and tap water.

The model foods were based on a formulation for Turkish delight but adjusted to achieve the full range of stickiness encountered in our diet. The stickiest of the model foods was comparable to toffee, while the least sticky model food was akin to table jelly.

Model food preparation commenced by heating the mixture of sucrose and water to the desired temperature (Table 2). These temperatures were determined by the complete dissolution of sucrose in the water. When fully dissolved, citric acid was slowly added and the solutions were then heated for 40 minutes (for model foods A, B, C, D) and 60 minutes (for model foods E and F).

Starch and the remaining water were then slowly added (over a period of about 2 minutes). Further heating was undertaken such that A and B had an additional 90 minutes, while the 50g and 65g sucrose foods had an additional 75 and 120 minutes. In order to have a proper mixing, the solutions were then heated for 40 minutes (for model foods A, B, C, D) and 60 minutes (for model foods E and F).

Starch and the remaining water were then slowly added (over a period of about 2 minutes). Further heating was undertaken such that A and B had an additional 90 minutes, while the 50g and 65g sucrose foods had an additional 75 and 120 minutes. In order to have a proper mixing, the solutions were then heated for 40 minutes (for model foods A, B, C, D) and 60 minutes (for model foods E and F).

Table 1

| Model food formulations | A     | B     | C     | D     | E     | F     |
|------------------------|-------|-------|-------|-------|-------|-------|
| Sucrose (g)            | 10    | 35    | 50    | 50    | 65    | 65    |
| Starch (g)             | 8.5   | 8.5   | 8.5   | 8.5   | 8.5   | 8.5   |
| Citric acid (g)        | 0.3   | 1.0   | 1.0   | 1.0   | 1.0   | 1.0   |
| Water (ml)             | 81.2  | 56.2  | 41.2  | 41.2  | 26.2  | 26.2  |
| Desired temp. (°C)     | 79    | 84    | 99    | 99    | 108   | 108   |
| Heating time (min)     | 90    | 90    | 75    | 120   | 75    | 120   |

2.2. Sensory evaluation

Ten assessors (4 females, 6 males) aged between 21 and 27 years old were recruited from students of University of Nottingham, participated in two training sessions followed by two data collection sessions. Assessors were chosen from healthy individuals (self-reported) with at least 28 natural teeth. Exclusion criteria were participants who had dentures, crowns or dental prostheses. Male participants were asked to have a clean shaven before the sEMG sessions so the attachment of the sEMG probes to the skin was possible. Assessors were instructed not to smoke or drink coffee or other strong drinks at least 2 hours before attending their session.

Five descriptive terms developed by Mayhew 2018 were used in order to define stickiness. In order to prevent any complication of terms, just the definitions were given to the assessors and the actual terms have not been mentioned.

For the training sessions, at least one reference sample was selected from the UK market products in order to provide assessors with an example food of each definition. Terms, definitions and reference samples used in training sessions are given in below Table.

Table 2

| Term            | Definition                                                                 | Reference sample                      |
|-----------------|---------------------------------------------------------------------------|---------------------------------------|
| Enveloping      | Leaves residual material on side surfaces of teeth                        | Werrther’s original; Creamy toffees   |
| Stringy         | Forms strings as you pull teeth apart                                     | Rowntrees; Fruit gums (Nestle, UK)    |
| Tacky           | Adheres to teeth, resists separation                                      | Macam; Joystixx Swizzles (Dunhills, UK), Drumstick squashes (Swizzels, UK) |
| Cohesive        | Pieces reform together                                                    |                                       |
| Tooth packing   | Packs in teeth - related to quantity that packs                            | Rowntrees; Fruit pastilles (Nestle, UK) |

As stickiness is often associated with sweet sugary foods, we blocked the perception of sweetness through the use of a Gymnema sylvestre mouthwash. This was prepared using the method of Meiselman and Halpern [40]. Ten milliliters of the mouthwash was served in a 30ml pot. Each assessor was given the mouthwash twice.

2.3. Instrumental measurements of stickiness

A TA.HD Plus texture analyser (Stable Micro Systems, UK) fitted with a P/6 stainless steel probe (6 mm diameter, flat end and circular cross section) mounted on a 5 kg load cell was used for running a tack tests. The test protocol was to bring the probe into contact with the model food moving at 1 mm.s⁻¹ and then to apply 10 g force. The probe was then withdrawn from the surface at 10 mm.s⁻¹ and the peak area was measured[29]. Nine replicates were taken for each model food.

