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Review

Food oral processing—A review

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Abstract

Food oral processing is an essential procedure not only for the consumption and digestion of foods but also for the appreciation and pleasure of food texture and food flavour. The consumption of a food inside mouth involves various oral operations, including first bite, chewing and mastication, transportation, bolus formation, swallowing, etc. Exact mechanisms and governing principles of these oral operations are still not fully understood, despite of continuous efforts made by scientists from food, psychology, physiology, dental and clinical studies, and other disciplines. This article reviews recent progresses and literature findings about food processing and transformation in mouth, with particular attention on the physiology and rheology aspects of oral operations. The physiological behaviour of human's oral device is discussed in terms of biting capability, tongue movement, saliva production and incorporation, and swallowing. The complexity of oral processing is analysed in relation to the rheology and mechanical properties of foods. The swallowing and oral clearing process is also examined for its criteria, triggering mechanism, bolus deformation, and the rheology of swallowing.

Keywords: Oral processing; Oral physiology; Food rheology; Food texture; Saliva; First bite; Chewing; Mastication; Bolus; Swallowing

Contents

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0. Introduction

Human beings eat and drink for two reasons: to obtain energy and essential nutrients and to have the pleasure. These two reasons can be simply interpreted as we have to and we like to. It is not the purpose of this paper to discuss why we have to eat and drink. The essential need of eating and drinking is obvious to every single person and does not require much explanation. Main purpose of this review is to reveal the mechanisms and principles which underpin our enjoyment and pleasure of eating and drinking. We will discuss how a food is handled inside the mouth and how its rheological properties influence such processes. It is hoped that the review will help us to better understand physiology as well as rheology principles of food texture and sensory perception and to better interpret textural results from physical (instrumental) measurements. It is also hoped that the review will provide a useful knowledge to food researchers and manufacturers in producing high-quality foods (both nutritionally and texturally) to meet consumers' need, in particular the needs of some specific consumer groups such as, junior and senior citizens, denture wearers, and people with swallowing dysfunction.

The appreciation of foods comes from a combined perception of multi-contributions, including the texture, the flavour and taste, and the visual appearance. However, this review of oral processing is written with the main attention to food texture, no coverage is given to food flavour (aroma) and taste. This is not at all to suggest that food flavour and taste is less relevant to oral processing. The importance of oral processing to food flavour and taste has already been clearly evidenced by many observations of positive correlations between mastication and flavour release of the food (Neyraud, Peyron, Vieira, & Dransfield, 2005; Neyraud, Prinz, & Dransfield, 2003). The exclusion of food flavour and taste in this review is simply based on the consideration that food texture and food flavour and taste are commonly viewed by food scientists as two different disciplines. For progresses on food flavour and taste studies, readers are referred to various articles and textbooks (Fisher & Scott, 1997; Taylor & Linforth, 1996; Taylor & Roberts, 2004). The surface texture and surface appearance also play a significant role in influencing consumers' perception and preference of a food product. For progresses in this area, a recent review article on food surface texture (Chen, 2007) is recommended.

This review is organized as follows. Section 1 gives a brief description of the major achievements on food texture studies in the last half-century. Section 2 describes the physiology characters of humans' oral device, including oral cavity, teeth and biting, tongue, and the composition and production of saliva. Section 3 explains various operations involved in food oral processing, explaining the pathway of a food, from grip and first bite, to chewing, to bolus formation, to until swallowing. Section 4 focuses on the rheology aspects of oral processing, examining what happens to a food material inside the mouth. This will be followed by detailed analysis of swallowing process, including bolus formation, triggering mechanisms, swallowing criteria, and the deformation of food bolus. The review is ended with a brief summary.

1. A brief history of food texture studies

No one knows exactly how far we can trace back the history of human's appreciation of food texture. Probably as far back as human's evolution began. However, the term of texture for food description was first seen only at around the middle of last century (Matz, 1962), defined, rather less accurately to today's knowledge, as "the mingled experience deriving from the sensations of the skin in the mouth after ingestion of a food or beverage, as it relates to density, viscosity, surface tension and other physical properties of the material being sample". Since then, huge interests have arisen from food scientists and technologists in characterizing and quantifying the texture of foods, with extensive research publications. In 1969, a new journal (*Journal of Texture Studies*) was launched, dedicated particularly to reporting advances in the texture studies of foods. Over the last half-century, the progresses on food texture studies have been enormous and have made huge impacts on the practices of food manufacturing and food supplies and on the quality of humans' life, as can be seen from various review articles (Morris & Taylor, 1982; Guinard & Mazzucchelli, 1996; Peleg, 2006; Stanley & Taylor, 1993; Wilkinson, Dijksterhuis, & Minekus, 2000) and two major food texture textbooks (Bourne, 2002; Rosenthal, 1999). Comprehensive reviews can also be seen from special reports produced from the international workshop of food texture, on the sensory nature of food texture (Szczesniak, 2002), on the mechanical parameters of food texture (van Vliet, 2002), and on the physical and physiological aspects of food texture (Lucas, Prinz, Agrawal, & Bruce, 2002).

The earliest important break through in food texture studies was probably the work conducted by Szczesniak and her co-workers from the General Foods (now Kraft) in 1960s. For the first time, a direct link between the mechanical properties of a food and its texture profile was established (Friedman, Whitney, & Szczesniak, 1963). Using a so-called Texturometer, they demonstrated that the force–displacement curve obtained from a double-compression test (see Fig. 1) gave a meaningful interpretation to a number of texture features: hardness,

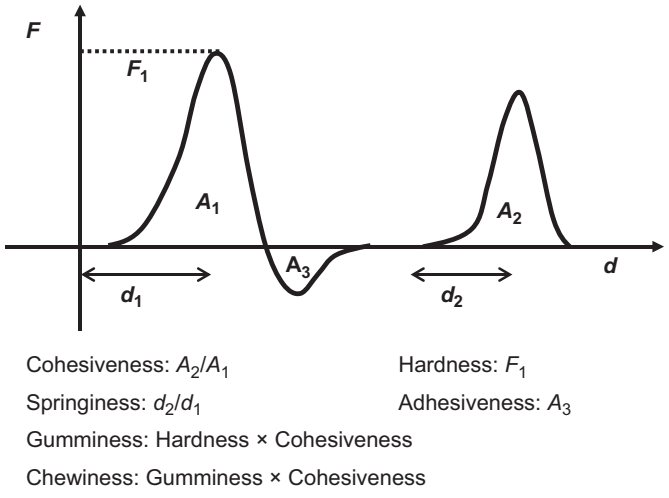

Fig. 1. A typical force–displacement curve obtained from a double-compression test using the texture profile analysis approach. One single test is capable to characterize a number of textural parameters.

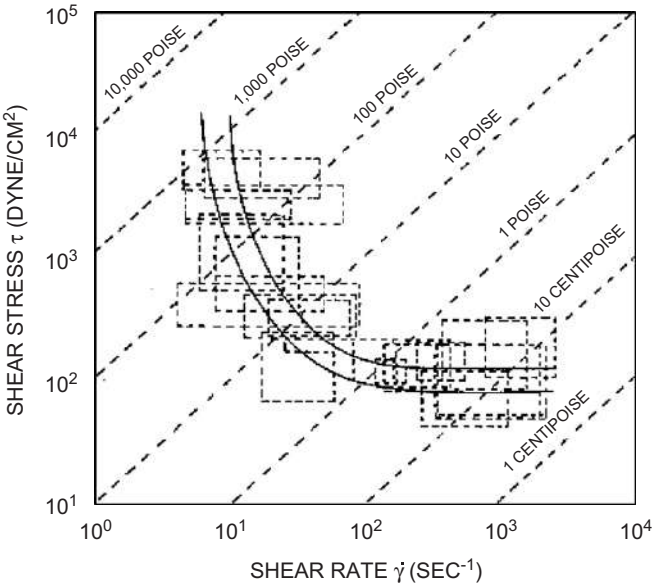

Fig. 2. A master curve for shear-stress and shear-rate associated with the oral viscosity evaluation of various foods (Shama & Sherman, 1973).

cohesiveness, viscosity, elasticity, adhesiveness, brittleness, chewiness, and gumminess. Szeczesniak's method was later named as *Texture Profile Analysis* (TPA) and is still frequently referred in literature as a standard method for texture characterization.

Another major development to food texture studies was the work published a decade later by Sherman and his co-workers. The important contribution of this study was the establishment of the link between rheological properties and the sensory perception. They studied the sensory evaluation of viscosity for a wide range of food materials (viscosity ranging between 1 mPa s and 10 Pa s) using both subjective approach (oral sensory tests by 26 panellists) and objective approach (viscometer) and produced a master curve of shear deformation of foods during oral processing (Shama, Parkinson, & Sherman, 1973; Shama & Sherman, 1973). They convinced that human beings apply different oral strategies when sensing and processing foods (of different viscosity). It was revealed that, when eating (or drinking) low viscosity foods, we apply a minimum stress while increasing the rate of deformation. On the other hand, when we process highly viscous foods, the deformation rate is maintained to a minimum but the applied stress is increased in proportion with the viscosity increase (see Fig. 2). This can be seen as the oral adaptation to the changing mechanical properties of the food. Cutler, Morris, and Taylor (1983) further found that the viscosity measured at $10\,s^{-1}$ gave the best correlation to the viscosity perception from sensory tests, a useful indication of the extent of flow deformation inside mouth. Such an analogy of sensory viscosity and shear rheology tests became widely accepted in correlating rheology test results with the sensory perception of foods (Akhtar, Stenzel, Murray, & Dickinson, 2005).

For a long time, mechanical and/or rheology approach dominated the literature of food texture studies (Dobraszczyk & Vincent, 1999; Peleg, 1997; Rao, 1999; van Vliet, 1999). It was even more so in the last two decades thanks to the availability of much advanced rheology techniques and instruments. However, even though rheological approach might have been very useful in revealing the mechanical and microstructural nature of a food, it becomes clear that such an approach oversimplifies the reality and the complexity of oral experience. For example, the use of small deformation rheology test is hardly applicable to cases of food oral processing, where the deformation is dominantly destructive and catastrophic. In one of his earlier paper, titled as "Is rheology enough for food texture measurement?", Bourne (1974) challenged the appropriateness of single-minded rheology approach. He indicated that "rheological tests describe only a portion of the physical properties sensed in the mouth during mastication".

Realizing the limits of rheology approach in food texture studies, Hutchings and Lillford (1988) proposed a dynamic approach to characterize the perception of food texture. The philosophy behind their approach is based on the breakdown path of the food during oral processing. This model interprets texture perception in three aspects (or in three dimensions): the mechanical/rheological behaviour of the food (the degree of structure), the oral experience or saliva participation (the degree of lubrication), and the sequences of oral processing (the time) (see Fig. 3). The concept of involving oral experience and time in texture studies was a significant development, which turned the texture appreciation from static process to a dynamic one. This model would be a very useful platform for both objective studies and subjective studies of food texture. Disappointedly, the importance of this model has not been fully recognized and there has been no follow-on research

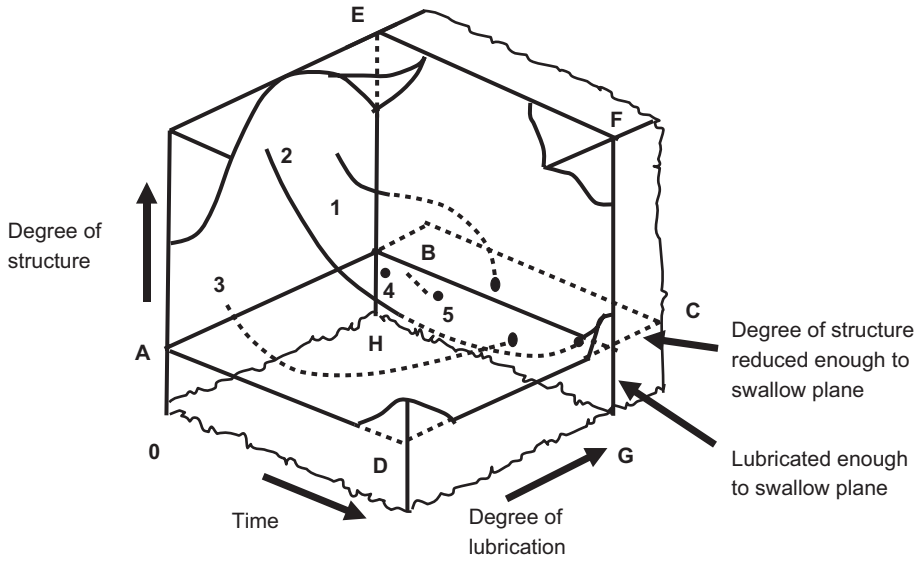

Fig. 3. The 'mouth process model': (1) tender juicy steak; (2) tough dry meat; (3) dry sponge cake; (4) oyster; (5) liquids. Before a food may be swallowed, its 'degree of structure' must have been reduced below the level of plane ABCD, and its 'degree of lubrication' must have crossed plane EFGH (adopted from Hutchings & Lillford, 1988).

on this model almost two decades after it was proposed. The technical challenge in characterizing and quantifying these dimensions could be partly to blame, but the main reason is probably due to the lack of the knowledge of food breakdown throughout the eating process (or food oral processing).

