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New approach to food difficulty perception: food structure, food oral processing and individual's physical strength

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Abstract

The present study aims to study the effect of the interaction between food physics and human physical strengths on food oral processing and difficulty perception in the young population. As the first step in human nutrition is the food oral processing, special emphasis has been given to the oral strengths. Fracture mechanics of fifteen commonly consumed food products of fruits, vegetables and dairy origin were analysed using penetration test. Among the different products studied, six products (carrot, banana, mozzarella, potato, soft cheddar and hard cheddar) were selected and given to eleven young participants (<25 y.o.). Individual physical assessments included measurements of dominant hand grip force, isometric tongue pressure and bite force. Participants ranked the food products in the order of difficulty perceived using a visual analogue scale. Additionally, the number of chews and the time at swallow were analysed from video-recording for each participant. Food score difficulty showed that high break force of food products were related linearly with difficulty perceived (r=0.729) and with higher oral processing time (r=0.816). Other food breakdown characteristics such as number of peaks and gradient of the penetration curves showed linear correlation with mastication time (r=0.830, r=0.840) and number of chew cycles (r=0.903, r=0.914). However, no relationship could be established between individual physical forces (hand and oral) and food perception difficulty for young participants interviewed. This might be attributed to the selected healthy and young population having higher hand force/tongue force ratio, which might not interfere with their eating process.

Practical applications

This study investigates the relationship between human physical strength (with special emphasis into oral forces), food difficulty perception of food of different textural properties and their chewing and swallowing behaviour. The main hypothesis of this work is that healthy young population with different levels of oral strengths and eating behaviour will perceive food difficulty as a function of food textural characteristics and their individual capability of eating. To do that, eating capability measurements has been combined with texture analysis and video-recording of individual eating process (first bite-to-swallowing event). Understanding the interplay of physical, physiological and psychological elements of oral processing is a relative new area of research. Thus, the combination of tools and insights generated in this article could be a bridge between oral physiology and food science, and also could be of interests to new product developers in designing food with just-right texture.

Keywords: food structure, oral residence, difficulty at eating, oral forces, hand grip force

Introduction

In order to get nutrients from food, human beings transform the food at mouth. The strategy of food oral processing is different for different food products (Wilkinson et al., 2000) and also varies among individuals (Peyron et al., 2011). The physical and biochemical properties of the food product change while the food is masticated in a continuous and dynamic process (Wilkinson et al., 2000). Foegeding et al. (2015) used examples of pudding and carrot to describe different kinds of oral processing behaviour. For instance, puddings are manipulated with the tongue and hard palate, whilst, carrot has to be reduced in to smaller-sized particles by teeth and then need tongue, oral palate and saliva to form a cohesive bolus. The consequence of these different oral processing needs i.e. to commute particles or not is reflected in the different actions that the mouth has to perform, such as squeezing by tongue directly, or breakdown by teeth etc. Engelen et al. (2005) found a significantly different number of chews for different food structures, such as 17 for cake and 63 for carrot. Authors also found that hard and dry products needed more chewing and longer time to form a coherent bolus.

From a human physical capability point of view, the components of the oral cavity (including orofacial muscles such as lips and cheeks), teeth, tongue, palate and facial muscles) have to work in a coordinated manner and under close control by the upper central nervous system to generate efficient masticatory movements. Apart from the muscle coordination, muscle tone has been also reported to be an important factor for effective food oral processing. Alsanei and Chen (2014) revealed that the muscle strength of the oral cavity is one of the contributing factors to the maximum capacity of oral volume. In agreement with Palastanga and Soames (2012), they observed that when some of the labial muscles are paralysed, a constant saliva drip from the corner of the mouth occurs, an indication of weakened capability in keeping food inside the mouth. Engelen et al. (2005) studied the influence of the oral physiology on oral processing, and inferred a significant but rather low correlation between the maximum bite force and the masticatory performance. Although, the influence was found to be less than 10%, it seems to be of enough importance to understand objectively why some foods are perceived more difficult than others.

The ability to perform a bite is also dependent on the dentition status, and it is well-known that masticatory efficiency decreases for subjects who have teeth missing (Fontijn-Tekamp et al., 2000; Miyaura et al., 2000). Apart from the dentition status, several authors highlighted the importance of tongue force in proper bolus propulsion down to the oesophagus (Martino et al., 2005; Logemann, 2007; Ickenstein et al., 2012; Alsanei and Chen, 2014). Also, the tongue is considered to be crucial for eating because it acts as a mechanical device for food manipulation and transportation (Heath, 2002) from the anterior region of the mouth to the pharynx (Pereira, 2012).