2.4. sEMG acquisition

The signal was collected by bipolar Ag/AgCl electrodes (Duotrodes 614S, Myotronics, USA) with a center to center distance of 19mm, from the masseter and temporalis muscles of both sides from the assessors’ face. The digastricus muscle was considered less useful and it was not considered in the analysis because of the low signal-to-noise ratio (SNR) that can result in false detection errors. An epoch of 5 seconds was chosen to analyze the EMG features along time to match with the epoch used in the sensory analysis. The EMG signal vector was considered as the signal between the first chew to the swallow event. Therefore, the last epoch of each individual is relative to the epoch when the swallow occurs.

The equipment used was a Noraxon Telemetry transmitter (TeleMyo 2400T G2) with a sampling frequency of 1500 samples/second and a digital resolution of 16 bits. Each of the six model foods was served in all
of the four sensory/EMG sessions.

2.5. Signal processing

Figure 1 shows an example sEMG trace after filtering and without normalization. Simultaneous signals from different muscle groups are shown (Left and right Temporalis, Left and right Masseter muscles, as well as the Left and Right Digastricus).

Each chew can be divided into segments using the Double Threshold Onset Segmentation (DTOS) algorithm, which consist in finding the segment in two steps. First, a threshold based on the noise baseline defines the onset (beginning) and offset (end). The threshold \( t_h(BL) \) is calculated as:

\[
th(BL) = \mu_{BL} + k \times \sigma_{BL},
\]

where \( BL \) is the baseline noise extracted from the signal vector, \( \mu_{BL} \) is the mean of the baseline, \( \sigma_{BL} \) is the standard deviation of the baseline and \( k \) is a predefined factor. If the signal overpass the threshold a onset is detected and when the signal return to a value under the threshold the offset defines the signal segment starting and ending boundaries (signal window). The second step is to verify if the window length \( W \) between the onset and offset is over a predetermined critical value \( W_{crit} \). This is because short signals may be associate to signal artifacts which does not represent a chew signal. Therefore, if we call \( t_{on} \) and \( t_{off} \) the instant of time that the onset and offset are detected, we can say that a segment is detected if:

\[
W = t_{off} - t_{on} > W_{crit}.
\]

The factor \( k \) was heuristically defined iterating in the range of \([1:20]\) with 0.1 steps till the number of found segments converged to the expected value of number of chews using the double threshold (amplitude and time).

Figure 2 depicts the process of segmentation. The sEMG signal is rectified, smoothed and the signal from the masseter and temporalis are summed together. The threshold defines the begin (onset) and end (offset) of each burst. Each pair of onset and offset is used to limit the signal window and are the base to extract signal features.

2.6. Feature extraction

The features used in this work are mainly based on temporal aspects of the sEMG activation: the burst duration, the cycle duration and interchew time. Moreover, the sEMG information within the window (during the burst duration) is also used to construct the features, as the area of the sEMG signal within section is related to the muscle activation (chew work). These aforementioned metrics are illustrated in the Fig. 3.

Denoting the onset and offset of the \( i \)-th chew during a trial as \( t_{on}^i \) and \( t_{off}^i \), respectively, the burst duration of the \( i \)-th chew \( (BD_i) \) can be written as:

\[
BD_i = t_{off}^i - t_{on}^i.
\]

The same way we can define the Cycle Duration of the \( i \)-th chew \( (CD_i) \) as the period between the begin (onset) of the burst and the begin of the next one:

\[
CD_i = t_{on}^{i+1} - t_{on}^i.
\]

The Interchew Time of the \( i \)-th chew \( (ICh_i) \), which is the period between bursts, is calculated from the period between the end of a burst and the begin of the consecutive burst:

\[
IChT_i = t_{off}^i - t_{off}^{i-1} = CD_i - BD_i,
\]

and it is equivalent to the difference between \( CD_i \) and \( BD_i \).

Considering the whole mastication process, the total time \( (T) \) is the period between the commencement of the first burst and the end of the
last:
\[ T = t_{on}^i - t_{off}^{i-1} \]  

where \( M \) is the number of detected chews or the cardinality of the feature vector mathematically expressed by \( M = \text{card}(t_{on}) \).

The area of the sEMG signal within the burst section of the \( i \)-th chew (IEMG\(_i\)), which represent the chew work, is equal to the integration of the sEMG signal (sum of each amplitude within the section). Considering that the \( i \)-th chew have length equal to \( N_i \), and being the signal represented by \( x_i = \{x_{i,1}, \ldots, x_{i,k}, \ldots, x_{i,N_i}\} \), the area within an analysis window is:

\[ IEMG_i = \sum_{k=1}^{N_i} |x_{i,k}| \]  

(7)

This metric is a descriptor of a single chew during the process (notated as the \( i \)-th chew). To describe the whole mastication process of a food sample a features using the aforementioned metric is calculated.