In the last decade or so, the availability of advanced physical techniques has made texture studies much more diverse. Classical mechanical and rheological tests are becoming increasingly smart in both accuracy and reliability (increased range of torque and increased resolution for stress and strain control). The development of new techniques brings in new dimensions (parameters) for food texture interpretation. For example, the application of acoustic technique makes the characterization of food crispness and crunchiness far more convincing (Duizer, 2001; Zdunek & Bednarczyk, 2006). The acoustic detection of food fracture corresponded closely to human's perception of food crispness (Chen, Karlsson, & Povey, 2005; Varela, Chen, Fiszman, & Povey, 2007) and correlated well with the zig-zag force–displacement curve (or force drops) from the classical mechanical compression test of crisp foods (Vincent, 1998).

Another important development worth of mention is the application of electromyography (EMG) technique (González, Montoya, & Cárcel, 2001; González, Montoya, Benedito, & Rey, 2004). By monitoring the activities of facial muscles, the technique makes it possible to correlate food physics with the physiology of oral processing and food sensory perception (Kohyama & Mioche, 2004). Imaging techniques has also been proved extremely useful in revealing oral experience in relation to texture appreciation. Developed for medical applications, videofluorography (Heath, 2002; Jack, Piggott, & Paterson, 1993; Mioche, Hiiemae, & Palmer, 2002; Okada, Honma, Nomura, & Yamada, 2007) and real-time magnetic resonance imaging (MRI) technique (Buettner, Beer, Hannig, & Settles, 2001; Divakar, 1998; Hall, Evans, & Nott, 1998) have been applied successfully to provide insight visual evidence of food transformation and transportation at different stages of oral processing. It is foreseeable that the use of such imaging techniques together with the classical mechanical and sensory methods will be a powerful combination in characterizing food texture.

There is no doubt that extensive studies in the past half-century have led to significant progresses in understanding and in objective characterization of physical and microstructural attributes of food texture and sensory perception. Despite of these achievements, a number of important questions remain unanswered, and in particular, (1) the dynamics of food breakdown during eating and drinking process; (2) the correlation between objective measurements and the sophisticated humans' sensory perception; (3) the relevance of set conditions of an objective measurement to the complex oral environment; (4) the applicability of a single parameter from objective measurements to multi-contributes of human's sensory perception; and (5) the physiology contribution of human's sensory perception of food texture. To answer these questions, a thorough understanding of the principles and mechanisms involved in food oral processing will be essential. Without such knowledge, our studies of food texture probably would not go far.

2. Oral physiology

2.1. Oral cavity

Mouth is human being's ultimate device for food consumption and appreciation. Although we use our oral

device all the time throughout the whole life, most of us appreciate little of its complexcity. Fig. 4 shows an anatomic diagram of human's oral organ. While the general features and functionalities of mouth would be same for all human beings, the oral individuality should never be underestimated. Sex, age, race, health status, etc., will all make a difference and it is this variation that causes a huge problem for a universal characterization and quantification of textural perception of foods.

The oral cavity is where foods are manipulated and processed and can be defined roughly as the void space between the lips and the velum. The velum separates oral cavity from the pharynx during oral mastication and separates nasal cavity from the pharynx during swallowing, while the epiglottis separates the esophagus from the trachea (the windpipe) and prevents inhalation of food or drink. The size of oral cavity varies significantly from person to person. It has been shown that, for adult males, a normal mouthful can take around 30.5 ± 10.1 g water, while, for adult females, it takes around 25.2 ± 8.1 g water (Medicis & Hiiemae, 1998). Assume water fills the whole void space of the mouth, this measurement is probably the closest estimation of the volume size of oral cavity. However, our oral capability in taking foods decreases significantly once solid foods are consumed. For example, for each mouthful, males take on average 18 ± 4.9 g of banana, while females take only 13.1 ± 4.0 g. Each mouthful becomes even smaller for peanuts bites, 5.5 ± 2.3 g for males and 3.6 ± 1.4 g for females (Medicis & Hiiemae, 1998). This suggests that the amount of food intake will not only depend on individuals, but more importantly depend on the physical properties of the food. It appears that the amount of food for each mouthful decreases from liquid foods to soft solids and further to hard solids. The reason for this decrease is probably due to the increased difficulty of oral breakdown and oral manipulation for solid foods.

2.2. Teeth and biting

Teeth are the structures found on our jaws and are the main agent for food mastication. A tooth has its exposed part, the crown, and its root covered by gum. The external layer of the crown is called enamel, the hardest and most highly mineralized part of the body. The central part of a tooth is the dental pulp, a soft connective tissue containing blood vessels and nerves that enter the tooth through the

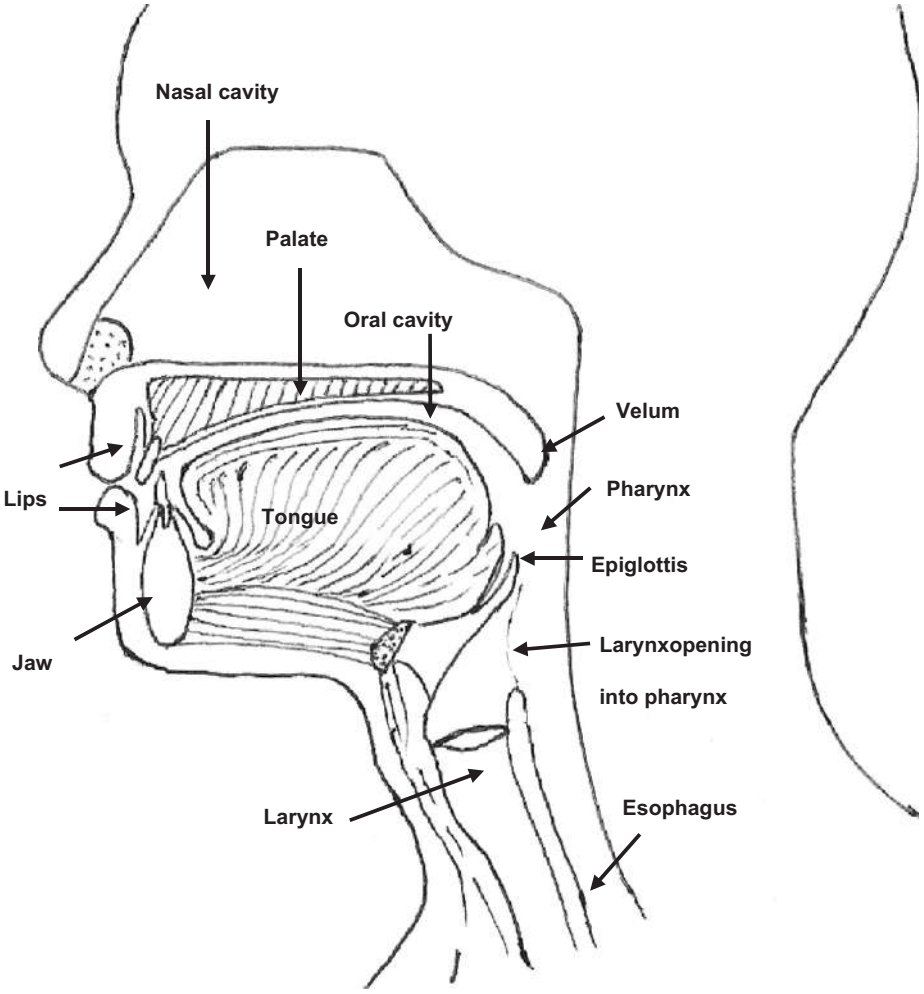

Fig. 4. An anatomic diagram of oral organ.

hole at the apex of the root. The periodontium is the supporting structure of a tooth, helping to attach the tooth to the surrounding tissues and to allow sensations of touch and pressure. The periodontal ligament (a specialized connective tissue) attaches the cementum of a tooth to the alveolar bone. Each ligament has a width of 0.15–0.38 mm and consists of a number of bundles of fibres (Nanci, 2003). When a pressure is exerted on a tooth, such as during chewing or biting, the tooth moves slightly in its socket and stretches the periodontal ligaments. The nerve fibres will send the information to central nervous system for (textural) interpretation.

Full dentition in an adult consists of 32 teeth, 16 in each jaw, including the incisors, the canine (or the cuspids), and the molars. These teeth serve for different purposes. For example, incisor teeth are for cutting, canine teeth are for cutting and tearing, while molar teeth are mainly for chewing and shearing. Researches show that the force applied by teeth varies among different ethnic groups, between sexes, and even more among individuals. Table 1 shows that males are generally capable of applying a larger (up to 50% higher) force than females. Ethnic Eskimos are able of exerting a much larger biting force than white Americans (Bourne, 2002). The large variation of biting force between individuals has also been observed by Paphangkorakit and Osborn (1997). They used a U-shaped pressure sensor to measure the biting force exerted by the central incisor tooth of 18 adults and observed a variation of biting force between 110 and 370 N. This may explain why, for the same food, its texture is often perceived so differently by different consumers. A food with a yield force of, for example, 200 N, may be sensed as weak and fragile to the person who could exert 370 N force, but will be perceived as hard and not fracture-able to the one who could only apply a maximum of 110 N force.

The applicable biting force also varies between teeth, dependent on their location. For example, the incisors apply smallest force (up to ~150 N), the canines could apply a medium range of force (up to ~300 N), while the molars are capable of applying a force of up to 500 or even to 800 N. Even though human teeth are able to apply a rather large biting force, this does not mean at all that such a high biting force will be applied during food consumption. As a matter of fact, depending on the mechanical nature of the food, the real amount of force applied during food consumption should be much smaller than the values shown above (Mioche & Peyron, 1995).

Table 1
Forces exerted between teeth (in Newton) (from Bourne, 2002)

	Male		Female	
	Mean	Max.	Mean	Max.
Eskimo	1202	1549	890	1451
American	534	890	378	734

In addition to force and pressure, human teeth are also very sensitive to vibration. Robertson, Levy, Petrisor, Lilly, and Dong (2003) used an electromechanical vibrator to assess the tactile sensitivity of maxillary and mandibular central incisors in healthy human subjects. They found that both maxillary and mandibular incisors were tactile sensitive. While there was no significant difference in tactile sensitivity between maxillary and mandibular incisors, the mean vibrotactile thresholds increased with the increase of vibration frequency. The vibrotactile perception of teeth is probably an important reason why consumers with hearing difficulty are still able to enjoy eating crispy and crunchy foods. However, such tactile perception will become not available to denture wearers, because of the loss of the connection with the central nerve system. Without such a connection, to sense the pressure and force exerted on a tooth will also be a problem. It was also found that, for denture wearers, the biting and chewing behaviour became significantly different. Veyrune and Mioche (2000) found that the masticatory pattern of complete denture wearers was less adapted to the texture of food than that of the control group, even though texture perception appeared to be little different. A separate research reported that, in eating hard food, complete denture wearers would normally apply higher chewing rates, higher muscle activities, but shorter cycle durations (Karkazis, 2002).

2.3. The tongue

The tongue is a large bundle of striated muscles on the floor of the mouth. As well as for tasting and speaking, tongue is also crucial for food manipulating and swallowing. The tongue contains no bony supports for the muscles and it depends wholly on the extrinsic muscles to anchor firmly to the surrounding bones. The tongue extends much further than it is commonly perceived, past the posterior border of the mouth and into the oropharynx. The upper surface of the tongue (the dorsum) can be divided into two parts: an oral part (approximately the anterior two-thirds of the tongue) and a pharyngeal part (approximately the posterior third of the tongue). The oral part lies mostly in the mouth, but the pharyngeal part faces backward to the oropharynx.

The dorsal mucosal surface of tongue consists of stratified squamous epithelium, with numerous papillae and taste buds. There are four types of papillae: filiform (thread-shaped), fungiform (mushroom-shaped), circumvallate (ringed-circle), and foliate. All papillae except the filiform have taste buds on their surfaces, responsible for various taste and flavour. The movement and shaping of the tongue are controlled by both the extrinsic and intrinsic muscles. The four paired extrinsic muscles are responsible for the reposition of the tongue, with the *genioglossus* responsible for tongue protruding, the *hyoglossus* responsible for tongue depressing, *styloglossus* responsible for tongue elevating and retracting, and the *pallatoglossus*

responsible for elevating the back of the tongue and depressing the soft palate. The intrinsic muscles are arranged along the length of the tongue and are in control of the lengthening and shortening of the tongue, the curling and uncurling of its apex and edges, and the flattening and rounding of its surface. There are also four paired intrinsic muscles: the *superior longitudinal muscle* along the superior surface of the tongue under the mucous membrane; the *inferior longitudinal muscle* along the sides of the tongue; the *verticalis muscle* in the middle of the tongue, extending between the upper and lower surfaces of the tongue; and the *transversus muscle* originates from the lingual septum, a sickle-shaped flat plate of dense connective tissue in the midline of the tongue, and run laterally toward the both side of the tongue (see Fig. 5). These intrinsic muscle fibres array orderly into three planes of space (longitudinal, transverse, and vertical) and are interlaced. Like extrinsic muscles, actions of intrinsic muscles change the contour of the tongue and contribute the great versatility of its postures and movements. Contraction of all fibres increases internal pressure making the tongue rigid. Contraction of transverse and vertical fibres with controlled release of longitudinal fibres elongates and slims the tongue to promote protrusion. Contraction of longitudinal fibres with controlled release of transverse and vertical fibres shortens and thickens the tongue resulting in retraction (DuBrul, 1988, Chapter 6).