Elderly population are especially sensitive to tooth loss and motor-related problems. The reason to elderly malnutrition seems to be multifactorial: functional, behavioural, environmental, nutritional, and medical variables (Keller, 1993). In a previous work, we interviewed over 200 elderlies for their eating capabilities (Laguna et al., 2015a; Laguna et al., 2015b), finding that participants with low eating capabilities i.e. with relatively lower magnitudes of dominant hand grip forces, isometric tongue pressure and bite force perceived high consistency food products as more difficult to process orally. Furthermore, it is well studied that when dentition status is low (i.e. wearing complete dentures), the difficult-to-chew food items (e.g. roots, vegetables, fruits and meat) becomes less pleasing. As a result of this, these populations tend to have lower intakes of vitamins (especially vitamins A, C and carotenes), proteins and some nutrients such as thiamine, iron, and folic acid (Ranta et al., 1988). Furthermore, subjects with a reduced masticatory efficiency tend to over prepare the food. For example, some fruits and vegetables need to have their skins removed and some foods need to be overcooked to compensate their mastication deficiency (Walls and Steele, 2004). Also, such food difficulty perception might lead to food avoidance.

Hence, the research question raised is how an individual develops a perception that a food product is difficult to eat and how they decide to avoid it. Hayakawa et al. (2014) quantified the difficulty as the time period lapsed between the oral ingestion and the end of swallowing. We hypothesize that this increase of oral residence time is a sum of two key unfavourable factors i.e. low physical strength (especially oral strengths) and harder food texture. In this study, our aim was to objectively identify in healthy young individuals whether their oral strength influences their food difficulty perception and oral processing behaviour. Physical strengths (oral forces and hand grip force) of the eleven young individuals, their food oral processing behaviour (oral residence time, chewing cycles and number of swallows) and food difficulty perception during oral processing of different categories of food were assessed.

Materials and Methods

Product selection and texture properties. Fracture mechanics of fifteen commonly consumed food products (pear, carrot, apple, banana, watermelon, pineapple, potato, gherkin, baby sweetcorn, heart of palm, mild cheddar, soft cheddar, mature cheddar, mozzarella and spreadable cheese) were analysed using penetration tests (Texture analyser, Stable Micro Systems, Godalming, UK) with upper Volodkevich Bite Jaw. This probe is an imitative bite method used successfully by previous study (Varela et al., 2009).

Samples were placed on a flat platform, using the upper Volodekevich Bite Jaw. Samples were penetrated for 20 mm at test speed of 1 mm per second at trigger force of 5 g. Each test was performed on five replicates of each sample. The maximum breaking force (N) as a measure of hardness, the number of force peaks (with a threshold of 0.1 N and the gradient of the initial steep slope of the curve (N/sec) as a measure of food deformability were assessed.

Fifteen foods were initially tested for their textural properties using a texture analyser. Then, the six foods differing in their breakage profile were selected for oral processing experiments: mild cheddar, mature cheddar, cheese, banana, carrot, and canned diced potato. The food samples were cut into specimens measuring 1 cm in diameter and 2.5 cm in height for both instrumental and consumer's evaluations.

Individual's eating capability measurements

The present study design was approved by Faculty Ethics Committee at the University of Leeds [ethics reference (MEEC 14-006)]. Eleven students from University of Leeds (between the ages of 18-25, 5 males and 6 females) participated in this study and gave written informed consent before starting the study. Participants did not have any masticatory problems and participated voluntarily in these experiments. Eating capability measurements of hand grip force, isometric tongue pressure and bite force were measured using the methodology described in a previous study (Laguna et al., 2015a), all measurements were done in triplicates. Hand gripping force was measured with an adjustable handheld dynamometer (JAMAR dynamometer, Patterson Medical Ltd., Nottinghamshire, UK). To measure the bite force, a thin flexible force transducer was used (Tekscan, South Boston, Massachusetts, USA) with two adhesive silicon discs (diameter: 1.5 cm, thickness: 0.3 cm to sandwich the force sensor) connected to a multimeter. Finally, for the isometric tongue pressure, the Iowa Oral Performance Instrument (IOPI®, Medical LLC, Redmond, Washington, USA) was used. Prior to using the equipment, each measurement was demonstrated to the participant by a trained demonstrator and any questions were answered before conducting the experiments on subjects.