Before the feature extraction, the signal amplitude was normalized in the range of [0:1] using the maximum values of each assessor. This procedure maintains the signal of every assessor in the same range, which may mitigate bias between individuals. Also, the signal of all four
muscules considered in the analysis were summed up together to form a single signal that represent the mastication process. The Total Chew Work (ChW) is defined as the IEMG (Area) of all chews in the process González et al. [20]. The first bite is not accounted because it have distinct characteristic from the following chews [37]. This way, considering a mastication process with $M$ chews, the ChW features can be calculated as:

$$\text{ChW} = \sum_{j=1}^{M} \text{IEMG}_j,$$  

(8)

The Median Frequency (MF) is a frequency at which the EMG power spectrum is divided into two regions with equal amplitude, which is defined by:

$$\sum_{j=1}^{M} p_j = \sum_{j=M-MF}^{M} p_j = \frac{1}{2} \sum_{j=1}^{M} p_j$$  

(9)

where $p_j$ is the EMG power spectrum at the frequency bin $j$. This feature is sensitive to the firing of the motor unit, level of recruitment and synchronization [46].

The decline in the spectral characteristics is related to fatigue [13], being the shift of the median frequency a commonly used feature and considered a gold standard for muscle fatigue assessment [27,46].

Therefore, the Median Frequency Shift of the $i$-th chew in relation to the first bite can be calculated as an indirect measure of muscle fatigue:

$$\text{MFS}_i = \text{MF}_i - \text{MF}_1,$$  

(10)

Beyond the ChW and MFS features, there are a wide set of parameters that could be derived from the aforementioned metrics [20,34,37]. The Chew Work Rate (WR) is defined as the ChW over the Cycle Duration and the Proportional Work (PW) is the IEMG of a chew over the total Chew. Both metrics are used to measure the muscle effort of a chew. The Average Duration of Chews (Ach), Number of Chews (Nch) and Chew Time (ChT) are metrics directly calculated from the number of detected chews and cycle duration. The Chew Rate (ChR) is the number of chews per unit of time, and it is a measure of chew frequency. The interchew Time (IChT) and Burst Duration (BD) are indirect measures of the phases of the chew cycle: BD measures the period when the muscle is active and IChT the period when the muscle is inactive. The Maximum Voltage Peak Amplitude (MV) and Average Voltage Peak Amplitude (AV) are related to the sEMG activation and are calculated from the peak of the signal during contraction. Amplitude measurements are related to the ChW. Table 3 summarizes the features used in this work.

Some metrics are derived from the whole process (e.g. Number of Chews) and others can be extracted from the individual chew (e.g. Chew Work). Features can also be extracted from epochs, which are defined time intervals which could contain one or more detected chews. Features that can describe the characteristics of a single chew or an epoch should be more useful to explore the chewing behavior and how the physiology of the oral processing change over time.

### 2.7. Statistical analysis

Multivariate general linear model was used with the Tukey HSD post-hoc comparisons in order to highlight significant differences of sensory evaluation results. sEMG features were compared using Friedman’s test, which is a non-parametric version of balanced two-way ANOVA, for each pair of model food. A non-parametric test was applied as the null hypothesis of data normality was rejected by a Kolmogorov-Smirnov with $p < 0.05$. The multiple comparison procedure was performed using the Bonferroni post-hoc correction. The Cohen’s d size effect was calculated to elicit differences between the model foods.

Similarity between features was analyzed using correlation as a metric. This was calculated for each pair of features and a tree of hierarchical clusters was defined based on the single linkage algorithm using the inner squared distance.

### 3. Results and discussion

A linear regression ($R^2 = 0.96$) was obtained when correlating the overall sensory stickiness with the instrumental data. This reinforces the validity of the sensory data.

Fig. 4 shows the sensory response of the assessors to the six model foods. Each assessor evaluated each model food on four occasions thus each result consists of up to 40 evaluations. Analysis of variance (ANOVA) and the Tukey HSD post-hoc test showed which of the model foods were significantly different from each other. Each rectangle has one or more model food codes along with the mean assessor response and standard deviation. Sample codes contained in the same box are not statistically different from each other ($p < .05$) - on some occasions the same sample code appears in more than one box in a column, depending on statistical relation to other samples. The percentage value adjacent to each sample code shows the actual number of assessments included in the statistics - this is because some of the model foods samples were not assessed every time, for example in the column headed “30 sec”, some of the assessors will have swallowed the sample before 30 seconds had elapsed and therefore the statistics were based on a smaller number of values.

During the sensory sessions the assessors had two task, to provide temporal values of relative stickiness at every 5 second interval (the six left hand columns of Fig. 4), and to provide an overall value of sample stickiness (the right hand column of Fig. 4).