During oral processing, the position and movement of the tongue is highly coordinated with the activities of both intrinsic and extrinsic muscles through the linked control of the motor nerves (Miles, 2004, Chapter 8). Kayalioglu, Shcherbatyy, Seifi, and Liu (2007) examined the roles of intrinsic and extrinsic tongue muscles of pigs and found that the majority of activities in the intrinsic and extrinsic tongue muscles occurred during jaw opening and the occlusal phases of chewing. It was also observed that the activities of the extrinsic *genioglossus* and the intrinsic *inferior longitudinalis* played a major role during ingestion. Kakizaki, Uchida, Yamamura, and Yamada (2002) monitored the EMG activities of *digastric* muscle as the jaw-opening muscle, the *masseter* as the jaw-closing muscle, the *genioglossue* as the tongue protruding muscle, and the *styloglossue* as the tongue retracting muscle and found that the *digastric* and *genioglossus* muscles were very active in the jaw-opening phase, while *masseter* and *styloglossus* muscles overtook the activity in jaw-closing phase. This indicates highly coordinated oral operations: the coordination between jaw opening and tongue protrusion and the coordination between jaw closing and tongue retraction.

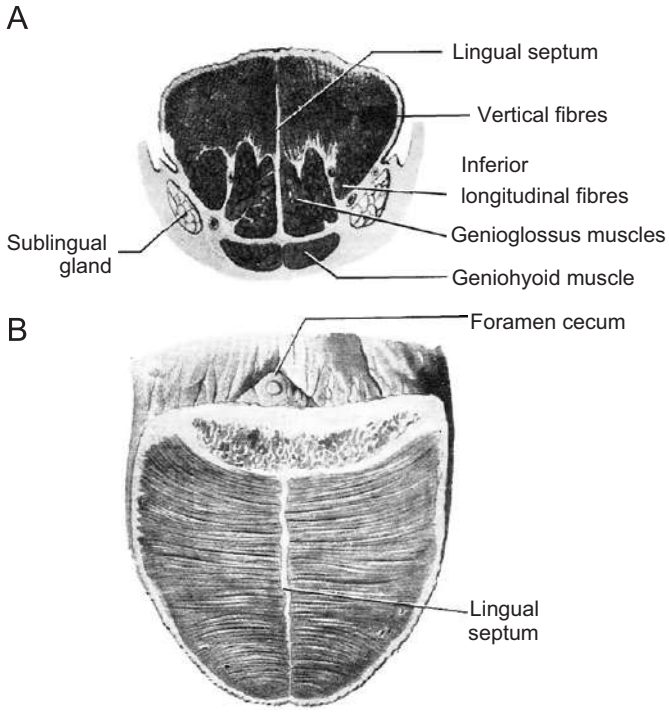

Fig. 5. The tongue: (A) cross section through the tongue; (B) horizontal section through the body of tongue: lingual septum and transverse fibres of tongue (from DuBrul, 1988).

2.4. Saliva

The presence of saliva is essential in the consumption of foods. However, the interaction of saliva with the food presents a great challenge to food scientists in establishing correlations between the physical and microstructural properties of a food and human's sensory perception of its texture. Saliva is a complex heterogeneous clear fluid consisting of roughly 98% water and 2% organic and inorganic substances, including electrolytes, mucus, glycoproteins, proteins, antibacterial compounds, enzymes, and others (Levine et al., 1987). The natural pH of saliva is fairly neutral ranging between 5.6 and 7.6 for healthy individuals, with an average of 6.75 (Jenkins, 1978). The pH of saliva could also vary from time to time during a single day to a same person (Van der Reijden, Veerman, & Nieuw Amerongen, 1994).

The majority of oral saliva originates from the three pairs of major salivary exocrine glands: the paired parotid gland (located opposite the maxillary first molars), the sublingual gland (located in the central part of oral floor), and the submandibular gland (located in the front and both sides of oral floor) (see Fig. 6). Other sources responsible for the production of saliva are the gingival crevicular sulci (area between tooth and marginal-free gingival), an estimated number of 450–750 minor accessory salivary glands (or the Ebner's glands, situated on the tongue), the buccal mucosae and the palate, and oro-nasopharyngeal secretions, etc. (Aps & Martens, 2005). Major salivary glands contribute 90% of saliva production, with the remaining 10% coming from minor glands (see Table 2) (Humphrey & Williamson, 2001). However, the capability of salivary glands varies significantly under different stimulations. For example, the parotid glands almost cease functioning during sleep, but become very active once stimulated, contributing to 58% under a mechanical

stimulation and to 45% under an acidic stimulation (see Table 3) (Aps & Martens, 2005).

The mean rate of unstimulated saliva flow was 0.43 ml/min (or 26 ml/h) with a range between 0.042 and 1.83 ml/min (or 2.5 and 110 ml/h), but when stimulated, the rate increased to between 0.77 and 4.15 ml/min (46 and 249 ml/h) (Jenkins, 1978). After studying a total of 266 healthy adult subjects, Engelen, Fontijn-Tekamp, and van der Bilt (2005) found a mean rate of 0.45 ± 0.25 ml/min for unstimulated saliva flow and 1.25 ± 0.67 ml/min for stimulated saliva flow, agreeing well with the results from Jenkins' study. Engelen et al. also investigated the saliva flow rate at different times during a day (between 8:30am and 2:30pm) and found that the unstimulated saliva flow rate remained little changed throughout the day, but the stimulated saliva flow had the highest rate during the early morning and at around noon time (Engelen et al., 2005). It is not sure yet whether different flow rates of saliva affects our capability in perceiving food texture, but it is true that people do prefer eating different types of foods throughout the day.

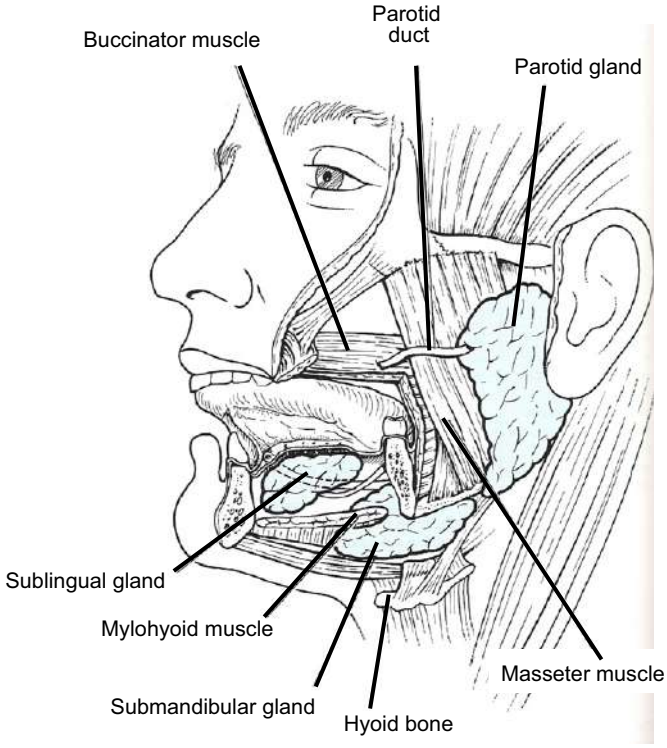

Fig. 6. A diagram showing the location of major salivary glands (from Ferguson, 1999).

Size of salivary glands was believed to be the main reason for the varying capability of saliva production. Ono et al. (2006) used magnetic resonance image to measure gland size of young adults and found that a larger gland size correlated with a higher rate of saliva flow for both parotid and submandibular glands. Age, health status, and the use of drug also have significant influences on saliva production. It was found that elderly people have significantly reduced and altered salivary secretion (Dodds, Johnson, & Yeh, 2005; Nagler & Hershkovich, 2005a, 2005b). People in their 70s have on average a flow rate almost half of that of the population in their 30s (Dodds et al., 2005).

Saliva plays a vital role in food oral processing and in maintaining oral health. Saliva has the following physical functionalities and biological benefits: maintaining tooth integrity, providing antibacterial activity, helping lubrication and protection, food buffering, and enhancing taste and digestion (Humphrey & Williamson, 2001). As a seromucous coating, saliva lubricates and protects oral tissues, acting as a barrier against irritants. The lubricating effect of human saliva can be seen from a recent work (Bongaerts, Rossetti, & Stokes, 2007), where the boundary friction coefficient of human saliva ($\mu \approx 0.02$) was found to be two orders of magnitude lower than that obtained for water. It is this lubrication effect which smoothens food movement inside the mouth and minimizes any irritation to

Table 2
Summary of salivary gland features (produced from Humphrey & Williamson)

Salivary	Location	Secretion	Contribution to salivary volume
Parotid gland	Near the ear	Serous	20%
Submandibular gland	Ramus of the mandible	Mixed, mostly mucous	65%
Sublingual gland	Underneath the tongue		7–8%
Ebner's glands	Surrounding circumvallate papillae	Serous	<10%
Minor glands	Tongue, cheeks, lips, and palate	Mucous	

Table 3
Mean contribution of different salivary glands to the total salivary production under different stimulation (from Aps & Martens, 2005)

Salivary glands	Sleep (%)	No stimulation (%)	Mechanical stimulation (%)	Citric acid stimulation (%)
Parotid glands	0	21	58	45
Submandibular gland	72	70	33	45
Sublingual gland	14	2	2	2
Minor glands	14	7	7	8

soft oral tissues. The main functional constituents responsible for oral lubrication are the mucins, large extracellular glycoproteins with molecular weights range from 0.5 to 20 MDa. Mucins are highly glycosylated, consisting of around 80% carbohydrates primarily *N*-acetylgalactosamine, *N*-acetylglucosamine, fucose, galactose, and sialic acid and traces of mannose and sulphate. The protein core makes up the remaining 20% of the molecular mass and is arranged into distinct regions (Bansil & Turner, 2006). Mucin imparts a slimy mucus character to the saliva, thus assisting in the lubrication of food particles against oral surfaces (Bourne, 2002). Prinz, de Wijk, and Huntjens (2007) showed that this lubrication effect became more efficient at higher surface speeds and under an increased surface load (Fig. 7), possibly due to the shear thinning effect of the saliva (Prinz & Lucas, 2000). It is also recommended that oral friction is based on a combined mechanism of boundary friction and hydrodynamic friction (Prinz et al., 2007).

Saliva will response to food intake and provides buffering effect. It was indicated that the pH of saliva rises during the first 5 min after the intake of most foods and falls to its minimum of around 6.1 (or lower), approximately 15 min after food consumption. Afterwards, the pH of plaque gradually returns to its resting pH between 6 and 7. The pH variation during and after food consumption is believed to give protection to oral tissues and in particular to teeth (Humphrey & Williamson, 2001).

Saliva could also interact with food components, leading to structure formation or structure breakdown. It has been shown that saliva lead to a depletion flocculation of neutral or weakly negatively charged emulsion droplets (Silletti, Vingerhoeds, Norde, & van Aken, 2007) and thus gives emulsion an enhanced sensory feeling. The presence of amylase, a major component of parotid saliva, plays an important role in an early breakdown of starch components. The interaction of amylase enzyme with starch ingredients produces almost an immediate effect on hydrolysis, and thus making the food much easily mixable and digestible in the stomach. Hoebler, Devaux, Karinthi, Belleville, and Barry, (2000) and Hoebler, Karinthi et al. (1998) found that during a short period of oral processing, about 50% of bread and 25% of pasta starch was hydrolysed and transformed into smaller molecules. They concluded that the starch hydrolysis began in the mouth and the different rate of starch hydrolysis was caused by the structural differences of the solid foods. Such observation was further confirmed by an in vitro investigation. It was found that, in less than 10 s of mixing with the saliva, custard showed almost a ten-fold decrease of its viscosity (Janssen, Terpstra, de Wijk, & Prinz, 2007; Prinz, de Wijk, & Huntjens, 2007; Prinz, Janssen, & de Wijk, 2007). It should be noted that the α-amylase is most active at its optimum pH of 7.4. So, it works to full function inside the mouth, but becomes inactivated in the stomach because of the gastric acid. It is also worth to note that, even though enzyme interaction begins almost immediately after food ingestion, its contribution to starch full breakdown is relatively insignificant. Most of starch digestion results from pancreatic amylase, rather than from salivary amylase.