Food oral processing parameters

Food oral processing parameters were studied using video-recording technique. Prior to the video recording session, participants had the complete explanation: they consumed different food product in the order they preferred. They were showed the tray with the real food products (carrot, banana, soft cheddar, canned potato, mozzarella and hard cheddar). Participants had the right to withdraw at any time. They were also informed that in case of any of the product causing discomfort, they did not have to masticate and/or swallow the same. They were aware that the main focus of this video-recording session was to record their mastication and swallowing behaviour. Experiments were conducted in a sensory test booth with minimum distractions. The researcher was seated in front of the participant, beside the camera. The researcher assisted participants with tissues or water if required, but water was not offered at the beginning. Participants were video-recorded using a video camera (Canon Powershot SX500 IS). Videos were visually analysed to study the total oral residence time, number of chew cycles, number of swallows and swallowing time.

All tests were carried out between 10:00 and 12:00 p.m. and between 2:00 and 4:00 p.m. This was approximately two hours after the university eating time table.

As shown in Figure 1, chew cycles refers to the cycle from the jaw closing after placing food inside the mouth to the upward and downward mandible moment. In order to visualize better the chew cycles two lines were drawn: red line to indicate the start or basal position; and black line to indicate the jaw displacement. Normally, lips have two postural positions: relax and closed-lip position (Burstone, 1967). In relaxed lip position, lips are without contraction and hanging loosely (Burstone, 1967). In the closed-lip position, the lips are lightly touching in order to produce an anterior seal of the oral cavity (Burstone, 1967). To record the time at swallowing (or oral residence time), researchers observed two factors: closed-lip position and consequently pulling the corner of the mouth and lower lip downward, followed by stop of breathing and pharynx movement. The swallowing process was considered finished once the participant has returned to breath, normally shown by slight mouth opening. An example of the frame-by-frame video analysis is shown in Figure 1.

Rating of difficulty perceived

Eating difficulty definition given to participants for food difficulty evaluation was based on the previous work by Hayakawa et al. (2014), i.e. “effort required to eat a sample during the period between entry into the mouth and the end of swallowing”.

In a visual analogue scale of 10 points, participants were asked to rank the level of perceived difficulty for the six food products given from “too easy” to “too difficult”.

Data analysis

Pearson’s correlation was carried out in order to study the relationship between different parameters (participant’s strength and food oral processing parameters); this analysis was performed using XLSTAT 2009.4.03 statistical software (Microsoft, Mountain View, CA). Analysis of variance (one-way ANOVA) was applied to study the perception of difficulty among food products using SPSS (IBM SPSS Statistics for Windows, Version 22.0. Armonk, NY: IBM Corp).

Results and discussion

1- Individual physiological capabilities

Participant’s characteristics chosen for this study are shown in Table 1. All the participants were young and in good health status. The magnitudes of dominant hand grip forces correspond to the normative grip strength data (Budziareck et al., 2008) and tongue pressure values are in line with results of young population (Alsanei and Chen, 2014; Alsanei et al., 2015). Bite force is known to be dependent on the geometry of the instrument as well as the position where it is located (Laguna and Chen; Gibbs et al., 2002; Ferrario et al., 2004; Laguna et al., 2015a); in such way, for young population some authors has been reported higher forces (Tortopidis et al., 1998; Chen et al., 2010) whilst our results are within the range of values obtained by Fernandes et al. (2003) using a similar flexisensor placed in the incisors.

The relationship between different forces (hand, bite and tongue) was assessed (Table 2). Hand grip strength is a significant health indicator for elderlies and thus, can be related with oro-facial muscular function (Luna-Heredia et al., 2005; Bohannon, 2008; Yamada et al., 2010). As shown in Table 2, among young participants, no relationship could be established between oral (bite and tongue) and hand grip forces. Interestingly, in a previous work involving 200 elderly participants (Laguna et al., 2015a; Laguna et al., 2015b), a significant but low correlation (0.4; at 0.01 level) was observed between hand and oro-facial forces measured. Probably in this study, with the number of consumers interviewed, the spectra is not big enough to observe such correlations. Furthermore, it is also likely that such correlations only exists where the forces are rather limiting due to overall weakening of oral as well as physical forces as observed in case of frail elderly population in the previous study.