It can be seen that sample F is the stickiest model food with sample A being measured to have the least stickiness. Generally the stickiness increases with rising sugar content. However, model foods D and E did not follow this pattern, probably due to the action of the citric acid on the hydrolysis of starch and inversion of sucrose during the longer heating period of preparation. It is also possible that greater water losses occurred during lengthy heating, which would fit with Brennan and Mohamed [5] who showed that higher soluble solids led to higher viscoscy resulting in a higher stickiness perception. Unlike Brennan and Mohamed who worked with relatively dilute syrups, the gels used in this study were definitely viscoelastic materials.

The results show that at the first stickiness rating point (five seconds), all the model foods (except for D and F) are perceived significantly different. The same pattern occurs after 15 and 20 seconds. Curiously at 10 seconds after the first chew, all the model foods are ranked as significantly different by the assessors. In reality the mean and standard deviation for model foods D and F are close to each other during the first 20 seconds - presumably borderline on statistical significance, sometimes being above the critical value and sometimes below.

We should bear in mind that at long time periods there are less assessors still chewing (Fig. 4, % values) as many have swallowed already, and the reduction in data points reduces the discrimination of the test. This is most evident at longer times (e.g. 25 and 30 seconds) where the action of saliva may have normalized the overall sugar content.

The statistical analysis of the sEMG data is summarized in Fig. 5. The matrix on the left shows which pair of model foods (A to F) are being compared where yellow squares mark which model foods are being compared. The matrix on the right shows the effect size (Cohen’s d) in a color scale (where the scale is defined on the side color bar) for each pair of model foods. The columns in matrix are the sEMG features extracted. As a reference, a d of 0.5 can be considered medium difference, while a value of 0.8 represents a large effect size. Moreover, values over 1.2 represents large differences and huge effect sizes if over 2. The asterisk marks (*) and double asterisk marks (**) on the Table represent a significant difference at the significance level of 0.05 and 0.01, respectively.

Results suggest that features based on the sEMG information within the windows (ChW, WR, pW, MV and AV) represent better the
differences between model foods than features based on sEMG periods and counting (Ach, ChR, IChT and BD). The feature ChT, which expresses the total chewing time presented also significant difference for most comparisons. This observation is especially interesting because the ChT feature is relatively simple to extract when compared to other features. The ChW feature is the most distinctive feature. Furthermore, model foods A and B which were measured by assessors the least sticky samples, are more distinctive than the other model foods.

Fig. 5 shows that with respect to the Chew time (ChT - oral residence times), model food A is distinctly different \((p < .05)\) from all the other model foods. Similarly model food F has a significant difference with respect to Chewing time from all but model food D, this is in keeping with Fig. 4 which suggests that model foods D and F are similar to each other. Model food D also shows a difference from model food B, yet all other comparisons of model foods have indistinguishable oral processing times. This is not only true for Chew Time, for none of the other parameters can distinguish C from D, or C from E, or D from E, or D from F (see Fig. 5). While the Chew Time appears to separate nine of the fifteen pairs of samples, Figure 6 shows considerable overlap between the Chew Time of the different model foods, making it perhaps a poor discriminator for the different model foods.

A dendrogram plot of the hierarchical binary cluster tree of the extracted features is depicted in Fig. 7. The height represents the distance between the two features being connected. The color is defined by a threshold set at 50% of the maximum height.

We collected a vast amount of data from the sEMG and classified it in terms of: Average Duration of chews; Average Voltage Peak Amplitude; Burst Duration; Chew Rate; Chew Time; Chew Work Rate; Inter-chew Time; Maximum Voltage Peak Amplitude; Number of Chews; Proportional Work; and, Total Chew Work. The inability to distinguish some pairs of model foods (CD, CE, DE or DF) is likely due to the fact that each food follows a trajectory and therefore, while the model foods all start with different consistencies - requiring different degrees of chewing, with time the muscle activities converge as the boli approach the point of swallow.

There were physiological differences in the sEMG results, indicating inter-assessor variation. By merely looking at the range of values we were able to see some assessors had high levels of Chew Work while others are much more restrictive in their Chew Work activity. It could be that these particular assessors tend to suck the samples rather than chewing them - hence the low values of chew work. Of course this kind of eating behavior could influence their perception of stickiness. Chewing behavior has been the subject of many studies e.g. Rosenthal and Philippe [49] who found gender differences in the rate of chewing hard candy particles, though not altering the overall eating time.