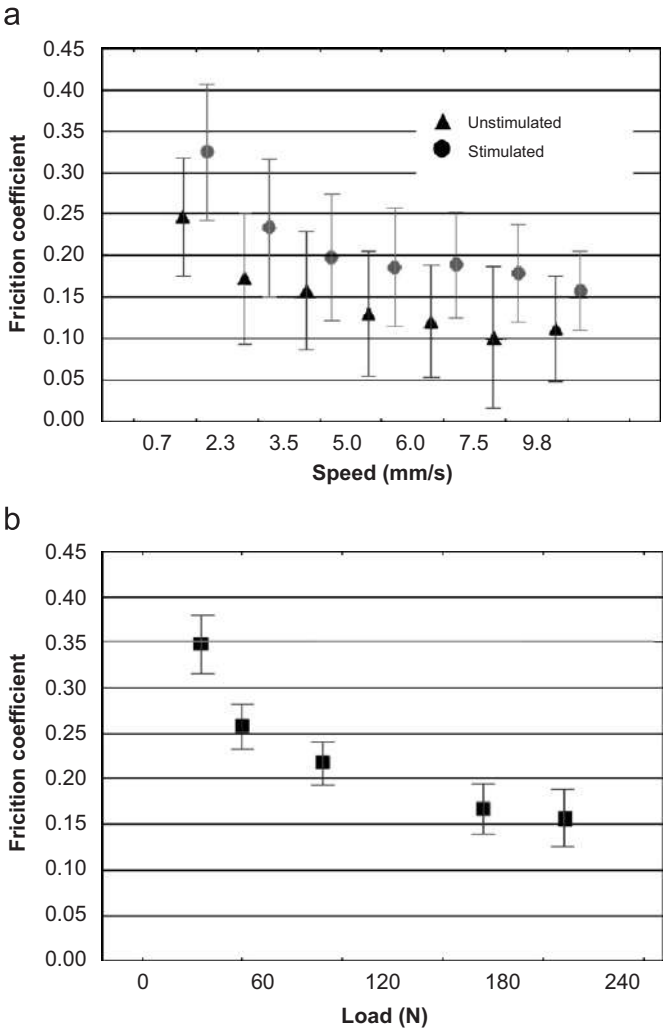

Fig. 7. Kinetic friction coefficient of human oral mucosa as a function of (a) surface speed and (b) surface load. The experiments were conducted between pig's tongue and pig's oesophagus (from Prinz, de Wijk et al., 2007; Prinz, Janssen et al., 2007).

3. Food oral management

3.1. Strategy of food oral management

Food management during oral processing, starting from the first bite till after swallowing or clearing, is to ensure that food is transformed from its initial shape and size to a form comfortable to swallow (a bolus) and to ensure a full appreciation of texture and flavour during this process. Food oral processing involves a series of decision makings and oral operations and it is critically important that these procedures occur in right sequence and are well coordinated. A number of models have been developed to

describe the sequences of oral operations and the strategy of food oral management. Lucas et al. (2002) proposed a simple model to describe the experience of a food inside the mouth, including grip, first bite, fracture, size reduction, transportation, and swallow (see Fig. 8), using different symbols to differentiate decision makings and oral operations. The first decision needs to be made is whether or not a fracture is needed. For example, for a liquid food (or drink), it will be transported straightforward without size reduction. During size reduction, decision also needs to be made on whether to continue chewing or to transport the food particles for swallowing. Hiiemae (2004) proposed a sequence of oral operations and defined specific steps of size reduction and two stages of transportation: from front teeth to molar teeth for size reduction (stage I transportation); and from molar teeth to the back of oral cavity for bolus formation (stage II transportation). There is no major difference between the two models, even though the one proposed by Lucas et al. (2002) appeared relatively simpler and easy-to-read.

The concept of a two-stage transportation is very helpful in describing food movement inside the mouth, even though it may not necessarily be true to the exact details. The first stage transportation is the transfer of food from the grip or first bite to the position of side teeth (molars or cuspids) so that size reduction can be made to the food. During this process, food particle size, textural features, the lubrication, the flavour and taste will be sensed. If food is perceived as noxious, it will be expectorated at this stage. Once food particles are reduced to a size comfortable to swallow, they will be moved selectively to the back of the oral cavity to form a bolus. This movement is called as the second stage transportation. Although we lack visualization of what goes on inside the mouth, the monitoring of jaw movement in three dimensions using a sirognathograph technique gave a strong support to these models (Hiiemae, 2004). As shown in Fig. 9, sequences of an eating cycle can be clearly identified, from first bite to swallowing and oral clearance. The jaw movement appears to be fairly regular in all three axes over the most part of the eating cycle, but becomes irregular during the stage of swallowing and oral clearance. Even though stage I transportation can be clearly identified from the sirognathograph signals, stage II transportation appears to be less evident. It is believed that the second stage transportation of food particles occurs simultaneously with chewing process and probably with the particle selection process (see Section 4.3).

An earlier research based on self-tracking of food particle inside mouth gave a visual illustration of what happens to the food during an eating cycle. Lee and Camps (1991) fed subjects with fluid and semi-solid foods and asked them to self-track the position of the food by clicking the mouse on a computer screen where a two-dimensional oral image (lower jaw) was shown. They showed that liquid foods went straight to the back of the mouth with no involvement of teeth. The stop-over time inside oral cavity increases with the viscosity increase of fluid foods. For

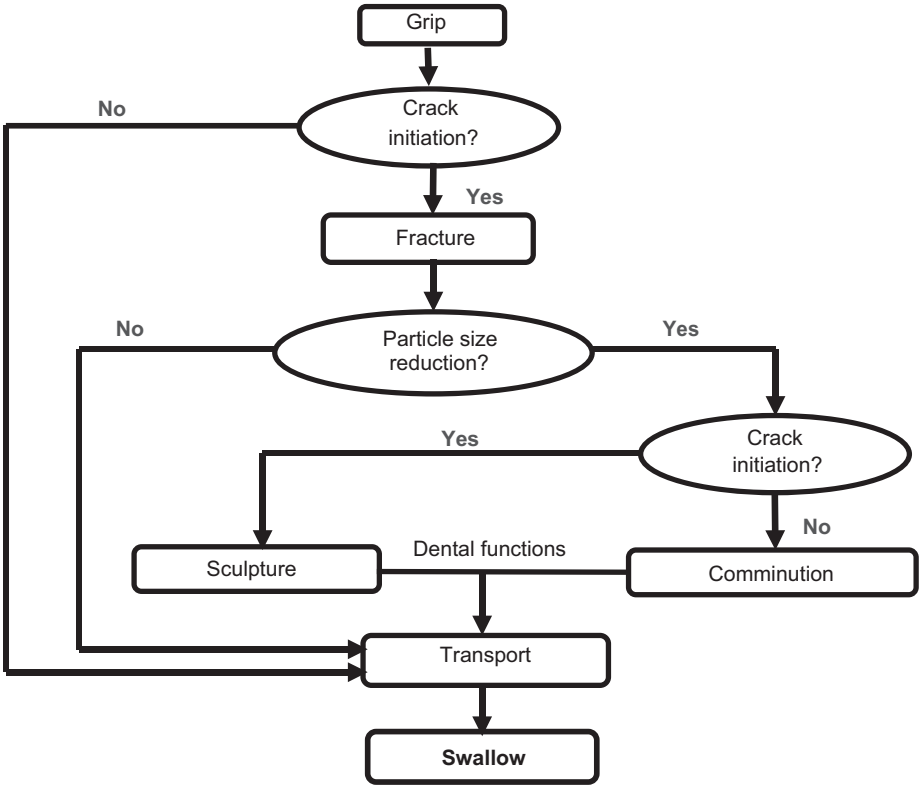

Fig. 8. Strategy of food oral management. Decision-making boxes are shown as oval while process boxes are rectangular (from Lucas et al., 2002).

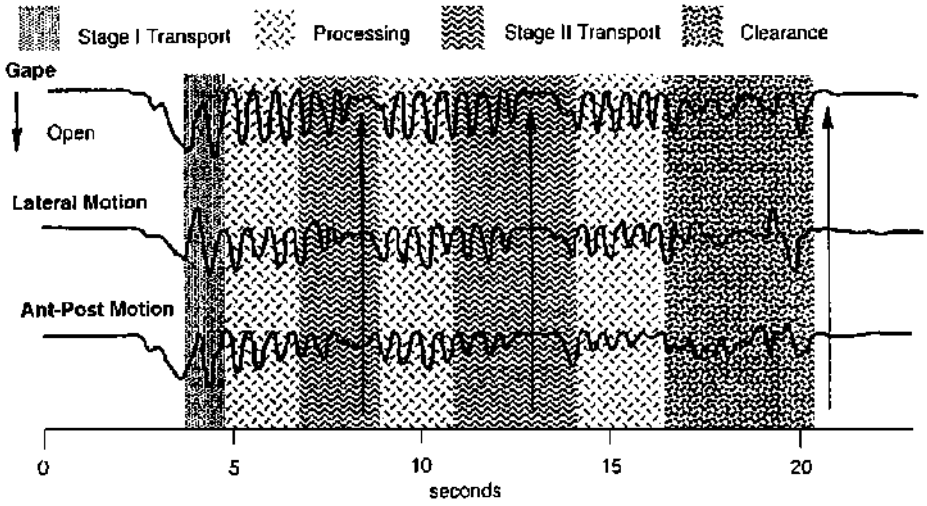

Fig. 9. Sirognathograph record of a normal human subject eating an unpeeled apple. A small magnet was attached to the teeth to monitor the jaw movement in three dimensions (top: vertical movement; middle: lateral movement; bottom: antero-posterior movement). Arrows highlight the main sequences of this eating cycle (reproduced from Hiiemae, 2004).

example, water only rests for around 1 s before being swallowed, but it takes 3 s before honey being swallowed. For solid foods, a substantial number of food movements were tracked between the molar teeth (Lee & Camps, 1991).

3.2. Food oral management and the tongue

Tongue plays a crucial role throughout the whole process of food oral management. It not only works as a major sensory organ to sense the temperature, to taste the flavour, and to perceive the texture, but, more importantly, works as a mechanical device for food manipulation and discrimination (Heath, 2002). The position and shape of the tongue has to change continuously throughout the whole eating cycle. Okada et al. (2007) used videofluorography technique to assess tongue movement during food intake and observed that the tongue moved forwards and backwards to introduce food into the mouth, to compress the food against the hard palate, and to transport food to the occlusal surface of the molar teeth. They believed that the tongue manipulation played an important role in recognizing and evaluating the volume of bite, and that the tongue's intra-oral compression of food had a role in the recognition of food texture. Some researchers even suggested that tongue began its positioning and movement even well before the food intake (Gisel, 1988).

Prinz and Lucas (2000) showed that tongue has a superb capability in positioning and aligning food. Using marked wax wafers of various geometries, they found that for foods which have longer axis, the tongue consistently positioned it with that longer axis in the line of teeth. The reasons for this alignment may be because of oral comfort or efficient fracturing of the food. Two other primary oral operations involving the tongue were rolling and folding (Prinz & Heath, 2000). The former rotates the food about its long axis mainly from tongue movement, while the latter fold the food along its long axis mostly due to teeth action. This is particularly true when some gum-type foods are consumed. Imai, Tanaka, Tatsuta, and Kawazoe (1995) used ultrasonic technique to monitor tongue's vertical movement of 6 young males during mastication of 7 different foods (rice, crackers, boiled fish paste, pickled radishes, pudding, and bananas) and found that the tongue turned the food, mixed it with saliva, sorted out unsuitable particles and aided in bolus formation. They concluded two phases of tongue vertical motions: sorting and bolus formation.

It is believed that the behaviour of the tongue in relation to jaw movement is essentially the same for all mammals. The tongue cycles as the jaw opens and closes. As the jaw opens, the tongue surface continues to travel forwards, but also downwards. During mouth closing, the tongue surface rises upwards and travels backward, reaching its maximum up position during the intercuspal phase (when the upper and lower teeth are in close proximity) and pausing (Palmer, Hiiemae, & Lui, 1997). Throughout the cycle, food would be chewed, moved, and transported inside the mouth, as well as been sensed and perceived for its texture and flavour.

In monitoring tongue's antero-posterior movement of 9 young subjects consuming 7 g cubic-shaped foods (banana, biscuit, tender, and tough meat), Mioche et al. (2002) observed that the food was initially ingested in the midline and then positioned on to the occlusal plane of one side by a combination of pushing, tilting, and twisting movement of the tongue. During chewing, food was kept on the occlusal surface by a combination of rhythmic tongue-pushing moving the food buccally (41% of cycles), and cheek-pushing returning it in the lingual direction (28% of cycles). It is probably this reciprocating movement ensures that different parts of the food are subjected to occlusal force in successive cycles. It must be stressed that the tongue movement depends highly on the textural nature of

the food. Thexton (1992) showed that the antero-posterior movements were much greater in cases of soft foods, where transportation is more important than the mastication.