2- Physical structure of food, oral processing and food perception difficulty

In Figure 2, the penetration curves for the fifteen food products are shown. All the curves represent the typical penetration curve, with the increase of load with increasing deformation, up to a point when the sample surface gets suddenly fractured as the probe penetrated. For vegetables (Figure 2a) , crack propagation in crisp tissues involved cell wall breakage, this initial pressure also affected the surrounding cells, which were stretched overloading the elasticity point, when the fractures occurred (Waldron, 2004). In our study, after this initial fracture, the different vegetables exhibited different behaviours. Once the probe had penetrated, in apple and watermelon, the force had continued to increase, with multiple low force peaks, highlighting the crispy nature of both the products. In the case of pear, gherkin, and carrot, the penetration force had decreased after breaking the surface. Similar curves have been reported by previous authors in fruits and vegetables, such as cucumbers (Dan et al., 2003), raw carrot (Kohyama et al., 2004; Kohyama et al., 2005), and apples (Dan et al., 2003b). In the case of palm, banana and canned potato, the penetration force remained constant, showing a plateau region for the rest of the test. Pineapple has been a case (probably by the geometry use) where the force seemed to not arrive at its maximum, or it is possible that the accumulative tissue around the probe was providing a force increment. In the case of potato, as it was cooked, the intracellular starch resulted in a high viscosity gelled network and the cell wall allowed more water as well as the pectin was degraded (Lillford, 2011), that translated into less force being needed to penetrate the cooked potato.

Cheese, is a product with a range of texture (Delahunty and Drake, 2004). In this study, hard (hard cheddar), semi-soft (mild- soft cheddar), and soft cheese (cheese flavour paste) have been investigated. In cheese products, milk is enzymatically coagulated to form an emulsion gel (Ong et al., 2011). Thus, during biting, the teeth cross a uniform matrix of emulsion gel network, which is shown by absence of peaks in the curve. The difference in hardness of the cheeses might be attributed to a higher aggregation of proteins and loss of water. A smooth penetration can be observed for the semi-soft and soft cheese (Figure 2b), without the typical break peak as in case of the pear, or the carrot. However, it seems that the hard cheddar does have a snap before the probe penetrates the cheese matrix.

Table 3 shows further analysis of the texture curves, those with statistical difference higher than $p>0.05$ were selected. As cited before food products were selected for the oral processing study was carrot, hard cheddar, soft cheddar, mozzarella, banana and canned potato. The area under the curve represents the resistance to the probe penetration. As it can be observed, the carrot was the food product with the highest area. The number of peaks is related with the breaking events that occurred when the probe passes through the product structure. For that, more homogeneous structure such as cheese (1 to 2 peaks) has less number of peaks than apple (32 peaks) or watermelon (28 peaks).

3- Oral processing and physical properties

Three food oral processing parameters were analysed: number of chewing cycles, number of swallows and time in mouth i.e. the difference in time between the first bite to the last swallow. In Table 4, the average values of all the different parameters as a function of the textural properties of food products are shown. In accordance with previous study (Engelen et al., 2005), high correlation (r=0.913) between number of chew cycles and time at swallow was found irrespective of the food type. In other words, food that resides in mouth longer needs more chewing to form a swallowable bolus. At the same time, both parameters (number of chew cycles and maximum oral residence time) was correlated significantly with the maximum peak force obtained by the texture analyser (r=0.894, r=0.816), with the number of peaks (r=0.903, r=0.830) and with the gradient of the food break (r=0.914, r=0.840). These results suggest that food textural parameters (maximum force at break, number of peaks, and gradient) were conditioning how individuals performed their mastication. The importance of the food fracture has been shown also by previous authors (Hiiemae et al., 1996; Engelen et al., 2005). Engelen et al. (2005) showed a linear relationship between yield strain and number of chewing cycles, and affirmed that other physiological parameters such as saliva or masticatory performance explained less than the 10% of the masticatory performance. However it was observed from one of the authors that for dry and highly fracturable food such as biscuits, mechanical strength had a limited influence on the number of chewing cycles, and the amount of saliva secretion was a determinant factor (Chen and Engelen, 2012).

4- Difficulty perceived in relation with food properties

Figure 3 shows a correlation between the perceived difficulty and the oral resident time in relation with the maximum peak force at penetration and the time at mouth. As it can be observed, there is a correlation between the difficulty and the maximum peak force. Hayakawa et al. (2014) assessed the eating difficulty using a trained panel; they found that the difficulty to eat a food is reflected by the time of consumption. Also, Witt and Stokes

(2015) recently reported that harder gels, require more oral residence time at mouth, more chewing and a greater muscle force. Carrot was the hardest food product given, which required more number of chews and resided longer in mouth, being in accordance with Witt and Stokes (2015). However, comparing all the food given, hard cheddar was perceived as the most difficult one, although it resided shorter time at mouth and broke at lower force than carrot (former being softer). This suggests that it is not only the force at break but also the structural property of the food that plays an important in the difficulty perceived.