To combat the wide levels of variation between the assessors we sought to normalize the sEMG data for each assessor by subtracting the mean value for the variable concerned and then dividing that by the range of that variable.

\[
\text{normalized value} = \frac{\text{value} - \text{mean value}}{\text{range}}
\]

This has the effect of spreading the variable being investigated across a graph with the mean value for that assessor at the zero point of the normalized axis. By doing this, we can overlay the response to the same variable for all the assessors, the common zero point being each individual’s mean and their ranges scaled to their maximum values. Fig. 8 is a scatter plot for the sensory stickiness and normalized chew work data of all the 10 assessors. Scatter is still evident, yet the different samples form overlapping clusters of values and provide a sense of sensory stickiness for the six model foods.

The clustering of samples into groups is apparent in Fig. 8, yet the
variable “Chew Work” does completely separate samples A-B, C-D, C-E, D-E and D-F (refer to Cohen’s $d$ - Fig. 5). The level of overlap between the data points does show this, and while significant differences may not exist, there are clear groupings of the data. We do need to be cautious when considering this data, for there is a time element lost in the scatter.

In reality each of the model food’s cluster of points includes values from the beginning, middle and end of oral processing, moreover the duration of oral processing is different for the model foods. This becomes apparent in Fig. 9 in which each of the assessor response for each of the samples is shown (the colored dots represent different time epochs of five seconds). The scatter data in Fig. 8 is difficult to summarize and so we have redrawn it as line plots in Fig. 9. Each model food enters the oral trajectory at the right hand end of that curve where the epoch is 1 and then moves towards the left. While there is a slight decline in the overall assessor reported stickiness during oral processing, it is only about 20% the initial values for each model food. Yet the span of chew work is considerable for all the foods. Fig. 9 shows some anomalous points at the left hand end of the curves for model foods C, D, E and F, whereby erroneous data points appear towards the left hand end. Just as the sensory data in Fig. 4 is not collected from all the assessors towards the end of oral processing (as some have swallowed), this is also true for the sEMG data and where data is sparse we lose the moderating effect of averages, hence the impact of individual values becomes more apparent. While we have included such points in the Fig. 9 we have not joined them to the rest of the series with a line. Despite these anomalous values at the left hand end of the Chew Work data, there are clear declining

---

**Table 3**

| Feature Full Name                | Abbr. |
|----------------------------------|-------|
| Total Chew Work                  | ChW   |
| Median Frequency Shift           | MFS   |
| Chew Work Rate                   | WR    |
| Proportional Work                | PW    |
| Average Duration of chews        | ACh   |
| Number of Chews                  | NCh   |
| Chew Time                        | ChT   |
| Chew Rate                        | ChR   |
| Interchew Time                   | IChT  |
| Burst Duration                   | BD    |
| Maximum Voltage Peak Amplitude   | MV    |
| Average Voltage Peak Amplitude   | AV    |

---

**Fig. 5.** Effect size (Cohen’s $d$) between each pair of model foods. The asterisk marks (*) and double asterisk marks (**) on the Table represent a significant difference at the significance level of 0.05 and 0.01, respectively. All abbreviations are summarized in Table 3.
Physiology & Behavior 242 (2021) 113580

8

All abbreviations are summarized in Table 3.

The height represents the distance between the two features being connected.

particular level, it could act as the trigger for the swallowing process. It

TDS helps us identify the dominant sensation, it does not identify the
trends in the normalized chew work for all the model foods.

This research was prompted by observations of researchers such as
Lenfant et al. [38] and Rosenthal and Pang [48] who found that low
water, high carbohydrate foods gradually become cohesive and sticky
towards the end of oral processing. Both of the above mentioned studies
used Temporal Dominance of Sensations (TDS) to ascertain the domi-
nant sensations during oral processing. Yet it is well known that while
TDS helps us identify the dominant sensation, it does not identify the
level of that sensation. The hypothesis of this work was that once
sticky-cohesive textures become dominant, the degree of oral stickiness
might decline through further oral processing and that when it reached a
particular level, it could act as the trigger for the swallowing process. It

is however clear from Fig. 9 that with these particular model foods the
level of stickiness does not appreciably change during the oral trajec-
tory. Yet regardless of the unchanging stickiness, the chew work does decline during the mastication process. As Fig. 9 shows, a time sequence
from right to left, we can see that at the end of oral processing, the chew
work has declined to a normalized value of -0.1 for all of the model
foods.