4. Oral processing and food rheology

Oral processing is both a physiological process controlled by central nerve system and a physical process modulated by mechanical and geometrical properties of the food. Scientists have the habit of grouping influencing factors into intrinsic and extrinsic. Readers are reminded to be cautious in using these two terms. Physiologists prefer to treat physiological factors as the intrinsic ones and food properties as the extrinsic, while food scientists may think in the opposite way. In order to avoid confusion, physiological factors and physical factors are used for discussion in this paper. The former explains eating variation between human individuals as affected by age, gender, dental and health status, etc., while the latter exams the variation as affected by the properties of the food (Woda, Foster, Mishellany, & Peyron, 2006a).

4.1. The first bite

First bite is normally seen as the starting of an oral (masticatory) process. It is usually a one-biting process, but the sensory perception received from the first bite covers a wide range of textural features, including hardness, springiness, cohesiveness, etc. Based on the pattern of mandible movement, a first bite can be roughly divided into three distinct phases named as opening, fast closing, and slow closing (Schwartz, Enomoto, Valiquette, & Lund, 1989).

The force applied during the first bite is food-related, dependent highly on the mechanical and geometrical nature of the food. The huge influence of mechanical properties of foods on the applied biting force was clearly demonstrated by a well-designed experiment by Mioche and Peyron (1995), who measured biting forces for various pellet-shaped model samples with the help of an intra-oral load cell (Fig. 10). They found that an elastic food produced almost a symmetric biting force, increasing to a maximum and returning back to zero while the product survived and gave no fracture. The length of each bite took around 0.8 s (Fig. 10a). A food of such would be probably the most texturally boring and hard for chewing. For a plastic material, the biting force increased to a yield point when the material started to flow till finally breaking up. One bite of a plastic material took much longer time (up to 1.8 s) (Fig. 10b). For brittle products, the biting cycle was the shortest (less than half-second). The increase of biting force was sharp and its decrease was also abrupt (Fig. 10c and d). Similar biting behaviour has also been observed recently by Duizer and Winger (2006) using an intra-oral measurement system. From these studies, it is clear that both the mechanical nature (elastic or plastic) and the mechanical strength (the yield stress) of a food have a huge influence on the biting pattern and biting length.

The food geometry also affects greatly on our biting behaviour. Peyron, Maskawi, Woda, Tanguay, and Lund (1997) found that human's perception of food hardness from the first bite increased with the increase of sample thickness. Kohyama, Hatakeyama, Dan, and Sasaki (2005) used a multiple-point sheet sensor to measure the real-time biting force and contact area, and calculated the biting

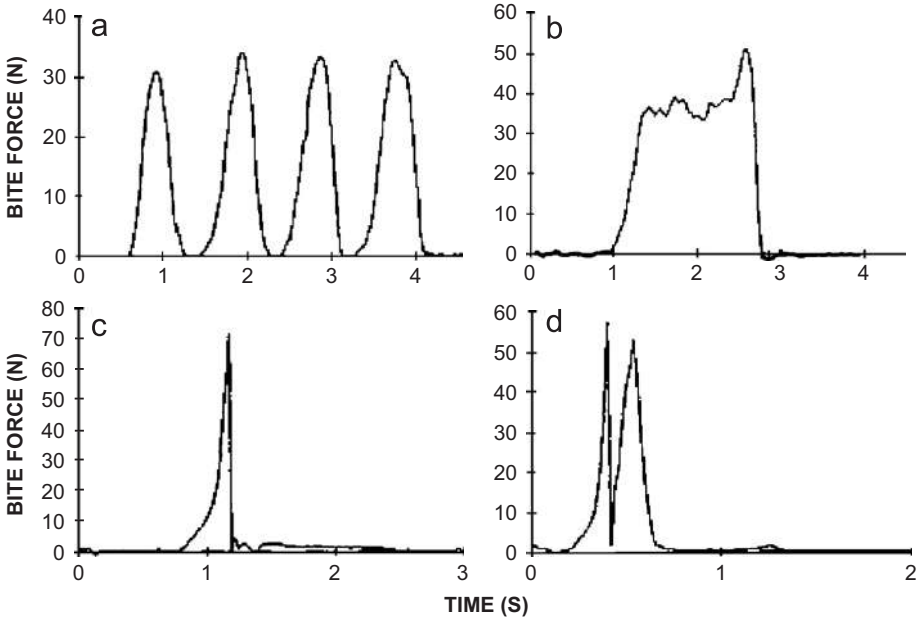

Fig. 10. Recorded biting force for pellet-shaped model products: (a) elastic products; (b) plastic products; (c and d) brittle products (from Mioche & Peyron, 1995).

stress based on the applied force and the contact area. They found that for hard and brittle foods (carrots), the peak force, contact area and peak stress at the fracture point were greater in thicker samples. For soft and tough foods (fish gels), the peak force and contact area increased as the thickness increases, while the maximum stress remained similar. However, Agrawal and Lucas (2003) believed that the effect of food geometry on the first bite was work-related rather than the magnitude of the force. They proposed that a thicker sample meant a larger cross-section area and, therefore, require higher fracture energy. Since force and work are two parameters with very different physical meanings, the above conclusions seem contradictory to each other. Furthermore, it is not clear yet whether human's sensory perception of hardness is based on the applied force or on the amount of work, or even on the power (the amount of work per unit of time). Such knowledge will be vital if we want to correlate the first bite with the sensory perception.

The biting force is believed to consist of two components: an anticipating one and a peripherally induced one. Using an EMG technique to monitor jaw movement and muscle activity, van der Bilt, Engelen, Pereira, van der Glas, and Abbink (2006) showed that the anticipating component started well before the onset of the food, followed immediately (23 ms after the onset of food) by the peripherally induced biting force. They further showed that around 85% of muscle activity needed to overcome the load is peripherally induced, a clear indication of mainly sensory-originated muscle activity and the critical importance of the material property to the oral processing. However, it was noticed that increased eating speed led to a decreased contribution of peripherally induced muscle activity (van der Bilt et al., 2006).

The speed of biting is another important feature of the first bite. The main controlling factors for the biting speed are the mechanical properties of foods and the physiology of individuals. Mioche and Peyron (1995) indicated that biting speed was highly dependent on the mechanical nature of food, in particular on the deformability, the flowability, and the fracture-ability of the food. However, Meullenet, Finney, and Gaud (2002) found that the biting speed could have a much larger variation among individual subjects than that among foods. Using commercial cheese products, they recorded a variation of biting speed from as low as 16.6 mm/s to as high as 39.0 mm/s from 7 subjects. But, surprisingly, the correlation between the biting speed and the sensory hardness of the food appeared to be insignificant (Meullenet et al., 2002).

It is not yet clear how a bite is terminated. In particular, how to avoid a collision between teeth when there is a sudden decrease of resistance, e.g. the fracture of a brittle food. ''Unloading reflex'' was believed to be a possible mechanism for a fast deceleration in such cases (Bosman, van der Bilt, Abbink, & van der Glas, 2004), even though the real meaning of the ''unloading reflex'' still remains a bit vague.

4.2. Chewing and mastication

Chewing or mastication after the first bite is the major oral operation for the consumption of solid and semi-solid foods. The need of chewing can be seen in two aspects: to fragment food particles small enough so that they are well mixed and properly lubricated by the saliva to form a coherent bolus that can be swallowed safely and comfortably (Alexander, 1998; Prinz & Lucas, 1995); and to have an enhanced release of flavour and aroma from food structure. Therefore, chewing and mastication is not only a process of texture appreciation but also a process of full appreciation of flavour and taste.

It has been noticed that the length of chewing and the number of chewing cycles vary hugely from food to food (as well as among individuals) and it is believed that the rheology of the food is the key influencing factor. A sirognathograph recording of a subject eating apple, banana and cookie showed significantly different number of chewing cycles (Hiiemae et al., 1996). For example, a mouthful apple took 7 chewing cycles to form the first bolus to swallow, while it took 16 and 19 chewing cycles to form a bolus to swallow a mouthful banana and cookie. It was found that the vertical movement of the jaw decreased gradually with the chewing process, probably due to the gradual decrease of food particle size (Fig. 9), even though the speed of chewing (seen as the time length for each chewing cycle) was very similar for the same subject eating different foods (Hiiemae et al., 1996).

The importance of food rheology on chewing behaviour has also been convincingly demonstrated by Engelen et al. (2005). They measured chewing cycles for a number of food products for which they have also determined the mechanical properties (the yield stress). By re-plotting the number of chewing cycles against the yield stress (Fig. 2 and Table 1 in Engelen et al., 2005), we obtain a perfect linear relationship between the two parameters (Fig. 11). An important conclusion from this graph is that a harder food would generally require more chewing cycles. This agrees well with the observation by Wilson and Brown (1997), who investigated the chewing of model gelatine gels. Similar conclusion was also made by Fontijn-Tekamp, van der Bilt, Abbink, and Bosman (2004) in observing the chewing behaviour of 87 subjects eating cheese, carrot, and peanuts. Engelen et al. (2005) even suggested that the oral physiology parameters (including saliva flow rate, saliva amylase content, the maximum biting force, and masticatory performance) explained less than 10% of the variance in swallowing threshold (or the number of chewing). The dominant factor for the variation of oral processing is the rheology of food.

Effects of food rheology on chewing behaviour seem to be more than just the number of chewing cycles. Using gelatine-made model food systems, Peyron, Blanc, Lund, and Woda (2004) and Peyron, Lassauzay, and Woda (2002) found that increased food hardness not only led to a higher number of chewing cycles, but also led to a higher

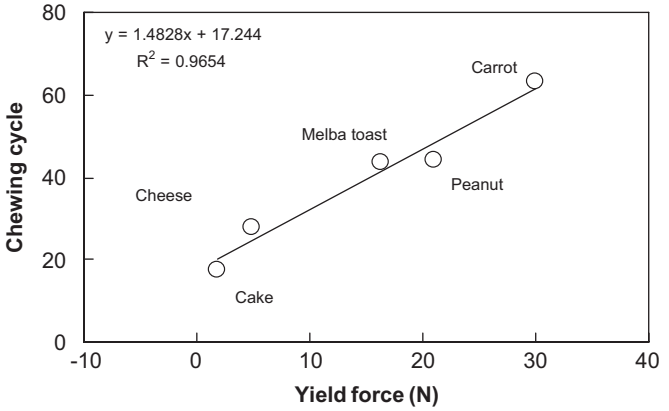

Fig. 11. Correlations between the mechanical properties of the food and the number of chewing cycles. A fixed volume (10 cm^3) of melba toast, cake, peanuts, and cheese were fed to 266 health adult subjects (42±12 years old). The graph was plotted based on the data obtained by Engelen et al. (2005).

sum muscle activity per sequence and a higher mean vertical amplitude, with the strongest modification observed during the first 5 strokes. Mioche (2004) also demonstrated a positive correlation between the mechanical strength of foods and the muscle activity during chewing. He went further to confirm that the sensory perceived tenderness of the food (cooked meat) had almost a linear correlation with the muscle activity and, therefore, with the mechanical strength of the food.

Foster, Woda, and Peyron (2006) studied the oral processing of two sets of carefully designed elastic and plastic foods (gelatine gels and caramel confectioneries). They found that for both types of foods, the duration of mastication, the number of chewing cycles, and the muscle activities increased significantly with the increase of food hardness (as quantified by the stress at 50% strain deformation), even though the masticatory frequency (number of chewing cycles per unit of time) showed little dependence. Another important finding from this research is the significant influence of the rheology nature of the food (elastic or plastic) on the chewing pattern. They observed very different vertical and lateral movements of the jaw for elastic and plastic foods of very similar hardness. For the elastic food, the trajectory of jaw movement was highly repeatable, but for the plastic one, a number of irregular movements were observed. It was also noticed that the jaw moved to a much bigger distance in both vertical and lateral directions when a plastic food was chewed (Fig. 12) (Foster et al., 2006). However, it was not clear yet whether these irregular jaw movements were due to major structure breakdown of the food or to some other reasons (e.g. food stickiness).

Although it is known that geometrical properties have big influences on the first bite, it appeared less clear of how they affect chewing and mastication. Kohyama et al. (2005) noticed that the biting force, contact area and the stress of molar teeth were little relevant with the sample thickness for both hard and soft foods. However, in a recent study, Kohyama, Sawada et al. (2007) observed a significant effect of sample size on mastication process. A smaller sample size (of rice cake) meant a shorter mastication time, a fewer chewing cycles, and a lower jaw-closing muscle activity. Miyawaki, Ohkochi, Kawakami, and Sugimura (2001) also showed that the ratio of temporal muscle activity almost coincided with the food height ratio (for cone shaped 10 and 5 g gum jellies). The status of food also influences chewing and mastication. Kohyama, Nakayama et al. (2007) prepared foods (raw carrot, raw cucumber, roast pork, and surimi gels) in 7 g block and fine cut ones with either the same volume or the same weight. They observed that the chewing number, masticatory time, total duration of mastication, and the total muscle activity were not significantly different between fine cut pork and surimi gels and the same weight block sample. However, the mastication efficiency showed significant increase when the same volume of fine cut food is chewed (Kohyama, Nakayama et al., 2007; Kohyama, Sawada et al., 2007).