It seems that food has to be treated in two separate groups, structured cell-wall or fibrous food (banana, potato and carrot), and the gel kind food (mozzarella, mild cheddar and hard cheddar) for relating to the ease of consumption. For gel-like products, it can be observed that difficulty perceived increased with the maximum force at break (r=0.818) but not with the time in mouth (r=0.387). In the case of the structured cell wall food, the difficulty perception and the oral residence, increased linearly with the maximum force at break (r=0.920, r=0.754).

However, not only the food structure but also composition may play a role. Boehm et al. (2013) found that in chips with different fat content, sensory perception varied dramatically during mastication although initially no changes in texture were perceived. Therefore, food composition (different level of water, fat, protein in vegetables or cheese) might also play a role in the oral lubrication and easiness perceived.

Overall, perception of oral processing difficulty was correlated with the oral residence and with the effort needed for food breaking.

5- Difficulty perceived in relation with participant's strength

In Figure 4, perceived difficulty is plotted as a function of the tongue pressure and bite force. Each force (or dot column) belong to a single participant; each colour belongs to a different food. Hence, each column can be observed by separate food, the participants and their individual strength. It is worth pointing out that the population of the study was in a good health condition, and the differences between them were within the norm. As it can be observed, there is a significant difference ($p<0.05$) among the perceived difficulty based on the food product, with banana being the easiest food followed by potato, mozzarella, carrot, mild cheddar and hard cheddar. However, no correlation among physical forces and difficulty perception could be established. It is worth noting that in this study the real food testing and the familiarity of the food presented, the liking, the postprandial satisfaction and flavour experience with well-known food-products (Prescott, 2012; Yeomans, 2012) might influence the overall oral processing behaviour as well as difficulty perception.

Several authors have identified and classified the different ways of chewing (BROWN et al., 1994; Brown and Braxton, 2000; Engelen and de Wijk, 2012; Jeltema et al., 2015) because it has an important influence in the texture perception, in the food product liking, and consequently, in the food choice. In the present work, these physiological differences have been studied through the measurement of oral forces. However, as it can be observed in Figure 5, the individual’s force did not influence their number of chews (and consequently the time in mouth). It has already been mentioned by previous authors (Ranta et al., 1988) that a lack of teeth in elderly population can determine their food choice, leading to avoidance of some “difficult-to-eat” food products. However, it does not seem that young population is affected by this, probably because for them physical capabilities are not a limiting factor. However, it does not seem that young population is affected by this, probably because for them physical capabilities are not a limiting factor. At the same time, no relationship could be derived between oral and hand forces, whilst other authors found the maximal grip strength correlated with other muscles groups (Rantanen et al., 1994). It is probably because the selected healthy and young population have higher hand force/tongue force ratio, which might not interfere with their eating process. However, it is worth noting that in the case of frail population as elderly, their physical strength does determine the activities of daily living such the action of eating (Desai et al., 2001), and it is worthy to investigate in future studies if elderly people will avoid food where they perceive eating difficulty and if so, to understand how they identified it.

Conclusions and future perspective

In this work, the relation among the food structure, food oral processing, human strength and difficulty perception has been studied. In accordance with previous authors, food structure (fracture behaviour) does affect significantly the food oral processing (number of chew cycles and time in mouth), and it is correlated with the difficulty perceived. On the other side, in young population, the perception of difficulty did not show any relationship with their individual physical strength (especially oral forces), nor their chewing behaviour.

The limitation of this study is the population chosen being young participants of < 25 years and a relatively low number of participants. For future steps, we aim to address the topic considering higher diversity of population (age range, different teeth condition, different saliva excretion), studying their dietary patterns (frequency of hard food) and making open question to participants regarding how they perceived the oral processing difficulty. Also, present authors believe that long food oral processing in frailty population may lead to exhaustion and is worthy to keep researching the influences between health status and food consumption.

In summary, in case of cellular food structure, such as vegetables, hardness was the driving force for oral residence time, i.e. harder the food, longer it was kept in mouth for oral processing, and the difficulty perceived was related with the food oral processing time. In the case of the food with gel like structure, such as cheese, the oral residence time in mouth was not dependent on the hardness, hardness was inversely related to the difficulty perceived that the oral residence time was dependent of the maximum breaking force.

As a key limitation of this study is the test with real food that can influence their time at mouth and overall oral processing behaviour due to food preferences. Hence, future studies will not only include to testing with elderly population, but will be directed to employ model hydrocolloid gel that is tasteless.

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Conflict of Interests

The authors declare that they do not have any conflict of interest.

Ethical Review

This study was approved by Faculty Ethics Committee at the University of Leeds [ethics reference (MEEC 14-006)].

Informed Consent

Written informed consent was obtained from all study participants.

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