In addition to not quantifying a dominant sensation, TDS is limited
by the attributes identified for the assessors to choose from. Where an
attribute might exist as a bipolar scale with an anchor point at both ends,
TDS requires only one of the anchors to be named. Thus in studies such as
Lenfant et al. [38] the attribute “hardness” was used and was found to
predominate at the early stages of oral processing. But of course on a
linear scale where hardness forms one end, softness might be the anchor
at the other end. Yet researchers often focus on the positive-decisive
attributes with a tendency not to address the negative-weaker anchor
points as attributes. Thus while oral processing of bran flakes and dry
crackers may start with hard dominant sensations, the reported loss of
hardness cannot be tracked towards an increase in softness as the
attribute was not available to be chosen. Instead another positive-decisive
attribute “stickiness” was offered, and became domi-
nant at the end of the oral trajectory. In this study we found that the level
of stickiness of our model foods only slightly changed during oral pro-
cessing. Despite this, the Chew Work declined substantially, suggesting a
change in the consistency of the oral contents towards the point of
swallow. Certainly during oral processing there is secretion of saliva and
chew work will no doubt mix and soften the bolus. We speculate that
perhaps it is a change in softness, which while not identified as dominant
in the aforementioned studies, leads to the point of swallowing.

Another related measure of muscle activity is the Frequency Shift
which is known to correlate with muscle fatigue. Fig. 10 shows the
frequency shift for the different model food samples. Whereas in Fig. 9
time commences on the right where the muscles are fresh in Fig. 10 the
first time epoch is at zero on the horizontal axis and subsequent epochs
are shown initially on the right where fast twitch muscle fibers are
recruited to overcome the varying consistencies of the model foods.
Progressive epochs of time move the trajectory through zero on the
horizontal axis after which the muscles progressively become fatigued.
Model food F which is known to be the stickiest and most cohesive
causes the muscles to fatigue the most, while there is a systematic
reduction in frequency shift for the less cohesive model foods. Thus
model food A only recruits a small number of fast fibers after the first
epoch and over the duration of oral processing does not result in much
fatigue.

In setting up the model foods, our intention was to control the degree
of stickiness. It is however virtually impossible to modify one textural
characteristic in isolation of the others. Without doubt the cohesiveness
also changed as perhaps did the firmness. We modified the food to
examine the oral behavior, yet it is the bolus which is swallowed and the
transformation of oral processing further changes the characteristics of
the bolus.

If during oral processing the chew work is lessening, then something
is happening to the contents of the mouth which allows the muscles
activity to decline. In the case of these model foods, the materials start
sticky and cohesive, they start as concentrated relatively low water
materials. During oral processing, while the stickiness did not decline,
they do change in such a way as to require less chew work to be applied.
This could be due to increased hydration through the secretion of saliva.
Hutchings and Lillford [23] theoretical model sets two triggers for
swallowing, the degree of structure and the level of hydration. While
these cohesive foods do not change in particle size - remaining as a
coherent sticky mass, they do become hydrated through the secretion of
saliva. Despite no appreciable change in stickiness, these model foods do
change in consistency. The initial firm, cohesive foods tend towards
much softer bolus through the mechanical action of the jaw muscles and
secretion of saliva. While the Hutchings and Lillford [23] model focuses

Fig. 6. Boxplot of the Chew Time for each Model Food. The central line in the
box indicates the median, the box limits are the 25th (bottom) and 75th (top)
percentiles. The whiskers represent extreme data. Outliers (point greater than
1.5 times the interquartile range) are marked as +. Samples that do not share a
lowercase letter are significantly different (p < .05) based on posthoc pairwise
comparisons.

Fig. 7. Dendrogram of the hierarchical cluster tree of the extracted features.
The height represents the distance between the two features being connected.
All abbreviations are summarized in Table 3.
on the properties of the food and its derived bolus, perhaps the trigger is actually physiological and related more to muscle activity.

4. Conclusion

We have disproved our starting hypothesis, that swallowing is triggered by a threshold level of stickiness. In fact our model foods did not appreciably lose their stickiness during oral processing. We did however observe a reduction in the chew work and an increase in muscle fatigue during the oral trajectory. These changes were greatest for the stickiest samples. We surmise that while stickiness is not changing, there are other textural changes in the consistency of the bolus associated with

---

**Fig. 8.** Sensory Stickiness versus Normalized Chew Work, showing the extent of the overlapping scatter.

**Fig. 9.** Normalized Chew Work for model foods along with their mean stickiness at different time epochs.
an increased level of saliva secretion with time. Such changes might include a softening of the bolus.

Ethics

This study was approved by the University of Nottingham Medical Ethics committee (ethics reference no. 270 - 1803). All participants gave informed written consent.

Declaration of Competing Interest

The authors state that they do not have any conflict of interests.

References

[1] B. Adhikari, T. Howes, B. Bhandari, V. Truong, Stickiness in foods: a review of mechanisms and test methods, Int. J. Food Prop. 4 (2001), https://doi.org/10.1081/IFP-100002186.