It is probably not surprising to see such critical influences of food rheology on food oral processing, if considered that mechanical breakdown of food is essentially the core part of oral processing. The details of mechanical breakdown of a food could be rather complex inside the mouth. Taking biscuit as an example, Brown, Eves, Ellision, and Braxton (1998) explained that a biscuit was fractured predominantly by the vertical compression in early chews, but by a shear action over the course of the sequence. Mioche et al. (2002) used videofluorography technique to record the trajectory movement of cheek and tongue and showed that there was around a 10 mm lateral movement and a 20 mm vertical compression within a chewing cycle (Fig. 5, Mioche et al., 2002), a clear indication of the shear deformation. Assuming the food has the thickness of the vertical gap and the chewing cycle takes half-second, one can estimate a unit rate of shear deformation (1 s^{-1}). As a matter of fact, due to the leverage effect, the gap between the molar teeth should be narrower than that between the front teeth; the real strain and strain rate could be much higher than this estimation or close to the lower limit of the shear rate indicated by Shama and Sherman (1973) in their master curve of food oral deformation (Fig. 2).

Although food rheology has the dominant influence on chewing and mastication, there is no question that some physiology factors also make important contributions. One of the most important physiology factors could be the age (Fucile et al., 1998). Peyron et al. (2004) showed that an increase of 1 year of age led to an average increase of 0.3 cycles per eating sequence. Kohyama, Mioche, and Martin (2002) found that for whatever type of food, elderly people produced a lower muscle activity per chew than young subjects. The decreased masticatory performance of aged population was attributed to both ageing and decreasing number of functional pairs of post-canine teeth. Interestingly, there was no significant difference between young and elderly populations in the total amount of muscle

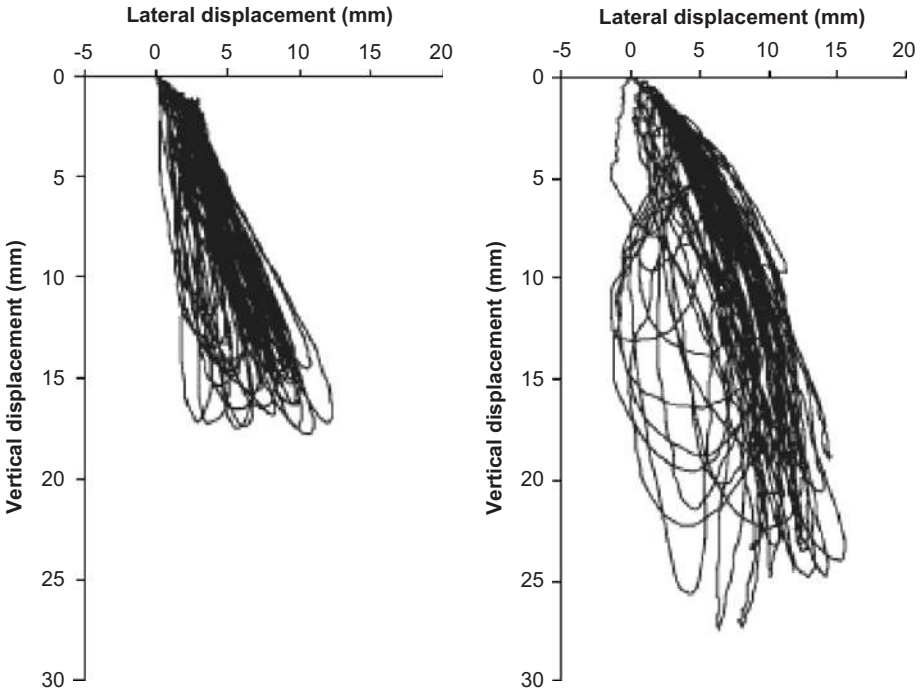

Fig. 12. Recorded jaw movement from the same subject consuming elastic (gelatine gel) (left) and plastic (caramel confectionery) (right) of very similar hardness (from Foster et al., 2006).

activities applied for food mastication (Kohyama, Mioche, & Bourdiol, 2003), suggesting that same amount of work is needed to transform the food from its initial form to a cohesive bolus, regardless of subjects' age.

Dental status is another physiology factor affecting the mastication performance. It was observed that chewing of denture wearers was less adapted to the texture of food (Veyrune & Mioche, 2000). Karkazis (2002) showed that denture wearers had more regular chewing patterns (indicating less adaptation to food structure change) and had to apply higher masseter muscle activities to provide improved chewing function. Yven, Bonnet, Cormier, Monier, and Mioche (2006) found that the chewing pattern of denture wearers was strongly impaired and not adapted to the structure changes of food during bolus formation. Denture wearers swallowed less fragmented boluses than dentate subjects, even though boluses from both groups of subjects had a similar level of moisture. Neuromotor deficiencies were believed to be the reason for the impaired mastication of denture wearers (Woda, Mishellany, & Peyron, 2006b).

Effects of physiology factors and physical factors on the mastication have also been summarized by Woda et al. (2006a, Table 1), where muscle activities and jaw movements were shown as a function of food hardness, elasticity, and size and as influenced by subject age, gender, and dental status.

4.3. Oral selection

Oral selection is a critically important oral operation in the processing of solid and semi-solid foods. It is to make sure that large particles are chosen for further size reduction while small-enough particles are moved to the back of oral cavity for bolus formation. Food oral selection was not identified as an independent oral operation in both oral management models proposed by Lucas et al. (2002) and Hiiemae (2004) (see Section 3.1). This may be because that oral selection occurs simultaneously with chewing and mastication and is seen by many as a part of size reduction operation.

The exact mechanisms and criteria of oral selection of food particles have not been properly explained in literature, but our experience tells us that the tongue movement plays a critical role in this selection process. It is believed that the tongue senses the size and lubrication status of food particles. Chewed food particles of right size are pushed by the elevated tongue to the back of the oral cavity (Mioche et al., 2002; Okada et al., 2007), while large particles are selected for further size reduction. From physiological point of view, it is the combined action of pushing, pulling, and/or twisting by the tongue that transports the food particle, either to push it back to molar teeth surface for size reduction or to pull it to the back of oral cavity for bolus formation.

The physical principle of food oral selection seems to be rather simple. Lucas et al. (2002) proposed a model using a selection function (S) to represent the chance of a particle being contacted by the teeth. It was demonstrated that, for any given mouthful of a particular food, the selection function showed a power relationship with the food particle size: $S(x) = f(x^2)$ (Lucas & Luke, 1983; van der Glas, van der Bilt, Olthoff, & Bosman, 1987) (see Fig. 13).

This model seemed to agree in general with an earlier investigation by van der Glas et al. (1987), who used coloured model food particles (of sizes between 1.2 and 8.0 mm) to monitor size reduction during mastication process. Because of its colour, each particle can be traced back to its parent particle. Although a larger particle was much more likely to be picked up for size reduction as predicated by the above power law model, it is interesting to see that the degree of fragmentation reached maximal when a particle had a size of about 4 mm.

The model proposed by Lucas et al. (2002) is generally accepted because of its simplicity, but its applicability to oral processing is still questionable. This is because: (1) the model interprets food particle selection almost as a random nature, which is highly unlikely in real case and (2) the model does not explain how the shape and geometric nature of the particle affect the oral selection.

4.4. The rheology of food breakdown

Huge efforts have been made in the past few decades in trying to reveal the rheological nature of food breakdown during oral processing and to establish possible correlations between rheological properties of a food and sensory perception. Various progresses in this area can be seen from review articles by Stanley and Taylor (1993) and Bourne (2004).

A most meaningful development on the rheology of food breakdown was probably the concept of breakage function (Lucas & Luke, 1983; Lucas et al., 2002), a quantifiable parameter reflecting the oral performance of a food. The term gives a quantitative characterization of size reduction produced by teeth when a selected particle breaks and provides a useful link between rheological properties of a food and its sensory performance. Breakage function is defined as the fragment distribution of broken particles formed per chew, referred to the size of the parent particle. The determination of breakage function is simple. Ask a subject to chew a food particle once and then sieve the fragments through a mesh size equal to half of the parent particle size. The percentage of the fragments passed through the mesh is taken as the value of the breakage function (Mowlana & Heath, 1993; van der Bilt, van der Glas, Mowlana, & Heath, 1993). The food particle is placed inside a sealed latex bag in order to avoid the interference of saliva (Fig. 14). Fractured particle fragments after the chew can also be optically scanned for the number or the surface area of fragments (Al-Ali, Heath, & Wright, 1999).

A food of high breakage function would mean that it is easy for mastication and requires less chewing. No doubt that two critical factors determine the breakage function: the rheological properties of the food and the dental performance of the subject. Agrawal, Lucas, Prinz, and Bruce (1997) tested the fragmentation of 28 foods from 3 product groups (cheese, raw vegetables, and nuts) and observed linear relationships between the breakage function of foods (expressed as the change in the square root of the specific surface of the particles divided by original particle volume) and combined mechanical properties. They found that the breakage function was either linearly related to the square root of the product of the toughness and the Young's modulus $\left(\sqrt{R \times E}\right)$ or inverse linearly related to the square root of food toughness divided by the square root of Young's modulus $\left(\sqrt{R}/\sqrt{E}\right)$. Lucas et al.

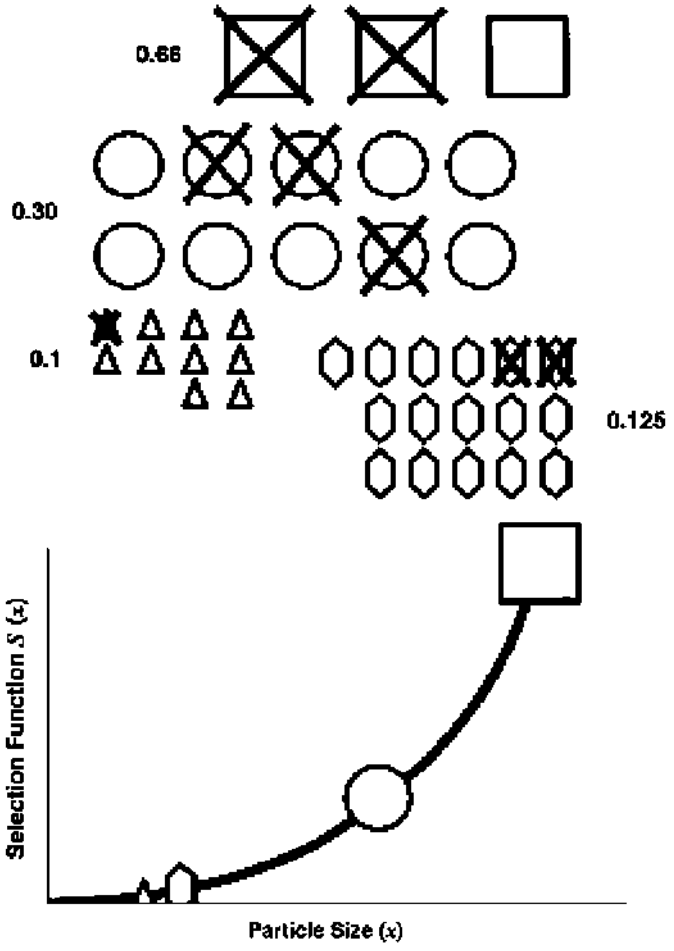

Fig. 13. The chance of a food particle being selected for further size reduction increases with the increase of its particle size (from Lucas et al., 2002).

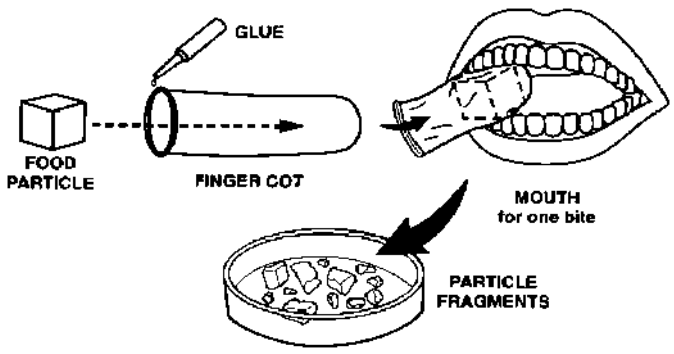

Fig. 14. Method for obtaining the breakage function of a solid food without problems of saliva interference (from Lucas et al., 2002).