[2] B. Adhikari, T. Howes, B. Bhandari, V. Truong, In situ characterization of stickiness of sugar-rich foods using a linear actuator driven stickiness testing device, J. Food Eng. 58 (2003) 11–22, https://doi.org/10.1016/S0260-8774(02)00328-X.

[3] B.R. Bhandari, N. Datta, T. Howes, Problems associated with spray drying of sugar-rich foods, Drying Technology 15 (1997) 671–684, https://doi.org/10.1080/073739997017255.

[4] D. Braxton, C. Dauchel, W. Brown, Association between chewing efficiency and mastication patterns for meat, and influence on tenderness perception, Food Qual Prefer 7 (1996) 217–223, https://doi.org/10.1006/qqnf.1996.0021-3.

[5] D. Braxton, C. Dauchel, W. Brown, Influence of chewing efficiency on texture and flavour perceptions of food, J. Texture Stud. 27 (1996) 433–450, https://doi.org/10.1111/j.1745-4603.1996.tb00086.x.

[6] W.E. Brown, Influence of chewing efficiency on texture and flavour perceptions of food, J. Texture Stud. 27 (1996) 433-450, https://doi.org/10.1111/j.1745-4603.1996.tb00086.x.

[7] W.E. Brown, Method to investigate differences in chewing behaviour in humans, J. Texture Stud. 25 (1994) 1–16, https://doi.org/10.1111/j.1745-4603.1994.tb00751.x.

[8] W.E. Brown, D. Braxton, Dynamics of food breakdown during eating in relation to perceptions of texture and preference: a study on biscuits, ibid this paper was presented at the third rose marie pangborn memorial symposium (lesund, norway, 9.13 august 1998), Food Qual Prefer 11 (4) (2000) 259–267, https://doi.org/10.1016/S0950-3293(99)00014-2.

[9] W.E. Brown, D. Eves, M. Ellison, D. Braxton, Use of combined electromyography and kinesthesiology during mastication to chart the oral breakdown of foodstuffs: relevance to measurement of food texture, J. Texture Stud. 29 (1998) 145–167, https://doi.org/10.1111/j.1745-4603.1998.tb00161.x.

[10] L. Carson, X. Sun, C. Setser, Y. Peng, Assessing cohesiveness of mass in foods using an electronic sensing system, J. Texture Stud. 33 (2002) 571–584, https://doi.org/10.1111/j.1745-4603.2002.tb01368.x.

[11] J. Chen, L. Engelen, Front Matter, John Wiley & Sons, Ltd, 2012, p. i–xviii, https://doi.org/10.1002/9781444360943.fmatter.

[12] C. Delahunty, M. Drake, Sensory character of cheese and its evaluation, in: P. F. Fox, P.L. McSweeney, T.M. Cogan, T.P. Guinee (Eds.), General Aspects volume 1, Academic Press, 2004, pp. 455–487, https://doi.org/10.1016/S1874-5580(04)80078-2.

[13] N. Dimitrova, G. Dimitrov, Interpretation of emg changes with fatigue: facts, pitfalls, and fallacies, J. Electromyogr Kinesiol. 13 (2003) 13–36, https://doi.org/10.1016/S1050-6411(02)00083-4.

[14] L. Duizer, E. Gullett, C. Findlay, The relationship between sensory time-intensity, physiological electromyography and instrumental texture profile analysis measurements of beef tenderness, Meat Sci. 42 (1996) 215–224, https://doi.org/10.1016/S0309-1740(95)00022-4.

[15] A. van Eck, E. Franks, C.J. Vinyard, V. Galindo-Cuspinera, V. Fogliano, M. Stieger, E. Scholten, Sauce it up: influence of condiment properties on oral processing behavior, bolus formation and sensory perception of solid foods, Food & Funct. 11 (2020) 6186–6201, https://doi.org/10.1039/d0fo00821c.

[16] R. Ergun, R. Litche, R.W. Hartel, Moisture and shelf life in sugar confections, Crit Rev Food Sci Nutr 50 (2010) 162–192, https://doi.org/10.1080/10408390802248833. PMID: 20112158.

[17] S.M. Fiszman, M.H. Damasio, Instrumental measurement of adhesiveness in solid and semi-solid foods. a survey, J. Texture Stud. 31 (2000) 69–91, https://doi.org/10.1111/j.1745-4603.2000.tb00285.x.

[18] E.A. Foegeding, C.J. Vinyard, G. Essick, S. Guest, C. Campbell, Transforming structural breakdown into sensory perception of texture, J. Texture Stud. 46 (2015) 152–170, https://doi.org/10.1111/jtxs.12105.