(2002) expanded this experiment further to include 38 foods of various types and obtained a master curve for the correlation between the breakage function and $\sqrt{R}/\sqrt{E}$ (Fig. 15). It shows that some hard and brittle foods (e.g. sugar crystals, roasted nuts, etc.) have the highest breakage function (above $0.5\,mm^{1/2}$) but very small values of $\left(\sqrt{R}/\sqrt{E}\right)$ (less than $5\,mm^{1/2}$). A small change in mechanical properties (either R or E) will lead to a significant difference in the fracture behaviour of such foods. Fruits and vegetables have reasonably high values of $\left(\sqrt{R}/\sqrt{E}\right)$ (between 5 and $20\,mm^{1/2}$), with a medium range of breakage function. Some soft foods (cheese, cakes, and breads) have highest $\left(\sqrt{R}/\sqrt{E}\right)$ value (up to $50\,mm^{1/2}$), but smallest breakage function. For such soft and easily deformable foods, the breakage function is very small and their mechanical properties seem to have limited influence on their breaking behaviour. The author tends to believe that the breakage function may serve well to indicate oral performance for hard brittle foods but have very limited use in assessing the textural properties of soft deformable foods. These food materials hardly break, but mostly deform and flow.

Lucas et al. (2002) further suggested that the criteria of oral fragmentation also depended on the geometry of foods. For example, the criterion for thick block foods is the square root of toughness divided by the square root of Young's modulus $\left(\sqrt{R}/\sqrt{E}\right)$. For foods in thin sheets, toughness R is the determining criterion, while for those foods which require high fracture force, the criterion would be the square root of the product of the toughness and the Young's modulus $\left(\sqrt{R\times E}\right)$. This theory was supported by Vincent and Saunders (2002) who used the critical stress intensity factor for objective quantification of food texture. Both Young's modulus, E, and the toughness, R, are common rheological parameters of a material and can be easily determined from standard mechanical and/or rheological tests. While Young's modulus can be measured by the ratio of the stress and deformation strain from a compression test, the toughness is the integration of the stress over the displacement distance, a parameter which quantifies the work done to a fracture process.

Even so, the above analysis has obviously over-simplified the complexity of food breakdown during eating. One main problem is the exclusion of saliva in the determination of breakage function and rheology properties. The method assumes no change to the rheological behaviour of a food, while such an assumption is often not applicable during an eating process. As a matter of fact, the mechanical and rheological properties of a food will change significantly because of the participation of saliva. This is particularly true for foods with an open structure and low moisture content, such as biscuits, cracks, and many others. So far very limited research has been conducted on the moisture intake and its effects on the rheological properties of a food. One relevant work could be the one conducted recently by Pereira, de Wijk, Gaviao, and van der Bilt (2006). They studied the texture perception of a number of solid foods when a controlled volume of tap water was added before chewing. It was observed that added fluid affects both the physiology (muscle activity and the number of chewing cycles) and the sensory perception of textural attributes. It is believed that adding fluid facilitates the chewing of dry foods, even though not much on the chewing of fatty (cheese) and wet products (carrot) (Pereira et al., 2006).

Another problem of the proposed breakage function measurement is the exclusion of enzyme interaction with food components. Janssen et al. (2007) showed that both

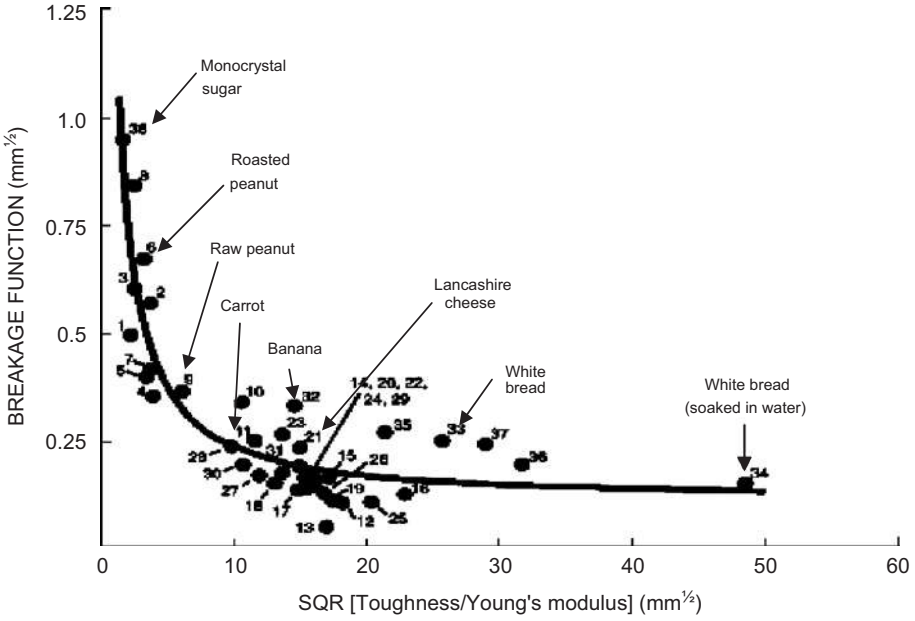

Fig. 15. A master curve showing the correlation between the breakage function and the mechanical properties of foods (from Lucas et al., 2002). The breakage function ($mm^{1/2}$) is plotted against $\left(\sqrt{R}/\sqrt{E}\right)$ ($mm^{1/2}$).

mechanical breakdown and enzymatic breakdown played significant roles in texture perception. It was found that enzymatic breakdown was a dominant mechanism involved in the perception of fattiness, roughness and stickiness of custards. The claimed influences of enzyme participation on food breakdown were also supported by some *in vivo* and *in vitro* investigations (Hoebler, Devaux et al., 2000; Hoebler, Karinthi et al., 1998; Prinz, de Wijk et al., 2007; Prinz, Janssen et al., 2007). de Wijk, Prinz, and Janssen (2006) concluded that starch breakdown by salivary amylase played a significant role in sensory perception of starchy foods. It was recommended that the saliva–food interaction should be incorporated into instrumental measurements, if at all possible.

5. Swallowing

5.1. The three phases of swallowing

Swallowing could be seen as the last stage of oral processing. Using videofluroscopy technique, Okada et al. (2007) concluded that human beings needed at least two swallows, even with one bit of (solid and semi-solid) foods. They suggested that a complete feeding sequence involves interposed swallows (preceded and succeeded by chewing cycles) and an isolated terminal swallow (to clear the food from the oral cavity and pharynx). The duration length of the swallowing may depend on the bolus volume and others. Each swallow consists of three phases: an oral phase, a pharyngeal phase, and an esophageal phase. The oral phase begins with bolus formation and ends as the bolus is passed to the back of the mouth. Both pharyngeal and esophageal phases are entirely reflex processes and last for much shorter time. There is no evidence of texture or flavour perception during the swallowing, even though retronasal aroma stimulation is possible (Buettner et al., 2001). Therefore, it is fair to say that swallowing is largely a process of transporting the processed food from the oral cavity through to the pharynx and the esophagus before finally entering the stomach. While various efforts have been made in understanding swallowing process, it must be admitted that little comes from food scientists. Knowledge on food swallowing mostly comes from physiologists and clinical researchers (Hind, Nicosia, Roecker, Carnes, & Robbins, 2001; Martin & Robbins, 1995; Martin-Harris, Michel, & Castell, 2005).

The oral phase of swallowing involves the moulding of food (particles) and saliva into a bolus and forcing them to the back of oral cavity. The pressure necessary to move the bolus is generated by bringing the teeth into centric occlusion and developing a lip seal. If the tip of the tongue thrusts against the anterior teeth, a pressure of up to 10 kPa can be generated in the midline of the tongue (Ferguson, 1999). The main muscle involved in generating the tongue pressure and in flattening the tongue against the hard palate is the mylohyoid muscle.

The pharyngeal phase, defined as from the triggering of swallowing reflex to the closure of the upper esophageal sphincter, lasts about 0.7 s. During the pharyngeal phase, the transport of saliva or bolus to the distal esophagus mainly depends on an efficient pharyngeal pump (an action caused by pharyngeal contraction) (Dantas, Oliveira, Aprile, Hara, & Sifrim, 2005). The initiation of pharyngeal phase is caused by the stimulation of the posterior part of oral cavity. The pressure in the pharynx rises to 4 kPa, only about two-thirds of the mean pressure previously in the anterior chamber of the mouth (Ferguson, 1999). Once the pharyngeal phase is initiated, both the larynx and the soft palate are simultaneously elevated as a result of muscle contraction. The larynx rises to beneath the epiglottis so that it functions as a passive cap and prevents food entering (Fig. 4), while the elevation of the soft palate seals off from the nasal cavity.

During the esophageal phase, the bolus is transported towards the stomach by the primary and secondary peristalsis (Buettner et al., 2001). The stimulation of the posterior wall of the pharynx causes it to relax and the pressure of the oropharynx helps to move the bolus down into the esophagus where the pressure is lower. A peristaltic wave begins with the sequential contraction of the superior constrictor of the pharynx, followed in turn by the middle and inferior constrictors and then by the striated muscle in the upper third of the esophagus. The esophageal phase takes a few seconds to complete (Ferguson, 1999).

People used to believe that oral and laryngopharynx sensation was essential for normal swallowing. But, after studying the swallow behaviour of 13 healthy subjects before and after the oral cavity, oropharynx, hypopharynx, and larynx being anesthetized by lidocaine, Bastian and Riggs (1999) concluded that this was not the case. It has also been indicated that bolus aggregation and swallowing has nothing to do with the gravity (Palmer, 1998). A healthy person has no problem at all of swallowing even in an upside down position. Swallowing of a food (and drink) is motivated by a mechanical action of the oropharyngeal organ. This is why astronauts have no problem of eating and drinking in the space where gravity is zero.

It is generally accepted that swallowing is a patterned behaviour driven by a Central Pattern Generator (CPG), a central nervous system for rhythmic behaviours (Jean, 2001). This program/pattern of neuromuscular activity is simply "inserted" into an eating cycle. Once the swallowing CPG is triggered, a sequence of patterned events is initiated which involves at least 25 pairs of muscles in the mouth, oropharynx, hypopharynx as well as in the esophagus. Once swallowing is started, it goes to completion (Hiiemae, 2004).

5.2. Bolus formation and the criteria of swallowing

Bourne (2002) defined a food bolus as a mixture of chewed food particles and saliva in the mouth, implying

2 important aspects of bolus formation: size reduction and saliva incorporation. Following this argument, one would think that both the mechanical properties of food (defined as the breakage function) and the rate of saliva flow are important influencing factors, reflecting the physical and physiological nature of bolus formation and swallowing.

One highly regarded theory of food bolus formation was proposed by Prinz and Lucas (1997), incorporating the two simultaneous oral processes (food comminution and lubrication). They recommended that size reduction was crucial for bolus formation. Small particle size makes it possible for the tongue to press against the hard palate and pack them tightly together. At the same time, saliva gradually fills the gaps between food particles and increases their viscous cohesion. Based on their theory, the criteria for swallowing should be the moment when the food bolus reaches the maximum cohesive force (Prinz & Lucas, 1997). This theory was called as optimum swallow model.

The cohesive force, F_C, is a measure of the cohesion strength between food particles and is defined as the difference between the viscous force, F_V, and the adhesion force, F_A. The former is the force required to separate food particles apart and the latter is the force required to separate a food particle from the oral lining due to the primary attraction through surface tension:

$$F_V = 3\pi\eta R^4 \Big/ 64d^2t, \tag{1}$$

$$F_A = 4\pi r\gamma, \tag{2}$$

$$F_C = F_V - F_A, \tag{3}$$

where η is the viscosity of the oral fluid, R the radius of the disc (bolus) of food particles, r the radius of food particles, t the time span over which the separation takes place, d the average distance between particles, and γ the surface tension of oral fluid (Fig. 16). This model predicts that smaller food particles and closer distance between food particles will lead to a higher cohesive force and are beneficial for easy swallowing. An extended chewing could lead to food bolus being flooded by the excessive saliva, which means an increased distance (d) between food particles and a much decreased cohesive force. This will make swallow precarious, a phenomenon most of us could experience. Prinz and Lucas (1997) further tested this model using carrot and Brazil nut and confirmed the existence of the maximum cohesive force for both foods after a certain number of chewing.

Engelen et al. (2005) compared the chewing behaviour of butter-coated toast against non-coated one and found that butter-coating led to a significant decrease in the number of chewing cycles. They believed that lubrication effect of butter was the main reason. Another possibility could be that the surface of butter-coated food particles becomes more hydrophobic and less wet-able by saliva. This may lead to a smaller adhesion force and, therefore, an increased cohesive force for the bolus. Assume the breaking

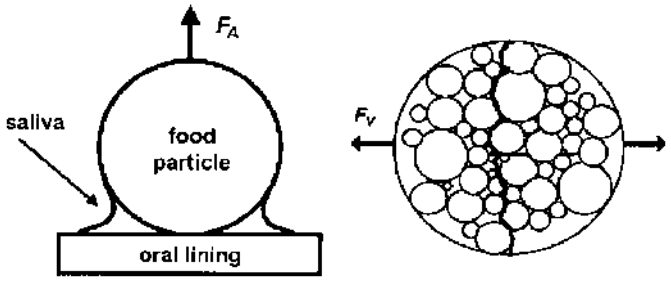

Fig. 16. An illustration of the adhesion force, F_A, acting on a food particle due to surface tension and the viscous force, F_V, on the food bolus (from Lucas et al., 2002).

behaviour remains the same for both butter-coated and non-coated toasts, this observation could be seen as an experimental support to the optimum swallow model.