[19] J. Gao, S. Tay, A. Koh, W. Zhou, Dough and bread making from high- and low-protein flours by vacuum mixing: part 3. oral processing of bread, J. Cereal Sci 79 (2017), https://doi.org/10.1016/j.jcs.2017.12.002.

[20] R. González, I. Montoya, J. Carcel, Review: the use of electromyography on food texture assessment, Food Sci Technol Int 7 (2001) 461–471, https://doi.org/10.1106/NRHT-L39D-HY1Y-8RGB.
[21] R. Gonzalez, S. Sife, J. Benedito, V. Noguez, Comparison of electromyographic pattern of sensory experts and untrained subjects during chewing of mahon cheese, J. Dairy Res. 69 (2002) 151–161, https://doi.org/10.1017/S002202990100525X.
[22] D. HawthorneWaite, R. Jamjan, A. Rosenthal, Oral processing of low water content foods - a development to hutchings and lilford’s breakdown path, J. Texture Stud. 46 (2015) 212–218.
[23] J. Hutchings, P. Lilford, The perception of food texture - the philosophy of the breakdown path, J. Texture Stud. 19 (1988) 103–115.
[24] S.C. Hutchings, K.D. Foster, J.M. Grigor, J.E. Bronlund, M.P. Morgenstern, J. Hutchings, P. Lejeune, I. Des, Comparison of electromyographic
[25] Jourdren, A. Saint-Eve, M. Panouilla, E. Saucy, M. Moser, C. Loret, Adaptation of mastication mechanics and mandibular kinematics in young adults, Biosci. Biotechnol. Biochem. 72 (2008) 1690–1695, https://doi.org/10.1271/bbb.707069.
[26] K. Koyama, M. Tsukamoto, K. Naishita, K. Yamaguchi, K. Yamaguti, F. Hayakawa, T. Sasaki, Mastication efforts on block and finely cut foods studied by electromyography, Food Qual Prefer 18 (2007) 313–320, https://doi.org/10.1016/j.foodqual.2006.02.006.
[27] K. Koyama, T. Sasaki, F. Hayakawa, Characterization of food physical properties by the mastication parameters measured by electromyography of the jaw-closing muscles and mandibular kinematics in young adults, Biosci. Biotechnol. Biochem. 72 (2008) 1690–1695, https://doi.org/10.1271/bbb.707069.
[28] M. Peyron, C. Lassauzay, A. Woda, Effects of increased hardness on jaw movement and muscle activity during chewing of visко-elastic model foods, Exp. Brain Res. 142 (2002) 41–51.
[29] A. Rosenthal, C. Share, Temporal dominance of sensations of peanuts and peanut products in relation to hutchings and lilford’s “breakdown path”, Food Qual Prefer 32 (2014) 311–316.
[30] A. Rosenthal, P. Thompson, What is cohesiveness? A linguistic exploration of the food texture testing literature, J. Texture Stud. 52 (2021) 294–302, https://doi.org/10.1111/jtxs.12586.
[31] H. Sakamoto, T. Harada, T. Matsukubo, Y. Takaesu, M. Tazaki, Electromyographic measurement of textural changes of foodstuffs during chewing, Agr Biol Chem 53 (1989) 2421–2433, https://doi.org/10.1016/0003-9969(89)90026-X.
[32] C. Schmidt, R. Bornmann, S. Schultf, Y. Schneider, H. Rohm, Thermo-mechanical properties of soft candy: application of time-temperature superposition to mimic response at high deformation rates, Food Biophys 13 (2018), https://doi.org/10.1007/s11483-017-9566-3.
[33] A. Sesmat, J.F. Meullenen, Prediction of rice sensory texture attributes from a single compression test, multivariate regression, and a stepwise model optimization method, J. Food Sci. 66 (2001) 124–131, https://doi.org/10.1111/j.1365-2621.2001.tb15593.x.
[34] K. Shirosawa, K. Koyama, K. Yanagisawa, Influence of ingested food texture on jaw muscle and tongue activity during mastication in humans, Japanese Journal of Oral Biology 41 (1999) 27–34, https://doi.org/10.2307/joralbiosci.1995.41.27.
[35] G.A. van Aken, M.H. Vingerhoeds, E.H. de Hoog, Food colloids under oral conditions, Curr Opin Colloid Interface Sci. 12 (2007) 251–262, https://doi.org/10.1016/j.cocis.2007.07.011.
[36] V. Maindanyk, Y. Roos, Water sorption, glass transition and ‘strength’ of lactose - whey protein systems, Food Hydrocoll. 70 (2017) 76–87, https://doi.org/10.1016/j.foodhyd.2017.03.025.