The principles behind optimum swallow model appear to be rather similar to those of the three dimensions model proposed by Hutchings and Lillford (1988). The main advantage of the optimum swallow model is its single parameter (maximum cohesive force) representing two dimensions in the previous model (the "degree of structure" and the "degree of lubrication"). It indicates that swallowing should take place when food particles of appropriate size are properly wetted and agglomerated by the saliva. However, Hiiemae (2004) indicated that, by assuming that bolus formation takes place in the mouth rather than at the oropharyngeal location, this model might have over-simplified the case.

A group of French scientists made a much simpler approach in assessing the criteria of swallowing and proved that the particle size was the key determining factor. Peyron, Mishellany, and Woda (2004) carefully measured the particle size distribution of food bolus from healthy young adults using sieving and laser diffraction methods and found that there was hardly any inter-individual variability in particle size distributions for the 6 tested foods (3 nuts and 3 vegetables), even though mastication sequences differed markedly between individuals. However, distinct differences in particle size distribution were observed between food samples. Overall, vegetables had much larger particle sizes than nuts. They believed that there was a need for a bolus to be prepared with a precise (pre-determined) texture (or structure) before it could be swallowed. This observation was further confirmed by a separate research in which a much wider range of food products were tested (Mishellany, Woda, Labas, & Peyron, 2006). They used the mean particle size, d_{50} (the particle size at 50% cumulative mass), to characterize food bolus and recorded an increased mean particle size for peanuts, chicken breast, carrots, egg white, and gherkins (0.82, 1.60, 1.90, 2.29, and 3.04 mm, respectively) (Jalabert-Malbos, Mishellany-Dutour, Woda, & Peyron, 2007). These results seem to suggest that the mean particle size of food bolus depends on the mechanical nature of the food, rather small for hard brittle foods (e.g. peanuts) but becoming larger for softer foods. Even though no further explanation was given

about the pre-determined bolus texture (or bolus structure), it is reasonable to believe that the flow behaviour (or the flow-ability) is probably the most important feature.

5.3. Bolus deformation during the swallowing process

So far, there has been limited research on the deformation and flow of food bolus, even though there have been numerous researches on the physiology of bolus flow by medical and clinical researchers (Hughes, Liu, Griffiths, Lawries, & Wiles, 1996; Ku et al., 2007; Logemann, Rademaker, Pauloski, Ohmae, & Kahrilas, 1998; Monte, da Silva-Junior, Braga-Neto, Souza, & de Bruin, 2005; Pauloski et al., 2002). One earlier attempt in understanding bolus deformation was made by Dantas et al. (1990). They observed that a higher viscosity caused a delay of oral and pharyngeal bolus transit and an increased duration of pharyngeal peristaltic waves, prolonged upper esophageal sphincter opening. They concluded that both bolus volume and bolus viscosity significantly affected swallowing behaviour. Similar observation was also made by Takahashi, Nitou, Tayama, Kawano, and Ogoshi (2003). They observed a fast transit speed for soft and easy to swallow semi-liquid foods (easy to move through the pharynx), but a slow transit speed for those hard and difficult to swallow foods (perceived as being difficult to move through the pharynx). These studies suggest that the flow-ability and/or the deformability of a bolus are a dominant factor affecting the perceived easiness of swallowing.

Because of the different geometric nature of oral cavity, pharynx, and esopharynx, one would expect some very different behaviour of bolus flow over the three swallowing phases. Based on the assumption that bolus flow is driven by the squeezing action of the tongue against the palate, Nicosia and Robbins (2001) calculated the bolus flow in the oral cavity using two parallel plates as a simplified mathematical model and demonstrated that the half-time, $t_{1/2}$, the time taken to clear half the bolus from the oral cavity, increased with the increase of viscosity and density and decreased with the increase of applied pressure (by the tongue). This means that the thinner the food bolus and the harder the tongue presses, the faster the bolus ejection from the oral cavity. They predicted a $t_{1/2}$ in the order of a unit.

The velocity spectrum of bolus flow in the pharynx has recently been determined by a group of Japanese scientists using the ultrasonic pulse Doppler method (Hasegawa, Otoguro, Kumagai, & Nakazawa, 2005). They fed subjects with water, yoghurt, and various gels made from gelatine and gellan and found that the velocity of bolus flow was food (viscosity) dependent, with an average of around 0.1 m/s. The maximum velocity reached as high as 0.5 m/s for water and 0.2 m/s for yoghurt. Miquelin, Braga, Dantas, Oliveira, and Baffa (2001) used a biomagnetic method to determine pharyngeal bolus flow. They observed a pharyngeal transit time of 0.75 s for a bolus made with 10 ml yoghurt and 5 g manganese ferrite ($MnFe_2O_4$) (giving a total volume of 11.3 ml). This gives a flow speed of around 0.05 m/s, assuming the pharyngeal cross-section has a diameter of 0.02 m. This speed seems to agree in general with the findings by Hasegawa et al. (2005).

Based on the above findings, one could predict a rather turbulent nature when a mouthful water is swallowed. Assume the esophagus pipe has a diameter of 0.02 m, a velocity of 0.5 m/s would give the flow a Reynolds number, *Re*, of around 10,000:

$$Re = \rho v d/\eta, \tag{4}$$

where ρ and η are the density and viscosity of water, d is the diameter of esophagus pipe, and v is the velocity of bolus flow. A Reynolds number above 2100 would indicate a turbulent flow. A flow with *Re* of 10,000 is indeed very turbulent. Although Hasegawa et al. (2005) attributed high velocity as a reason of less easy swallowing water than swallowing yoghurt, a real reason could be the turbulent nature of the former. A turbulent flow could cause a back flow and aspiration to the trachea. Based on this consideration, it is reasonable to believe that a relatively high viscosity of food (bolus) could have the advantage of slowing down the bolus flow and making swallowing easier and safer.

Kim, McCulloch, and Rim (2000) used finite element method (FEM) and images from cine-computed tomography technique (CT) to analyse the pharyngeal pressure during swallowing a liquid bolus. The region from the base of the tongue to the entry of the esophagus was divided into 8 levels, and the tongue was likened to a piston, forcing the bolus into the pharynx. They calculated pressure gradients from one level to another, ranging from 10 to 55 mmHg (or from 1.3 to 7.3 kPa). It was concluded that the contraction velocity as well as the pressure gradients were much higher at the upper levels of the pharynx. More recently, Meng, Rao, and Datta (2005) applied a computational fluid dynamics (CFD) method to simulate the swallowing flow of food boluses. They demonstrated that water ($\rho = 1000\,kg/m^3$, $\eta = 1\,mPa\,s$) was transported through the pharynx at a much higher flow rate than the barium sulphate mixture, a fluid of much higher density and much higher viscosity ($\rho = 1800\,kg/m^3$, $\eta = 150\,mPa\,s$). It was predicted that such a high flow rate would cause parts of the water bolus to flow backwards. This finding agrees well with the experimental observation by Hasegawa et al. (2005), where bolus flow was believed to be turbulent with a high Reynolds number (see above).

Meng et al. (2005) further indicated that non-Newtonian fluids increased swallowing time more effectively than Newtonian fluids and were safer to swallow for those who have swallowing difficulty (e.g. old people, patients with dysphasia, etc.). Food boluses of non-Newtonian nature could either slow down the swallowing process or trigger the subject to swallow a smaller amount, allowing the neuromuscular system more time to shut off air passage and reduce the risk of aspiration (Meng et al., 2005). These findings provide very useful guidance to food manufacturers in designing and manufacturing foods for consumers

with special needs, such as infants, senior citizens, and patients of swallowing disorders (Fujiu-Kurachi, 1999; Mitsuboshi et al., 2006; Penman & Thomson, 1998).

Regardless of these progresses, we still have very limited knowledge about the rate of bolus deformation (or the shear rate). So far no reliable technique is available to measure *in vivo* such a parameter and the irregular oral geometry makes the characterization of deformation even more difficult. Even though Cutler et al. (1983) showed that fluid viscosity obtained at a shear rate of $10\,s^{-1}$ was most relevant to the sensory perception, it is generally believed that the deformation to a food bolus may be hugely different from this prediction. The parallel plates model, used by Nicosia and Robbins (2001) to simulate the squeezing effect of food bolus from the oral cavity into the pharynx, predicted a maximum shear rate of 180,000 and $3000\,s^{-1}$ for boluses of viscosity of 1 mPa s and 1 Pa s, with the assumption that a pressure of 13.3 kPa was applied by the tongue against the palate. Even though there has no direct experimental evidence, it must be said that such high rates of deformation are very unlikely. The CFD simulation by Meng et al. (2005) appeared to be more realistic in predicting the deformation rate of bolus flow. They predicted a maximum shear rate of swallowing water of around $400\,s^{-1}$.

The deformation of food bolus is expected to be not only in shear but also in elongational. This can be clearly seen from the videofluroscopy and the real-time MRI pictures (Fig. 4, Buettner et al., 2001), where the bolus was extensively stretched during swallowing. Assuming a bolus of 15 ml being swallowed at a speed of 0.5 m/s (as determined by Hasegawa et al., 2005) and a transit time of 1 s, one can estimate that the bolus could be extensionally stretched at a rate of around $1\,s^{-1}$. Unfortunately, although limited work has been conducted on the extensional rheology of food materials (Chan et al., 2007), little attention has been on the extensional rheology of food oral processing and swallowing. An important reason for the lack of the progress on food extensional rheology is because of the limit of experimental techniques. With the recent developments of extensional rheometers (Meissner & Hostettler, 1994; Rodd, Scott, Coopper-White, & McKinley, 2005), it is for sure that more research findings will become available in future in this important area.

6. Summary

Food texture is a sensory perception derived from the structure of food (at molecular, microstructure, and macroscopic levels). The appreciation of food texture could involve one or many stimuli, including visual, audio, touch, and kinaesthetic, working in combination. While seeing and touching could provide useful information, oral processing is above all the most important stage for textural perception and appreciation.

Food oral processing involves a series of complex operations, including grip and first bite, first stage transportation, chewing and mastication, second stage transportation, bolus formation, and swallowing. These operations could happen in sequences (such as first bite, transportation, and mastication), or sometimes occur simultaneously (such as oral selection, second stage transportation, and bolus formation). For most cases, at least two swallows take place, followed by the final oral clearance. While chewing appears to be rhythmic, swallowing is a patterned behaviour controlled by the central nervous system and is an action "inserted" in the eating cycle.

Two major variations should be considered in food oral processing and sensory perception: the individuality of human beings and the properties of food materials. The former reflects the variation of oral physiology (because of age, sex, health status, etc.), while the latter reflects the effects of food rheology and texture (such as hardness, softness, geometric dimensions, etc). Both variations play an important role in influencing how a food is orally processed and sensually perceived.

The fracture and breaking of a food and/or the yield and flow of a food depend highly on its rheological properties. However, rheology analysis of food oral deformation is complicated by at least two other factors: the irregularity of oral cavity and the presence and incorporation of saliva. The irregularity of oral cavity makes it difficult to predict the dimension and magnitude of food deformation. The presence of saliva means that the food will not only continuously change its geometry (size and shape) but also change its mechanical properties because of the adsorption and interaction of saliva.

Food has to be chewed and masticated during oral processing, so that it is reduced to an appropriate particle size and incorporated with the right amount of saliva for bolus formation. A food bolus is essentially an agglomeration of fractured food particles lubricated by the saliva. The rheology of a food bolus will be very different from that of the food prior to oral processing. A plausible criterion of bolus formation and swallowing is the maximum cohesive force of the bolus. A food bolus is sheared and stretched prior to and during swallowing. It appears that a reasonable viscosity could be beneficial in decreasing the speed of bolus flow and, therefore, reducing the risk of aspiration.

From this review, it is clear that texture perception and appreciation is a dynamic process, based on the perception obtained from continuous oral destruction (and breakdown) of food material. Relating sensory texture of a food to its microstructural, rheological and fracture properties is not an easy task (Foegeding, 2007). Classical rheology and mechanical tests (both small deformation and large deformation) are still useful and essential in revealing material properties of foods. However, understanding and quantifying the dynamic changes of food structure during oral processing will be a key area for food texture studies in future. In doing so, more developments of measuring techniques to quantify the in-mouth structuring of food

materials will be needed (Van Aken, Vingerhoeds, & de Hoogs, 2007).

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